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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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ABSTRACT

Polymer gages developed by the National Bureau of Standards (NBS) have been tested extensively in the NBS Geotechnical Engineering Laboratory to evaluate their capability and reliability for use in determining dynamic soil stresses generated by blast loadings. Penetration of soil grains into the gage surface was found to be the major concern and a major effort was undertaken to develop the most appropriate protective covering. Gages were dynamically loaded to develop their corresponding calibration curves. The test results indicate that the gage provides a linear relationship between the input stress and the gage output over the stress range tested. The calibrated linear relationship is not affected by the gage location, i.e., whether in soil or on a concrete pedestal; the thickness of the protective covering; the frequency of the impact load; and the length of the co-axial cable used in testing.

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NOTATION

Ar = Aspect ratio; the ratio of total gage thickness to total gage diameter, T/D.

d = Diameter of active area of the gage in mm or inches.

d_h = Hydrostatic piezoelectric constant.

D = Total gage diameter in mm or inches.

D_{50} = Mean soil grain size in mm or inches.

Eg = Gage modulus in KPa or psi.

E_{gp} = Modulus of PVDF material in KPa or psi.

Egc = Modulus of Polycarbonate sheet in KPa or psi.

E_m = Soil Modulus in KPa or psi.

Emd = Modulus of sand under impact loading in KPa or psi.

E_{ms} = Modulus of sand in KPa or psi.

ER = Modulus ratio; the ratio of gage modulus to soil modulus, E_g / E_m.

Ko = Coefficient of earth pressure at rest.

t = Thickness of active area of the gage in mm or inches.

T = Total gage thickness in mm or inches.

σ_g = Gage stress in psi.

σ_a = Axial stress in psi.

ν = Poisson's ratio of soil.

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1. INTRODUCTION

The measurement of stresses in a soil mass due to external loads poses an important challenge to the geotechnical engineering profession. To properly measure these stresses is even more critical at present since these measurements are required for their comparison with numerous analytical methods that can be used for the prediction of these stresses.

There have been many studies conducted in the development and evaluation of soil stress gages, including the work by Abbott, et al. [1], Ingram [12], Hamilton [10], Selig [20], Triandafilidis [25], Krizek, et al. [15], Weiler and Kulhawy [26], and others. Most of their efforts were concentrated on the measurement of stresses due to static loads. An excellent review, evaluation, and synthesis of the development of soil stress gages was given by Weiler and Kulhawy [26].

Measurement of soil stresses due to dynamic loads is also critical for studying problems related to the response of soils and structures buried in soils subjected to earthquake and blast loading conditions. Many studies on this subject have been conducted in recent years. Some examples include the work by Baum and Kovarna [3], Burcham [6], Keough et al. [13], Labreche et al. [16], and Tracy [24].

A number of factors affect stress gage performance in soils. Weiler and Kulhawy [26] in their review separated these factors into three areas. They are: a) stress gage properties and geometry; b) properties of the soil in which the gage is placed; and c) environmental conditions.

Area (a) includes aspect ratio, A_r, the ratio of total gage thickness to total gage diameter, T/D; modulus ratio, ER, the ratio of gage modulus to soil modulus, E_g / E_m; gage deflection and arching; stress distribution over the gage surface; and lateral stress rotation. Researchers have long recognized that a gage with small aspect ratio, when it is emplaced in soil, should introduce the least disruption in a uniaxial stress field. A ratio of less than 1/5 was suggested by a Waterways Experiment Station study in 1944 [22] and this criterion has been followed by gage designers since. Early researchers also recognized the fact that a stress gage stiffer than its surrounding soil will result in an over-registration in its measurement and a softer gage will otherwise under-register. Several studies have been conducted to establish the correlation between aspect ratio and modulus ratio [22, 17]. A classical study was done by Loh in 1954 [17] describing the development of an internal stress gage for cementitious materials. Using the theory of elasticity, Loh developed the relationship between the response factor, i.e., the ratio of gage stress to axial stress, σ_g / σ_a and the modulus ratio, E_g / E_m, for such materials. This relationship is modified for the present study by using a typical

Poisson's ratio of 0.33 for sandy soil as shown in figure 1. This figure suggests that we should expect accurate measurement from a gage if the gage is designed with an aspect ratio not greater than 1/10 and the modulus ratio not less than unity.

A gage with low values of A_r and high values of E_R should also minimize the development of arching in soil. Arching is the phenomenon by which normal stresses in soil are changed into shear stresses, thereby developing the ability of the soil to support itself when the external support is removed. As a result, the gage will register virtually zero stresses when arching is developed at the interface of the gage and its overlying soil.

Normal stress distributions over gage surfaces, examined by Hvorslev [11] and called Terzaghi stress distributions, are shown in figure 2. Figure 2 also presents the results of elastic analyses by Monfore [18], and Peattie and Sparrow [19] to assess stress concentrations around the outer perimeter of a gage. The figure indicates that a fully active gage face will inevitably cause over-registration. Thus, it is necessary to use an inactive and stiff annular rim around the gage to reduce the sensitive area of the gage. Monfore [18] suggested that the sensitive area of a gage be less than 45 percent of its total area, i.e., $d^2 / D^2 < 0.45$. Peattie and Sparrow [19] considered it necessary to further reduce this ratio to less than 0.25 to ensure a relatively uniform stress distribution across the gage suface. Another factor affecting uniform stress distribution over the gage surface is the possibility of measuring point loads due to the particulate nature of the soil. From their study, Weiler and Kulhawy [26] suggested that the ratio of active gage diameter to mean soil grain size, d/D_{50}, had to be 10 or greater to keep the error from point loadings to less than 3 percent.

The amount of applied lateral stress acting normal to the gage surface was evaluated by Askegaard [2]. His findings were replotted by Weiler and Kulhawy [26] as shown in figure 3. Figure 3 shows that the Poisson's ratio of a soil is the overriding factor that controls the amount of lateral stress transfer. For example, a gage with an aspect ratio of 1/10 would result in about 12 percent of lateral stress transfer for a soil with a Poisson's ratio of 0.33; whereas the transferred lateral stress would be less than 5 percent if the soil has a Poisson's ratio of 0.4.

Area (b) affecting stress gage performance includes the properties of a soil itself that will affect gage stress measurement. Generally, two types of calibration tests have been conducted to determine the gage response under static loading: The K_o condition and the triaxial test condition. Different soil stress-strain relationships may be obtained from these two test conditions, resulting in different gage stress measurements. The method of gage emplacement in soil also affects the gage response to the imposed load. Taylor [23] introduced the term "pocket action" to describe the error in registration if the soil surrounding a gage is placed at a different density from the rest of the soil. Over-registration of the gage will occur if the surrounding soil is denser; otherwise it will under-register. Weiler and Kulhawy [26] indicated that an error of this type amounts to 10 to 20 percent of the actual stress. Nevertheless, the actual error in measurement is difficult to control during field operations. Hadala [19] suggested that the simplest placement techniques are the ones most easily reproducible and so cause the least scatter in results.

In area (c), the gage should be designed to resist corrosion as well as moisture which the gage will inevitably encounter during its use in the field. The gage calibration should also include the possible change of gage response due to the change of temperature of the environment that may occur during the service life of the gage.

When the gage is designed to be used to measure soil stresses generated by dynamic loads, other characteristics of the gage such as natural frequency, inertia force due to the weight of the gage, and response time should be considered. The natural frequency of the gage should be much larger than the maximum frequency anticipated from loading to allow for reliable stress measurement. From his study, Triandafilidis [25] suggested that the ratio of these two frequencies should be at least three to five for gage design consideration. A gage which is heavier than the soil it replaces will result in an additional inertial force during dynamic loading. This effect will be especially critical for high frequency loading conditions.

The stress-strain characteristics of a soil are affected by both the magnitude of strain and the stress level developed in the soil mass by dynamic loads. Figure 4 gives an example of the effect of the stress level on a stress-strain relationship [14]. From point 2 to point 3 in the figure, soil exhibits a seven times increase of its modulus as compared to the value from point 1 to point 2 which covers a lower stress range. Studies conducted by Shannon and Wilson and Agbabian-Jacobsen Associates [21] reported that for small strains associated with shock type loading, the modulus of elasticity of a soil may be as much as five to ten times higher than that measured when the associated strain magnitude is large.

At present, two types of gages are commonly used for in-situ soil stress measurement during blast loading. The first type was designed by the Waterways Experiment Station (WES) and is called the WES-SE gage. The gage is of the diaphragm type with an aspect ratio of about 0.1. For example, the 34.5 MPa (5000 psi) version of the gage used in an Air Force sponsored research conducted by the New Mexico Engineering Research Institute had a modulus of 3.3 GPa [16]. The second type, the SRI gage, which is a high modulus and low aspect ratio stress gage, has been under extensive development by SRI International and is referred to as the SRI gage. A detailed description of the gage is given by

Keough, et al. [13]. Figure 5 provides a schematic view of the gage. The gage consists of piezoresistance foil made of Ytterbium (Yb), bonded between thin layers of an insulating material (Kapton or epoxy). To increase the effective modulus of the gage, the foil and insulating layers are sandwiched between relatively thick, high modulus steel plates.

The gage NBS is developing, referred to as the NBS polymer gage, uses different principles. Principles and information on the calibration and testing of the gage are presented in the next three sections.

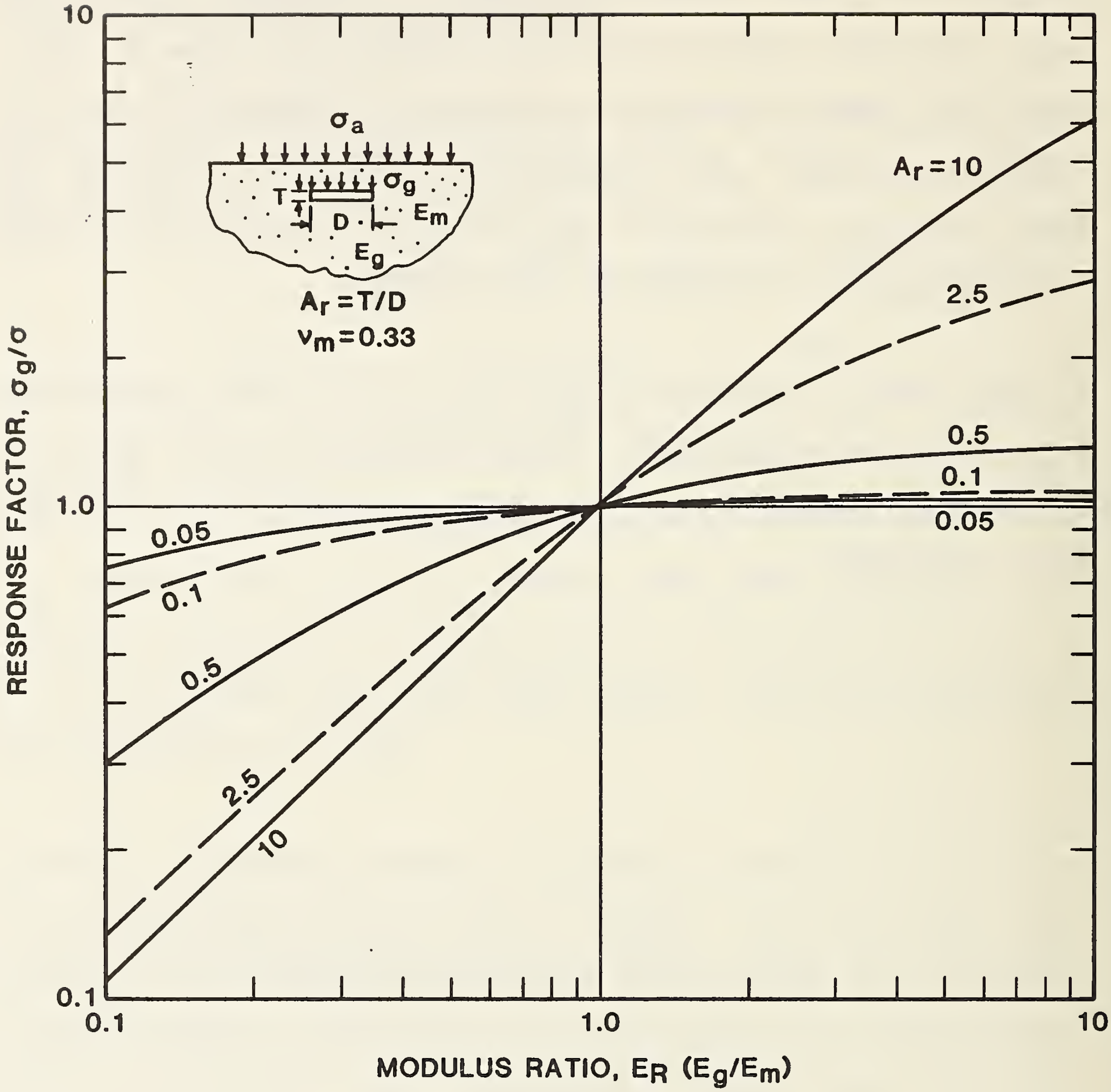

Figure 1 Theoretical Soil Stress Gage Response (Ref. 17)

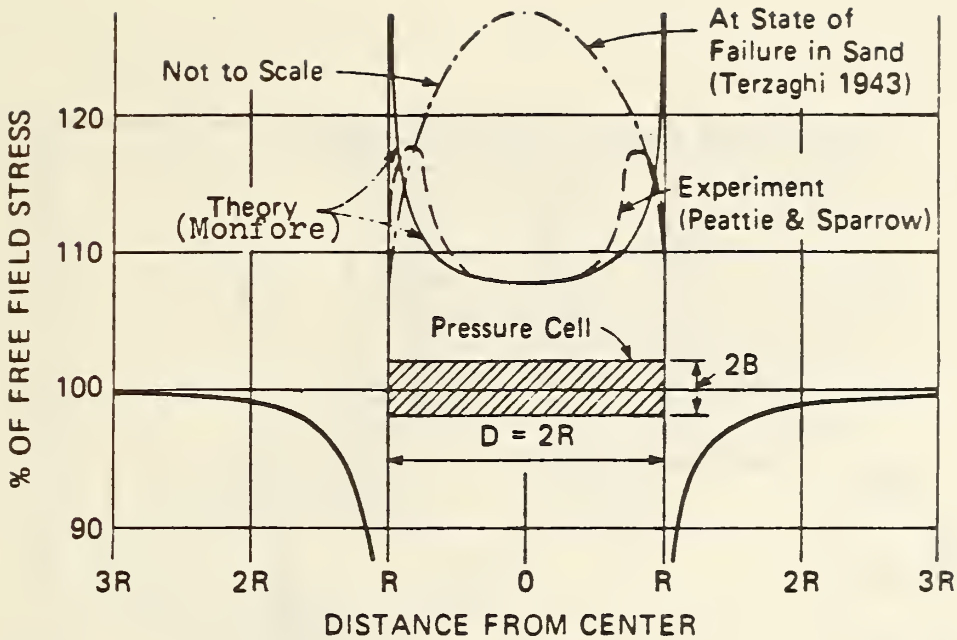

Figure 2 Stress Distribution over Stress Gage (Ref. 11)

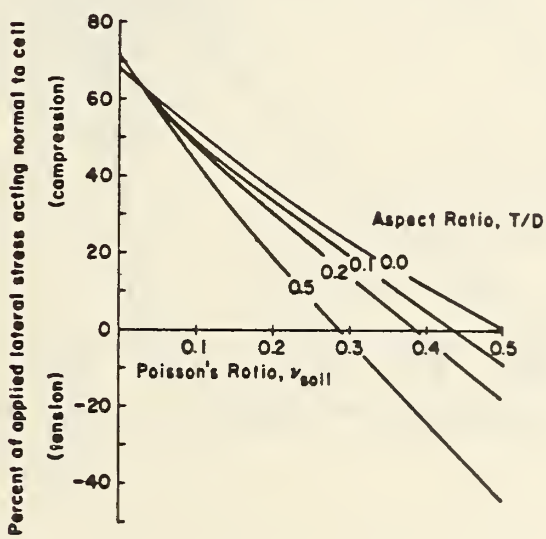

Figure 3 Theoretical Lateral Stress Rotation for Rigid Ellipsoidal Inclusion (Ref. 2)

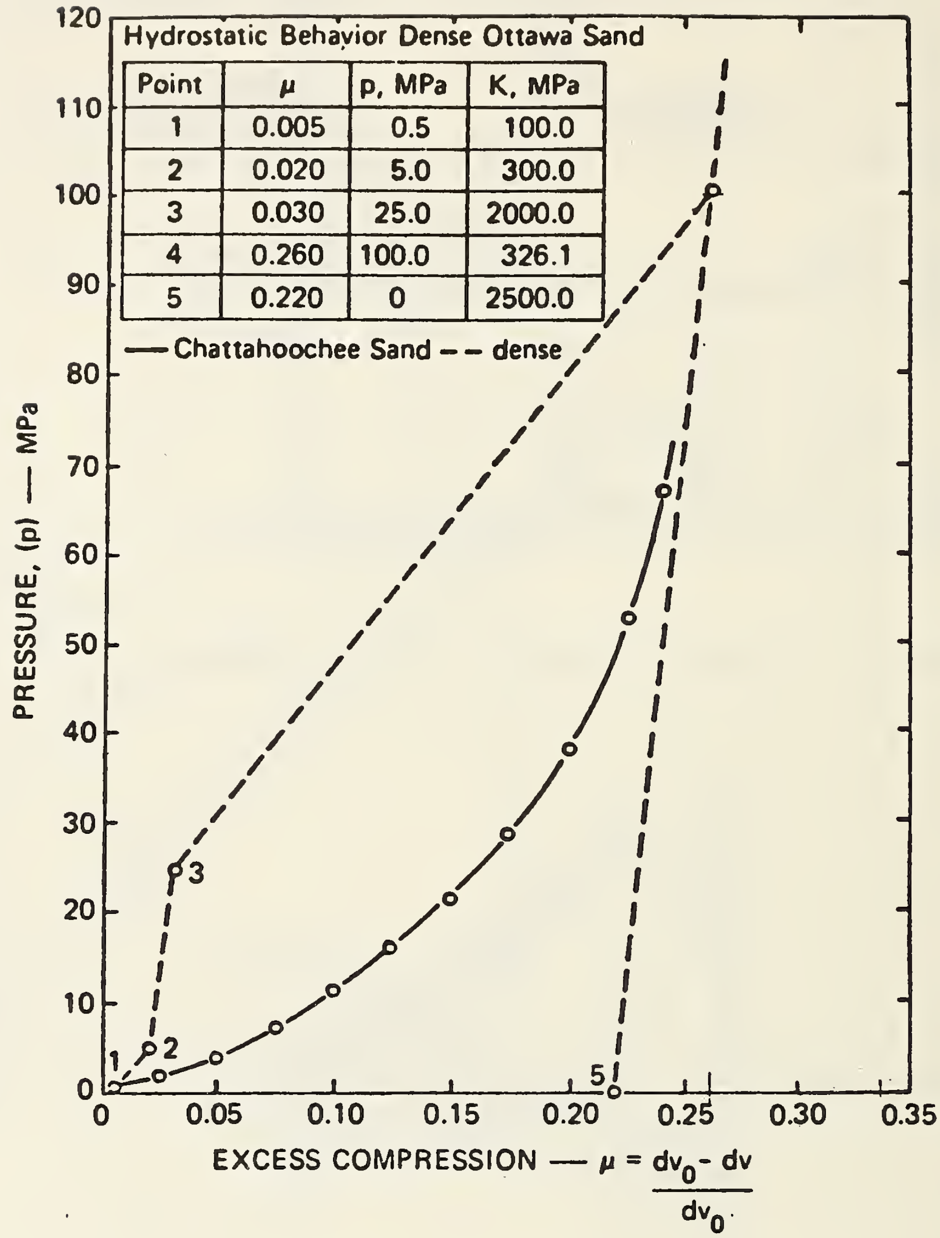

Figure 4 Computational Model of Dense Ottawa Sand - Volumetric Behavior (Ref. 14)

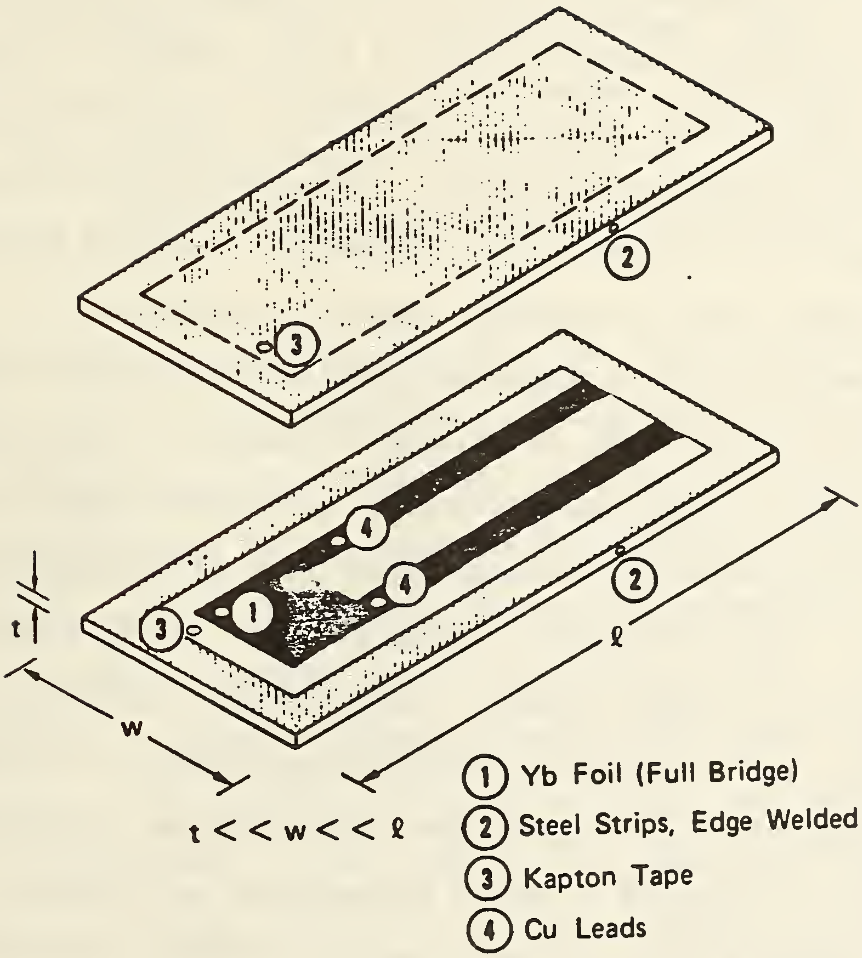

Figure 5 Basic High Modulus Configuration for the SRI Gage (Ref. 13)

2. THE NBS POLYMER GAGE

2.1 The Polymer Material

Piezoelectric polymers are a relatively new kind of material for use in measuring instruments and detecting devices. The principal advantages of this material are their extremely good sensitivity as a dynamic pressure detector, and a wide variety of properties that allow them to be used in situations where conventional sensing materials are unsuitable. These materials have high internal damping, high natural frequency, and can be obtained readily in thin, light, flexible sheets, in contrast to conventional piezoelectric and magnetostrictive materials, which are stiff, dense, brittle, and relatively resonant. Its flexibility makes this type of gage particularly attractive for its use in geotechnical engineering problems associated with dynamic loading conditions. For example, the gage can be placed behind retaining walls to study lateral earth pressure distribution due to earthquake loads, placed underneath pavement or airport runways to determine the stress distribution due to traffic and impact loads, or located in earth embankments at different orientations to measure stress distributions within the embankment during earthquake loading. The gage can also be installed in soil samples in laboratory test experiments to evaluate the stress distribution within the sample during dynamic testing.

The mechanism of piezoelectric activity in a polymer is complicated. The composition of the polymer, its division into amorphous and crystalline parts, the crystal structure, the presence of surface and space charges and of ionic impurities have all played parts in different explanations. Schematically, we may consider the polymer to consist of long chains of identical units called monomers. In the case of polyvinylidene fluoride (PVDF), which is the material used in the NBS polymer gage construction, the chains consist of linked carbon atoms. Each monomer has two carbons, one joined to two hydrogen atoms and the other joined to two fluorine atoms. Each monomer has a strong dipole moment.

As the material is received, the dipoles are oriented randomly as shown in figure 6a. The material is then heated and subjected to a strong electric field before returning to room temperature with the applied electric field maintained during the cooling process. This process results in the alignment of a significant number of dipoles normal to the plane of the sheet as shown in figure 6b. The dipoles can be considered to be stiffer than the bonds between dipoles in adjacent chains so that any stimulus that changes the thickness of the sheet will change the surface density of charge on each surface. A compensatory flow of charges through the circuit connecting the electrodes forms a measureable signal as shown in figure 6c.

Two methods are currently used for manufacturing the NBS polymer gages using PVDF material. One involves the technique of mechanically orienting a polymer sheet, followed by vacuum depositing aluminum electrodes on the sheet, and finished by poling the sheet in a high electric field. The other method includes annealing a PVDF sheet, evaporating aluminum electrodes on the sheet, and followed by poling the sheet in a high electric field. Detailed descriptions of the gage fabrication are beyond the scope of this report; however, they can be found in publications by Bur and Tsao [5] and DeReggi [7] of the National Bureau of Standards.

2.2 Previous Studies Using The Gage for Dynamic (Impact) Pressure Measurement

The polymer gage has been used in several studies to measure dynamic pressure developed by impact loads. In a 1975 study by DeReggi [7], the polymer gage was designed, constructed, and calibrated for recording pressure transients developed over the interface between two bodies as a result of impact. The measurement of interface pressure is of interest in studying injuries sustained in vehicular crashes. The intended primary response of the gage is to compression in the thickness direction, which is produced by either hydrostatic or normal pressure. Two methods of testing were developed to measure the gage response. The first method uses a mechanical press for static calibration of gage output under approximating uniaxial compression. The second method uses a drop-test machine for the measurement of gage output under conditions in which pressure and flexure are simultaneously applied.

Another study by Burcham [6] devoted its effort to evaluate the following aspects of the gage: a) charge/stress sensitivity under dynamic loading; b) survivability under repeated loading; c) survivability of thermal excursion, and d) response factor in sand. Tasks a) through c) were carried out in a series of dynamic tests using a dynamic test cell. The cell was filled with hydraulic oil and a plunger was employed to introduce a hydrostatic pressure step with a 10 ms rise time. Task d) was accomplished by embedding a polymer gage in sand inside a vertical shock tube. The rise time in this test was about 10 s. Results of Burcham's study indicated that the gage showed a very stable charge/stress sensitivity for a hydrostatic pressure range from 0 to 2000 psi. Compared to a Norwood reference gage in the same dynamic test cell set up, the difference in pressure response measured by these two gages was on an average 3 percent. However, a larger difference was observed from the results of tests under elevated temperature conditions. A test conducted at 97o F showed that the pressure registered by the polymer gage was about 19 percent higher than that measured by the Norwood reference gage. Additional tests following the elevated temperature test indicated that the difference in measurement between these two gages returned to 3 percent; i.e., the increase in charge sensitivity due to elevated temperature had no lasting effect. Shock tube tests conducted by emplacing a polymer gage in sand resulted in a response factor of 0.963, which was expected for a gage of this type with an aspect ratio of 0.002. Burcham concluded further that gage placement for a polymer gage is not as critical as it is for rigid gages with smaller aspect ratios, e.g., the WES-SE gage.

Two test programs were carried out by Tracy [24] using polymer gages. One program placed a bilaminated polymer gage in a Hopkinson Bar test set up to evaluate gage response to various impact velocities. The other program used a shaking table to study the gage response to various frequencies and higher g-load forces. Resistive type strain gages were used as reference gages during testing. It was found that the polymer gage produces an output signal, measured in volts, of over 500 times that of the resistive strain gage, indicating its superior charge/stress sensitivity. A good correlation between the polymer gage response and the measured impact velocity, as well as the resistive strain gage output was also established. Results of the shaking table tests indicated a linear relationship between the gage output and g-loads for a range of values from 2 g to 21 g, when the table was shaken at a constant frequency of 2000 Hz.

2.3 Gage Design and Calibration for the Present Study

Polymer gages used in the present study were fabricated in the laboratory of the Polymers Division of the National Bureau of Standards. In the current design, the pyroelectric characteristics of the polymer gage have also been considered in developing a temperature compensated pressure gage. Details of this development are given in References [4a, 4b, 4c, and 4d]. It should be noted that the gage design objective is to develop the gage to properly measure both air pressures and soil stresses due to blast loading. The pyroelectric response of the gage is produced by adiabatic heating of the gage itself and its surroundings due to the imposed pressure pulses. Adiabatic heating of the PVDF will coincide with its pressure change, i.e., there will be no time delayof a thermal energy pulse with respecttothepressure pulse. When adiabatic heating of the surrounding medium occurs, the thermal time constant for diffusion of heat into the gage will determine its pyroelectric response as a function of time. If the temperature changes in PVDF and its surroundings are identical, then there will be no heat transfer and the pyro-electric response will be due to adiabatic heating of the PVDF only. Calculation for this case shows that the pyroelectric charge signal is approximately 8 percent of the piezoelectric charge [8].

In general, adiabatic heating of both PVDF and its surroundings along with the time dependent nature must be considered. For the PVDF gages used in this study, the time constant for heat to diffuse into the gage from the surroundings is approximately 30 ms. Therefore, for pressure measurements in a time frame much less than the time constant of the PVDF material, temperature compensation can be achieved by applying an 8 percent correction factor to the gage signals [4d]. For longer times, the conduction of heat from the surroundings must be measured in order to apply the appropriate correction factor to the output signal of the gage.

This method of temperature compensation was developed using the following approach: a) measure the temperature change of the PVDF gage using a thermocouple with a fast response time; b) amplify the thermocouple voltage to equal that generated by the pyroelectric response of the gage; c) add the gage voltage to the amplified thermocouple voltage yielding a corrected gage voltage. A compensation amplifier was developed specifically for this purpose and was used in all the tests presented later in this report.

Temperature compensation is important if air pressure measurement is of interest. In an experiment conducted in a triaxial soil test chamber where the chamber was pressurized to 100 psi, the temperaturein the air chamber rose from 70 $^{\circ}$ F to a peak of 83 $^{\circ}$ F. Thechamber temperature returned to 70° F after about 70 minutes of observation when the chamber pressure was maintained at 100 psi. On the other hand, the thermocouple within the soil sample which was placed in the chamber indicated only a small rise of temperature from 70° F to a peak of 72.5° F after 25minutesof observation. As it will be shown later in this report, the temperature rise of the PVDF gage embedded in soil due to impact loading is even smaller being a maximum of about 0.6 $^{\circ}$F. As a result, no measureable difference between the corrected and uncorrected output signals from the polymer gage can be found for the range of stresses (up to about 2000 psi) introduced to the polymer gage.

Several versions of polymer gages were fabricated. The difference in each design evolved from the need to improve the gage design following Geotechnical Engineering Laboratory testing. In all cases, the gage consists of a basic unit called "bilaminate construction" with a thermocouple (figure 7). It is made from two sheets of PVDF which are laminated together using epoxy. Each sheet (0.012 or 0.025 mm thickness) contains an active area on which aluminum electrodes are deposited. The active area is 10 mm (d) with an overall gage diameter of 15 mm (D). A copper-constantan thermocouple junction, made of 0.075 mm wire, is placed between the two sheets and within 2 mm of the active area of the gage. The overall thickness of the active area of the gage in a bilaminate construction is approximately 0.1 mm (t). This gage design will be referred to as Type A in the presentation.

Prior to lamination the electroded regions are made piezoelectrically active by poling them at room temperature with an electric field of 2 megavolts per centimeter (MV/cm). The active areas are then laminated face to face so that the polarization vectors in each element point in opposite directions. In this bilaminate pattern, the ground electrodes are on the exterior surface and the inner electrodes carry the signal potential. The advantage of this design is that signals generated in the two elements by bending are opposite in polarity and add to zero.

Other gage designs are given in figures 8 and 9. Figure 8 shows a Type B gage which is a "bilaminately constructed" gage sandwiched by two additional layers of PVDF of equal thickness to serve as protection for the inner two layers so that the gage can be used in environments requiring mechanical ruggedness. The

Type C gage is similar to Type B but indium rather than aluminum is used as an electrode because of its better ductility. Figure 9 shows the final design of the gage. The protective covers used in this design are 0.125 mm polycarbonate sheets (Type D gage). The Type E gage is similar to Type D except that 0.250 mm polycarbonate sheets were used. As shown in figure 9, Type D and E gages use both aluminum and indium as electrodes. The overall thickness of the gage in its final design is about 0.35 mm (T). Figure 10 shows a picture of an NBS polymer gage in its latest design.

A check of the polymer gage in its present design against the criteria for gage design presented and discussed earlier in this report is of interest. To do this, we have selected the following information related to the characteristics of the gage and its surrounding medium:

<u>The NBS Polymer Gage:</u>

d = diameter of the active area = 10 mm = 0.39 in

D = overall diameter = 15 mm = 0.59 in

t = thickness containing the active elements = 0.100 mm = 0.004 in

T = overall thickness = 0.350 mm = 0.014 in

E_{gp} = modulus of PVDF = 10^6 KPa = 1.5 x 10^5 psi

E_{gc} = modulus of polycarbonate sheet (used in computation) = 10^7 KPa = 1.5 x 10^6 psi

<u>Surrounding medium</u>: Typical modulus values of sandy soils as used in the computation [27]

E_{ms} = modulus of sand
= 2500 psi (1.7×10^4 KPa) at loose state
= 9000 psi (6.2×10^4 KPa) at dense state
= 5700 psi (4.0×10^4 KPa) as an average and typical value

E_{md} = 57,000 psi (4×10^5 KPa) under impact loading

= Poisson's ratio = 0.33 as a typical value

D_{50} = mean soil grain size = 0.3 mm = 0.012 in

Parameters required for checking are computed as below:

$$E_R = Egc/Ems = 1.5 \times 10^6 / 5.7 \times 10^3 = 260$$

$$ER = Egc/Emd = 1.5 \times 10^6 / 5.7 \times 10^4 = 26$$

(if modulus under impact loading is used)

$$A_r = T/D = 0.014" / 0.59" = 0.024$$

$$d^2 / D^2 = 0.39^2 / 0.59^2 = 0.44 < 0.45$$

$$d / D_{50} = 0.39" / 0.012" = 33 > 10$$

Referring to figure 1,a gage with an aspect ratio, A_r , of 0.024 and a modulus ratio, E_R ,of either 260 or 26, will warrant a response factor, σ_g/ σ_a, of close to unity. The ratio between the sensitive area of the gage and the total gage area falls slightly below 0.45, which is satisfactory according to the criterion recommended by Monfore [18]. It should be noted that the dimensions of both d and D in the current gage design were decided upon for the convenience of soil testing. The active area of the gage can be made to any shape and any size to fit the specific need for using the gage. Likewise, the total area of the gage can also vary, reducing the ratio of d^2/D^2 to a valve much lower than 0.45. The ratio of d/D_{50} is 33 for the present gage and for the sandy soil from Florida used in testing. This value satisfies the minimum value of 10 recommended by Weiler and Kulhawy [26].

Several types of tests were performed on each gage in the laboratory of the Polymers' Division prior to its testing in the Geotechnical Engineering Laboratory. Details of these tests are presented in an NBS report by Bur and Roth [4d]. These tests are briefly described below.

Two experimental tests were devised in an attempt to simulate the onset of a thermal pulse at the site of the gage. The objective of these two tests was to determine the amount of temperature compensation attainable using a specially designed circuit. In the first test, which is called a water immersion test, a gage with an encapsulated thermocouple is immersed into a cold water bath by slapping the broadside surface of a gage against the surface of the water. In doing so, the surface of the gage in contact with the water is held at the bath temperature and heat diffuses in such a way that the gage reaches a temperature equal to that of the bath. In the second test, which is called a light flash experiment, the surface of the gage was sprayed with a dull black paint which serves as a light absorber. A light pulse was then directed at the surface of the gage and a pulse of thermal energy was imparted to the surface of the gage which subsequently diffused into the gage. At longer time intervals the gage has an average temperature which is higher than that of its surroundings. The water immersion test approximates the physical conditions present when the gage is buried in soil, i.e., the gage maintains contact with the soil which acts as a thermal reservoir. The light flash experiment approximates conditions relevant to the gage in air.

Gages were also tested in an oil pressure cell to obtain the value of the hydrostatic piezoelectric constant, d_h . The oil bath test set up is shown schematically in figure 11. The value of d_h was evaluated for dynamic pressure pulses having a pulse width of approximately 10 ms and peak pressures between 7×10^3 and 2.1×10^4 KPa (1000 and 3000 psi). The presure cell consists of a stainless steel block, 7.5 cm wide, 16 cm long and 15 cm high (3 in. by 6-1/4 in. by 6 in.), with a 1.9 cm bore traversing the 16 cm direction. At one end of the bore, the reference transducer is placed. At the other end, feedthrough connectors carry signals from the PVDF gage and thermocouple. A plunger fits as a piston into a 2.54 cm bore with vertical orientation which intersects with the horizontal bore. In preparation for measurements, the cell is filled with either a vacuum pump oil or an alkyl-benzene dielectric oil. Care was taken to remove all visible bubbles from the oil, but the oil was not degased. During the test, the cell was placed at the bottom of a vertical column which guides the drop weight as it falls onto the plunger.

The PVDF gage is placed in the oil pressure cell at room temperature and a pressure pulse is initiated by dropping a 16 kg (35 lb) mass through a distance of approximately 30 cm onto the plunger in the cell. Signals from an accelerometer, which is attached to the top of the drop weight, the gage, the reference presure transducer, and the thermocouple are captured individually by a transient recorder signal processor and are used to compute the hydrostatic piezoelectric constant, d_h. A typical plot between the temperature compensated pressure pulse from the polymer gage and that from the reference transducer as a function of time are given in figure 12.

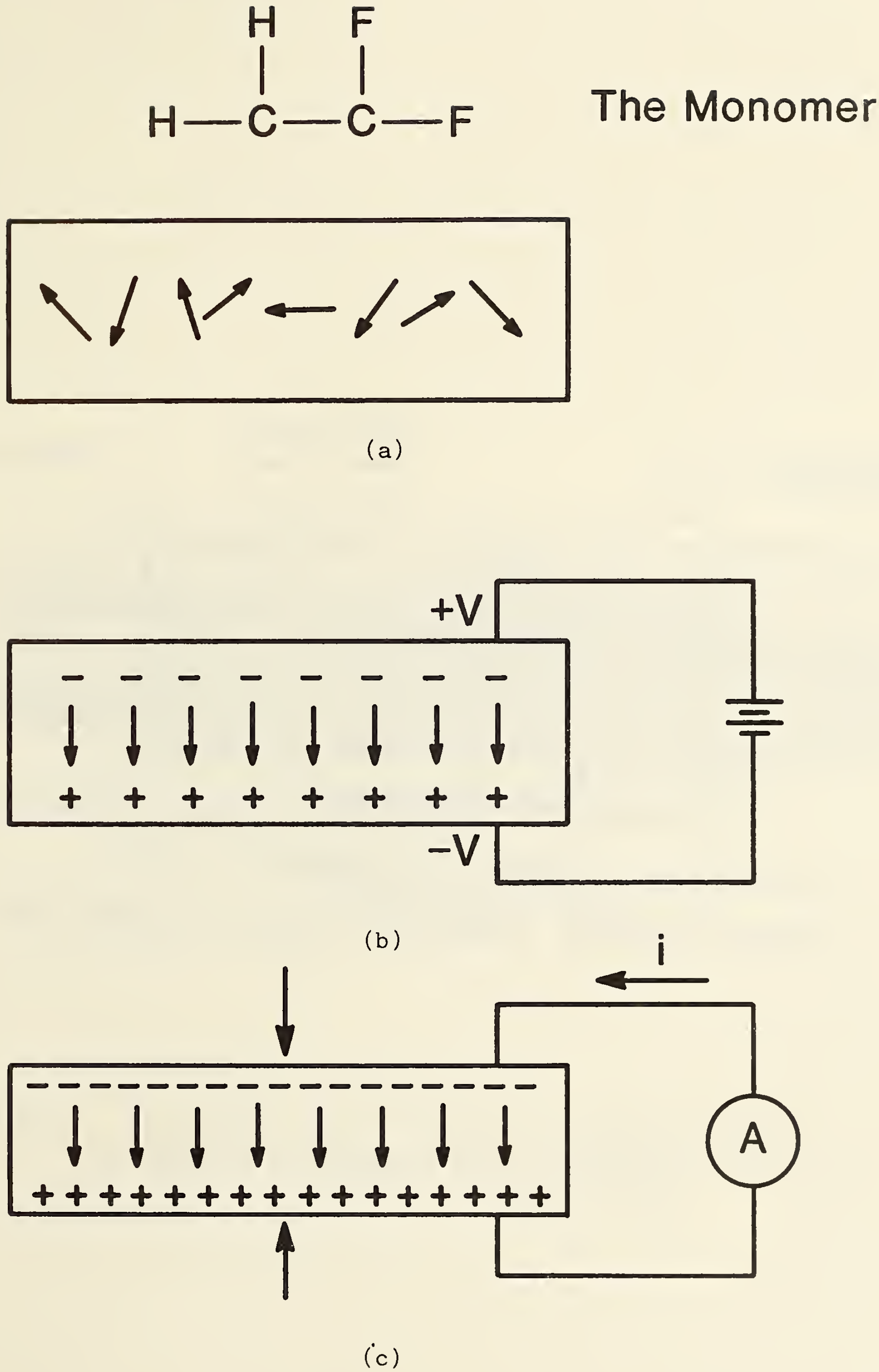

Figure 6 The Polymer Material – Polyvinylidene Fluoride (PVDF)

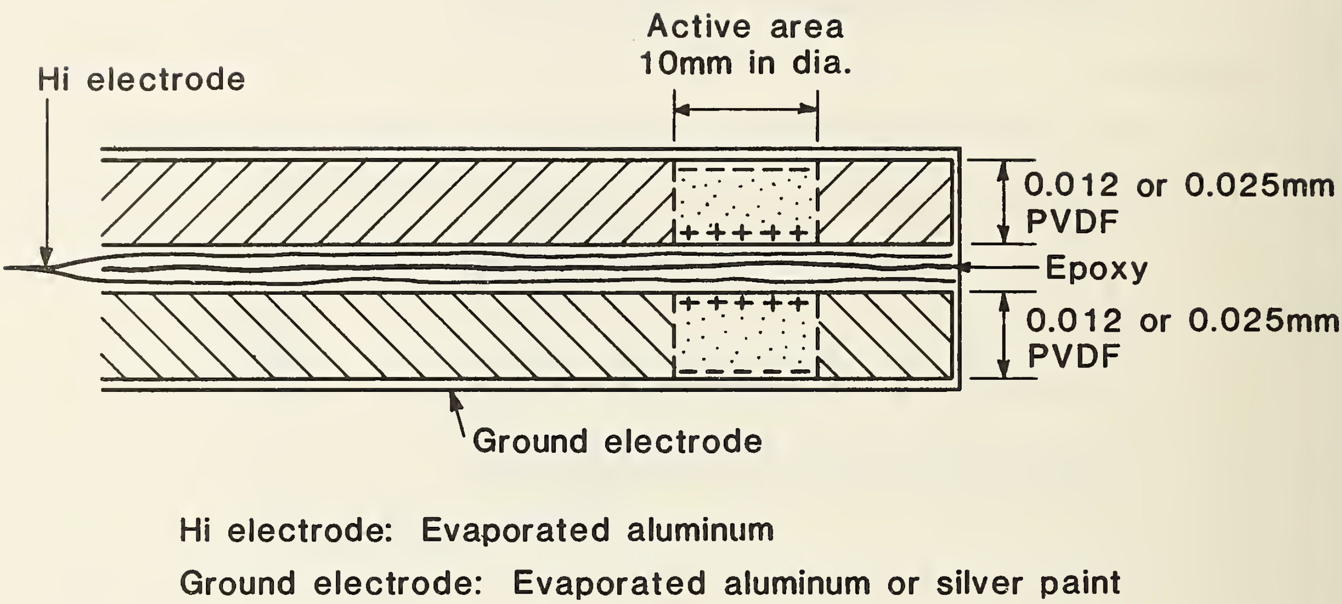

Figure 7 The Polymer Gage - Bilaminate Construction (Type A Gage)

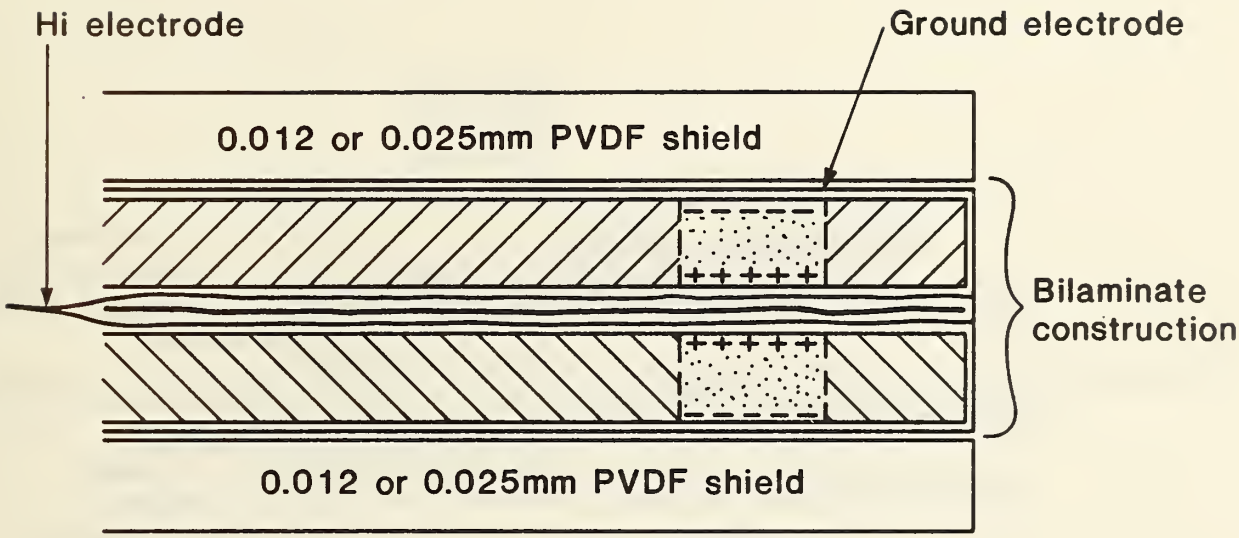

Figure 8 The Polymer Gage - Bilaminate Construction with PVDF Sheets as Protective Covers (Type B Gage)

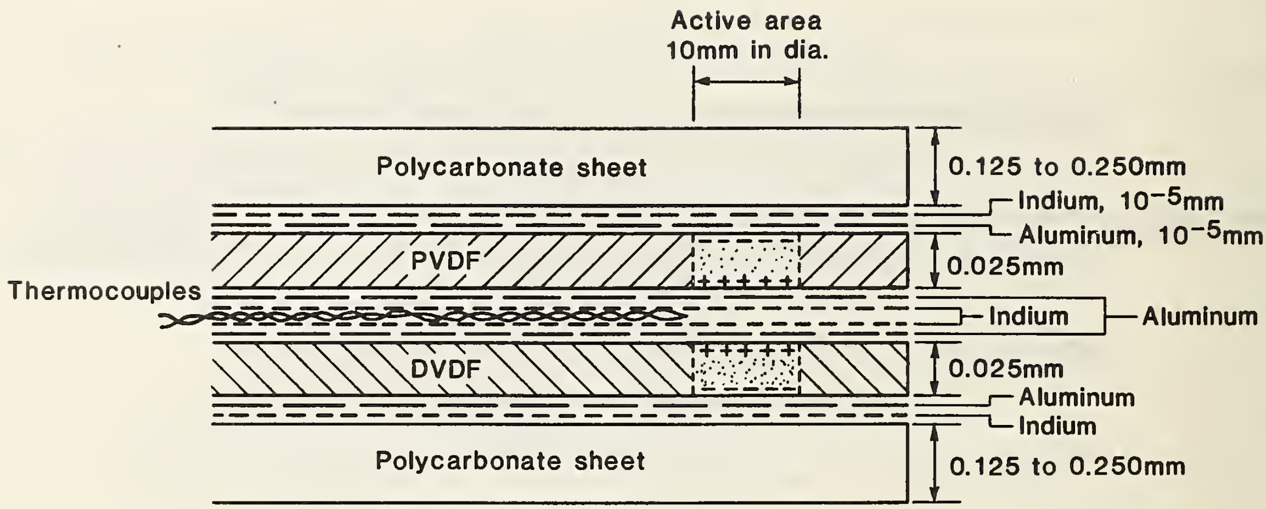

Figure 9 The Polymer Gage - Bilaminate Construction with Polycarbonate Sheets as Protective Covers (Type D and E Gages)

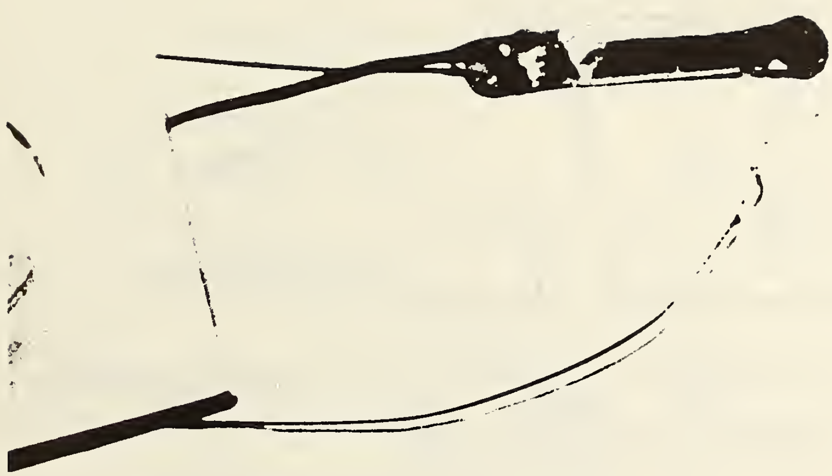

Figure 10 An NBS Polymer Gage at Its Latest Design (April 1985)

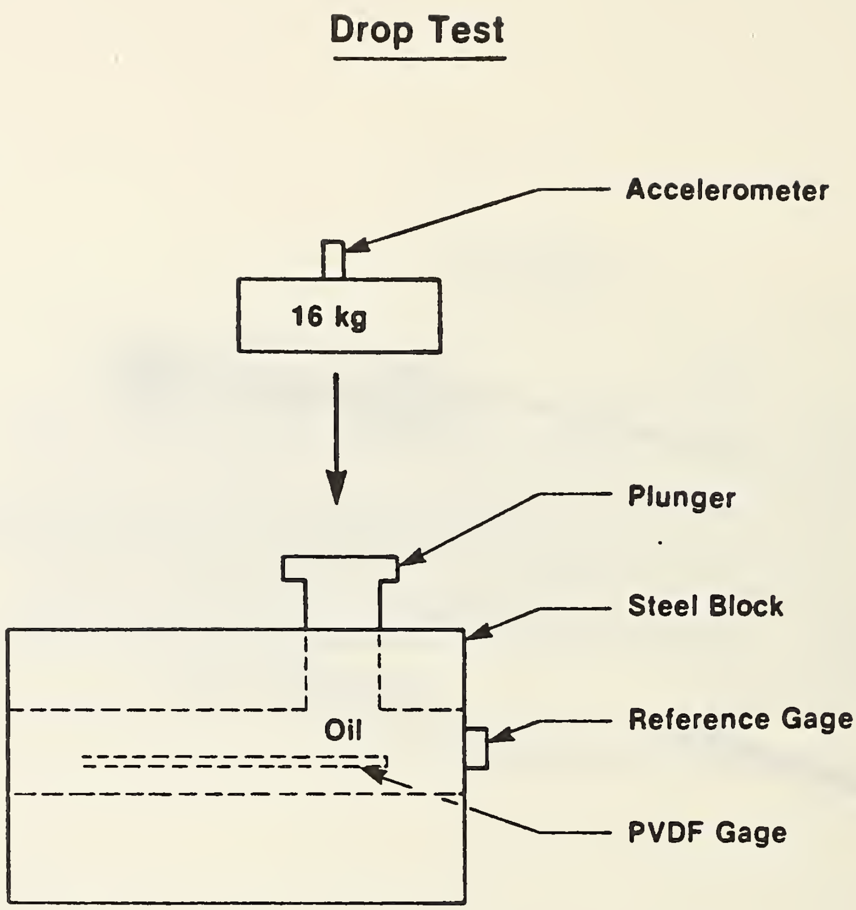

Figure 11 Drop Test Set-up

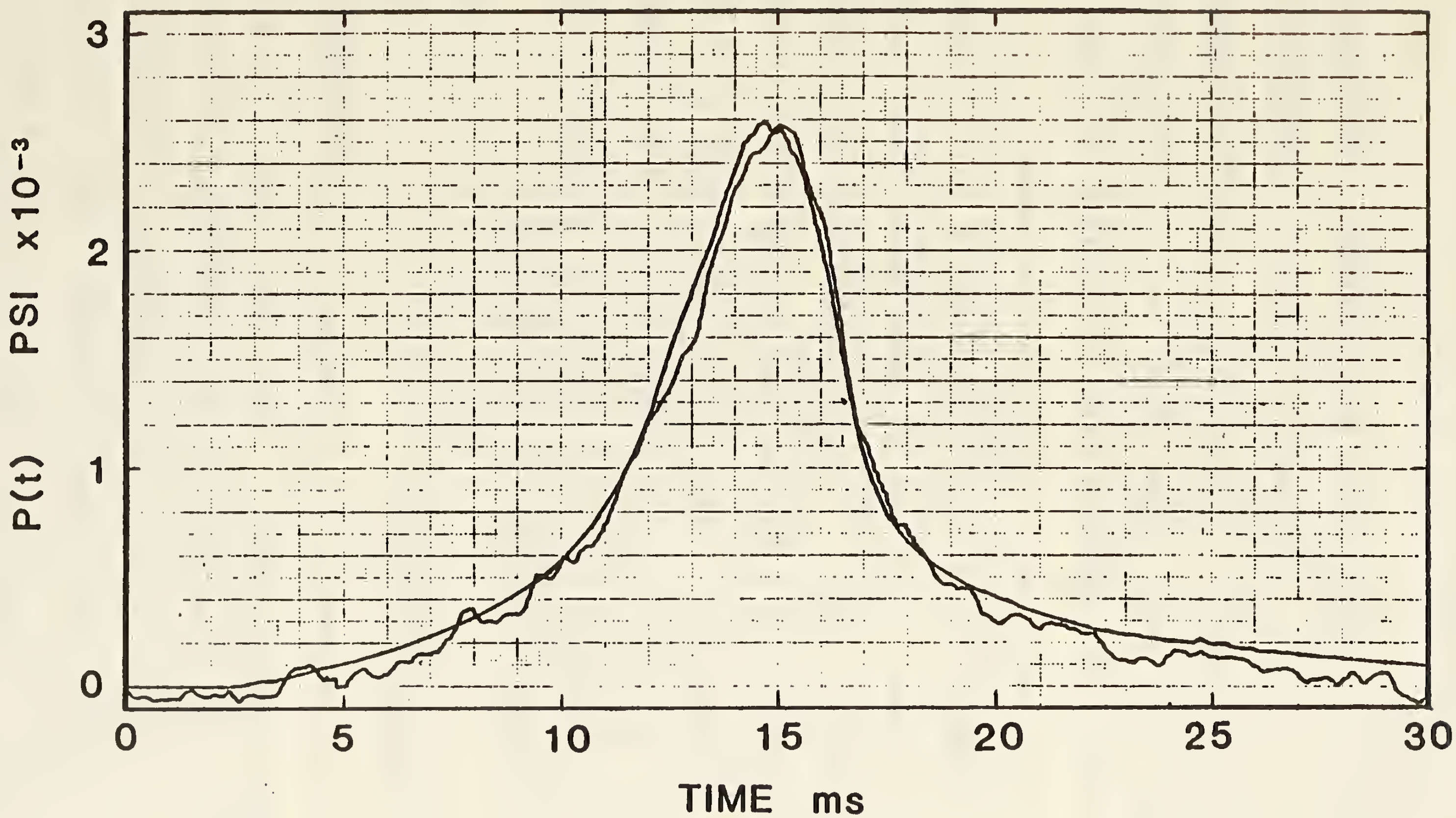

Figure 12 Typical Pressure Pulse Response by Polymer Gage and Reference Transducer from The Drop Test (Ref. 4d)

3. GEOTECHNICAL ENGINEERING LABORATORY TEST PROGRAM

3.1 Soil Used in Testing

A sandy soil shipped from Eglin Air Force Base in Florida was used as the material in the test program and is referred to as "Florida Sand" in this report. It was planned that the gages be field tested at Eglin Air Force Base once their calibration and testing in a laboratory environment were completed. The soil is reddish brown in color and was slightly moist when it was received with an average natural moisture content of 6.0 percent. A gradation curve is shown in figure 13 which describes the soil as being a fine to medium sand, a SP-SM material according to the Unified Soil Classification System containing a small amount of fine material. Compaction tests using ASTM test procedure D698 were conducted to develop the compaction curve shown in figure 14. The Florida sand has a maximum dry density of 114.5 pcf at an optimum moisture content of 12.5 percent.

3.2 Test Variables and Test Program

The test program carried out in the Geotechnical Engineering Laboratory is summarized in table 1. The way table 1 is organized and presented also illustrates the developmental nature of the project. A number of test variables were evaluated in the program including gage type, gage location, type of protective covering, effect of frequency, effect of cable length, and effect of mold insulation.

A polymer gage was placed under two different conditions within a test cylinder. In the first case, the gage was placed on a concrete pedestal covered by Florida sand to evaluate gage response when the gage is placed against the exterior wall of a buried concrete structure. In the second case, the gage was placed on a compacted surface of Florida sand and backfilled by the same soil to simulate the free field condition for gage response study.

The longer the coaxial cable, the higher the capacitance. The length of cable connecting the gage, from the test cylinder to the compensation amplifier, could have some effect on the measured gage response. Concern regarding this problem is certainly valid considering that only a few feet of cable are normally used in the laboratory whereas several hundred feet of cable will be required to carry out the same measurement in a field test set up. In this test program, we have used a 150 foot long cable to conduct some tests and compared these results with those obtained using only 3 feet of cable to determine the possible effects of cable length.

It was also thought that the high thermal conductivity of the aluminum test cylinder could affect the amount of heat buildup inside the soil-gage assembly, thus affecting the soil stress measurement using the polymer gage. For this reason, tests were conducted early in the program by having the test cylinder wrapped with and without insulation tape. These tests were conducted using the Type B gage without any additional protective covers.

We should mention here that several Type A gages were used to start the program. Although this type of gage offers the highest charge/stress sensitivity, it is also the most vulnearable type to damage due to indentations on the gage by sand grains. As a result, all Type A gages were damaged without completing a test.

The types of gages used in testing are given in table 2, which is a brief summary of that presented earlier. As a result of Type A gage testing, we decided that the gage surfaces needed additional protection. The Type B gage, which is a Type A gage with two layersof PVDF material, was thus developed and tested for its ruggedness and response. It was found that the added polymer sheets are not rugged enough to survive the impact loads applied to the soil/concrete pedestal column. Additional gage protection was required which led to experimentation with other types of protective measures as given in table 3, including the use of dry bentonite material, stainless steel shims, hardened steel shims, and photo negative films in addition to the 2 PVDF sheets in the Type B gage design. These protective covers were used to sandwich the gage in the test set up. Both the stainless and hardened steel covers did not work well in serving their intended function. The gages tested using the stainless steel shims were easily short-circuited during testing. This result is not surprising when the shims were viewed after testing. Numerous indentations by sand grain penetration were evident on the shim. Hardened steel shims were also considered unsuitable for gage surface protection since they are too rigid, making them incom patible with the PVDF material. Results from Test 25 (a) indicated that the gage was short-circuited because the lead of the gage was cut by the shims at their perimeter during impact load application.

The use of photo negative film was successful. This led to the present design using polycarbonate sheets of various thicknesses for gage protection (Types D and E gages). Most of the gages tested are Type D, which use two 0.125 mm thick polycarbonate sheets. The Type E gage design is identical to the Type D gage except that polycarbonate sheets of 0.250 mm are used as protective covers.

It should be noted that the use of other materials as electrodes in gage design was also carefully examined. Aluminum was in the original design; however, it was found that the aluminum is too brittle under impact loading. Indium, which is similar to aluminum in chemical properties, was thus introduced during gage fabrication because of its better ductile nature. It was thought a ductile material should have a better chance to heal after impact loading, thus improving the longevity of the gage. What we found was that indium flows too much when it is compressed. Furthermore, indium does not work as well as aluminum does with the PVDF material during gage fabrication. To take advantage of each material, both aluminum and indium are used in the final gage design, as shown in figure 9 where aluminum is deposited over the PVDF sheet and is covered by a layer of indium.

3.3 Test Set Up and Data Recording

All tests were conducted in a test set up, shown in figure 15 which includes a test cylinder, where the polymer gage is located, with impact loads being applied with a load piston from a MTS dynamic testing machine; an electronic control console which controls input magnitude and frequency of the impact load, and records the magnitude of specimen displacement; a Gould amplifier system connected to a multi-channel strip chart recorder to record all input and output signals from the test. A closeup view of the test assembly including the test cylinder is shown in figure 16. It shows a black paint coated gage coming out of the test cylinder connected to a compensation amplifier box placed next to the test assembly. The stainless steel cylindrical block is used to raise the elevation of the test assembly to facilitate testing.

A schematicdrawing is given in figure 17 to show in detail the test cylinder and its accessories. The assembly consists of a 10 cm by 10 cm base plate with a 2.19 cm diameter groove made in the middle of the plate to accomodate an O-ring. A test cylinder (inner ring) 2.19 cm in diameter and 4.10 cm in height is seated over the O-ring. An outer ring 4.75 cm in diameter is placed over the test cylinder resting in another groove made on the base plate. Aluminum is used in constructing these parts. The outer ring along with foam cut to fill the space between the outer and inner rings is used to hold the test cylinder in place during test preparation and testing. A slot approximately 18 mm wide was cut on the surface of the test cylinder to allow for insertion and extraction of the polymer gage before and after testing.

In testing a gage on a concrete pedestal, the pedestal was placed into the test cylinder first. The pedestal was prepared to have the same height as that of the slot location on the test cylinder. When protective covering of types 2 through 5 were used in the experiment, one cover was constructed or placed immediately over the surface of the concrete pedestal. A gage was then inserted through the slot and placed over the protective cover and another layer of protection was then constructed or placed. For tests using the final gage design, i.e., with polycarbonate sheets used as a protective cover, the gage was simply inserted through the slot to rest on the pedestal. Florida sand was carefully poured over the pedestal in small quantities and compacted by means of the loading rod connected to the load piston, using the static load application capability of the MTS test machine. The compacted soil surface was leveled off at the top of the test cylinder.

To simulate the free field condition, Florida sand was poured into the test cylinder and compacted in steps until the sand surface reached the level where the slot is located. The gage with its protective measures was then placed in the test cylinder with the rest of the space inside the cylinder being backfilled by the compacted sand in the same manner as described before.

Some words should be said about the density of sand placed in the test cylinder. At first, we planned to compact the sand at its natural moisture content to a density of about 105 pcf in accordance with the compactive curve in figure 14. However, we found that this was very difficult to achieve due to the small amount of soil needed to be compacted into place. Through trial and error, we have managed successfully to consistently prepare soil specimens to a dry density of 92 to 95 pcf at its natural moisture content.

The loading rod was then lowered to make contact with the compacted soil surface in the test cylinder in preparation for impact load application (refer to figure 16). The gage was then connected to the input port on the compensation amplifier through the use of microdot connectors and a 2 mm diameter co-axial cable. The thermocouple of the gage was also connected to the amplifier for temperature measurement and compensation. The impact load, which consists of a half cycle inverted sine waveform, was dialed in through the use of the MTS test machine. The magnitude of the load acting on the soil surface as well as the displacement of the specimen were recorded on channels 3 and 4 of the strip chart recorder, respectively. Outputs from the compensation amplifier which include the corrected and uncorrected gage responses with respect to temperature and the temperature measurement were recorded on channels 1, 2, and 5 of the strip chart recorder, respectively. A typical strip chart output from an impact load test is shown in figure 18. The frequency of the inverted sine waveform shown in figure 18 is 50 Hz, which is the frequency employed in most tests. Other frequencies ranging from 5 to 40 Hz were also used to study the effect of frequency on gage response. We should mention here that the temperature in this typical plot probably represents the most significant recorded thermocouple response in all the tests conducted and was estimated to be at about 0.6 $^{\circ}$F. Also, the difference in voltage recorded for the corrected and uncorrected gage signals is difficult to appreciate. Although the corrected gage responses were used for the plots in this report, we believe that gages without a built-in thermocouple should also yield good dynamic stress measurement in a soil environment.

The sequence of impact load application on each specimen is given below: An impact load at 50 Hz frequency which generated about 500 psi on the soil surface was dialed in through the control console of the MTS test machine and a recording such as that shown in figure 18 was obtained. This represents one data point on the plots shown in figures 19 through 31 in the next section of this report. The magnitude of impact loading was increased in steps of about 200 psi to develop a maximum input stress between 1000 and 1500 psi to study the gage response during loading. The magnitude of impact loading was then reduced in decrements of 200 psi to an equivalent input stress level of about 20 psi to study its characteristics during unloading. In most of the tests conducted, reloading characteristics of the gage were also evaluated by again increasing the magnitude of impact loading in increments back to the magnitude where the test was begun completing the cycle of testing for an individual specimen. All of these impact loads were applied at a frequency of 50 Hz.

The possible effect of frequency on gage response was studied on some test specimens when the above-mentioned loading sequence was completed. The study was accomplished by varying the frequency of the half cycle inverted sine waveform at 5, 10, 20, 30, and 40 Hz while maintaining the same dial setting for the impact load application.

Table 1 Summary of Test Program

Gage No.	Gage Type [a/]	Test No.	Gage Location	Type of Protective Cover [b/]	with Cable	without Cable	Remark
AF-31	B	12	on concrete pedestal	1		X	not insulated
		13	"	1		X	"
		14	"	1		X	insulated
AF-30	B	15	"	2		X	"
		16	"	2		X	"
		17	"	2		X	-
		18	"	2		X	-
		19	"	5		X	-
		20	"	5		X	-
AF-43	C	22	"	5		X	-
		24	"	5		X	-
		25	"	5		X	-
		25(a)	"	4		X	gage short-circuited
AF-44	C	25(b)	"	3		X	"
PC-49	D	28	"	6		X	-
		29	"	6		X	-
		30	"	6		X	-
		43	"	6	X		gage re-epoxyed
PC-54	D	32	"	6	X		-
		33	"	6		X	-
PC-62	D	34	"	6	X		exhibited non-linearity from zero to 400psi
		35	"	6	X		
		36	"	6	X		
		37	"	6	X		"
PC-64	D	38	in soil	6	X		-
		39	"	6	X		-
		40	"	6	X		-
		42	on concrete pedestal	6	X		-
PC-58	E	44	"	7	X		-
		45	in soil	7	X		-

a/ see table 2
b/ see table 3

Table 2 Gage Types

Type	Description
A	Bilaminate Construction, i.e., 2 layers of PVDF; aluminum as an electrode
B	Bilaminate Construction plus 2 layers of PVDF as a protective covering. Coated with black paint; aluminum as an electrode
C	Same as Type B except that indium was used as an elctrode
D	Bilaminate Construction plus 2 @ 0.125 mm polycarbonate sheets as a protective covering; aluminum and indium used as electrodes
E	Same as Type D except that the polycarbon sheets used are 0.250 mm in thickness

Table 3 Types of Protective Coverings Experimented with in the Test Program

Type	Thickness	Description
1	-	No protective covering other than the 2 PVDF sheets used in the Type B gage design
2	2.0 mm	Two bentonite layers as additional protection
3	0.074 mm	Two stainless steel shims as additional protection
4	0.126 mm	Two hardened steel shims as additional protection
5	0.182 mm	Two photo negative films as additional protection
6	0.125 mm	Two polycarbonate sheets in Type D gage design
7	0.250 mm	Two polycarbonate sheets in Type E gage design

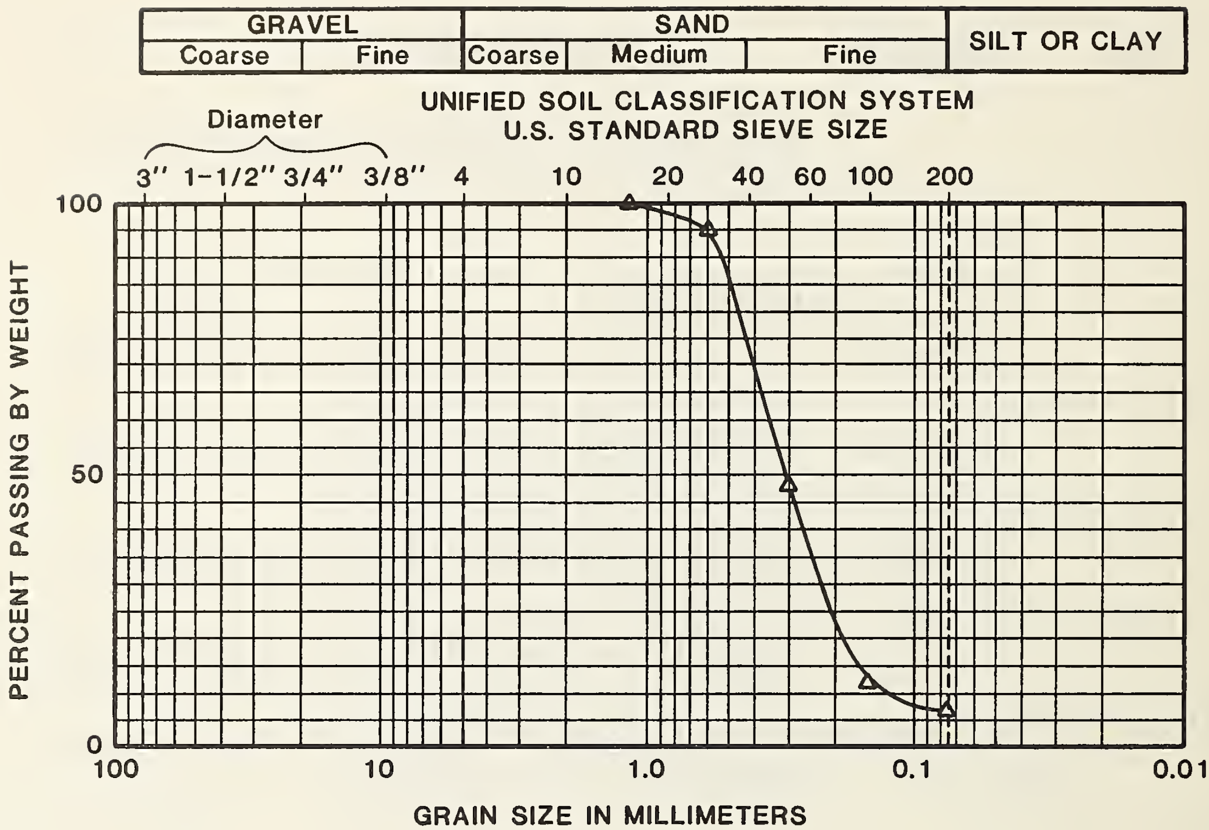

Figure 13 Grain Size Distribution of Florida Sand

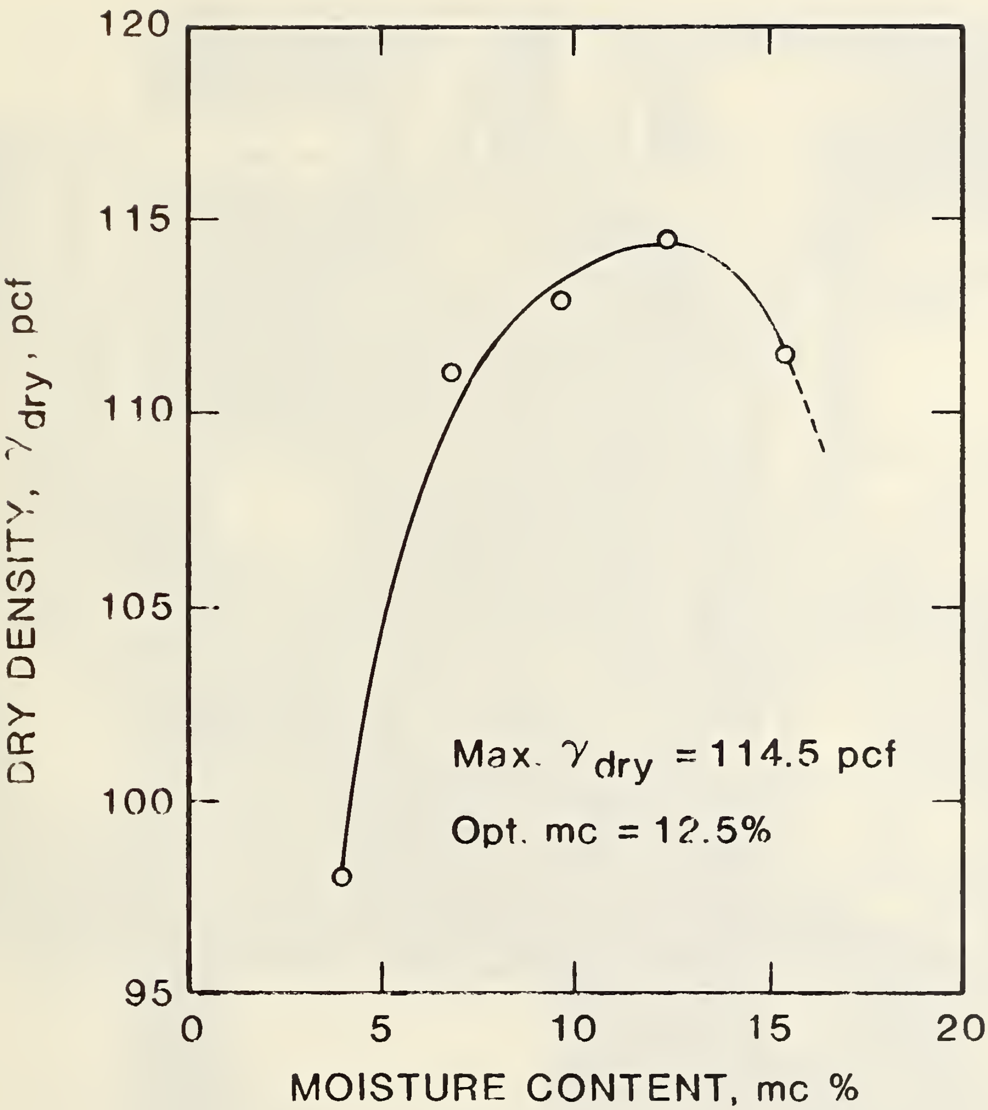

Figure 14 Compaction Curve of Florida Sand

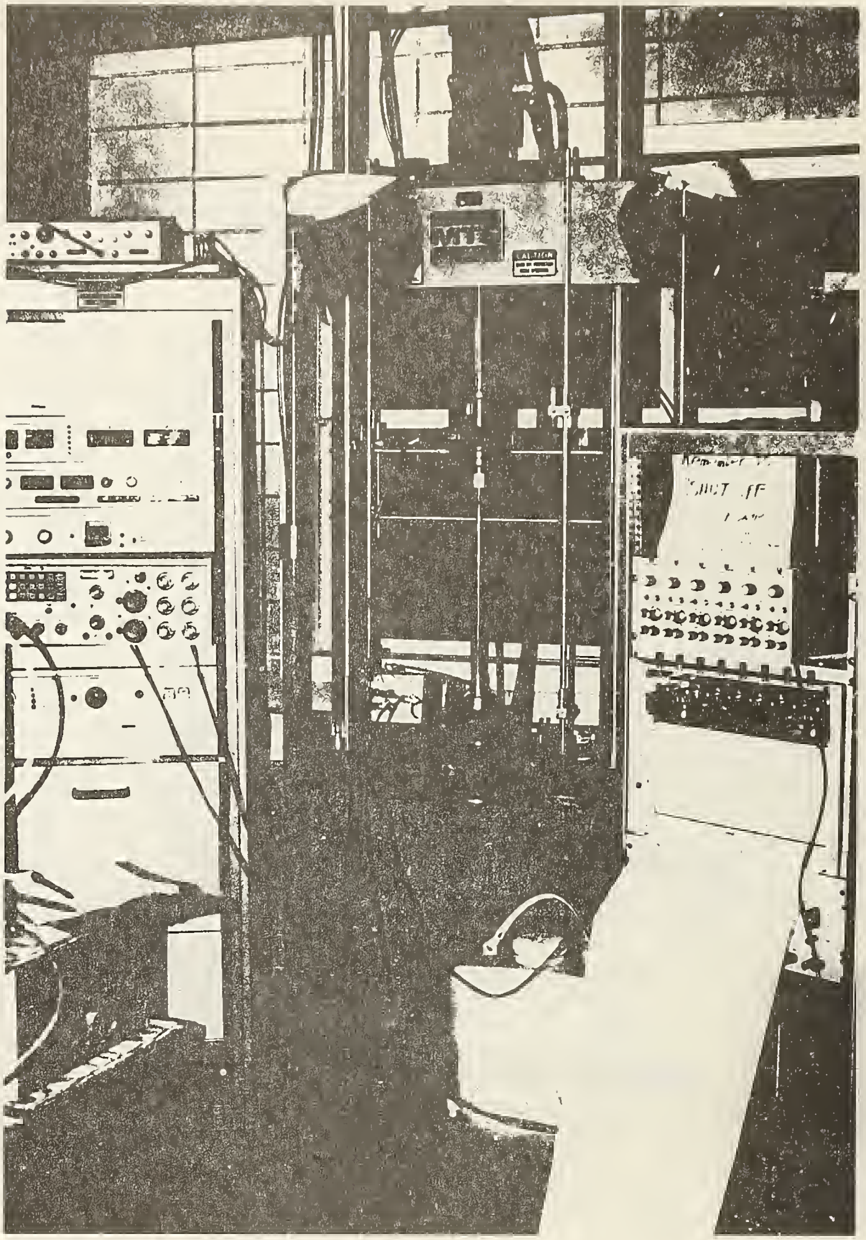

Figure 15 NBS Polymer Gage Test Set-up in The Geotechnical Engineering Laboratory

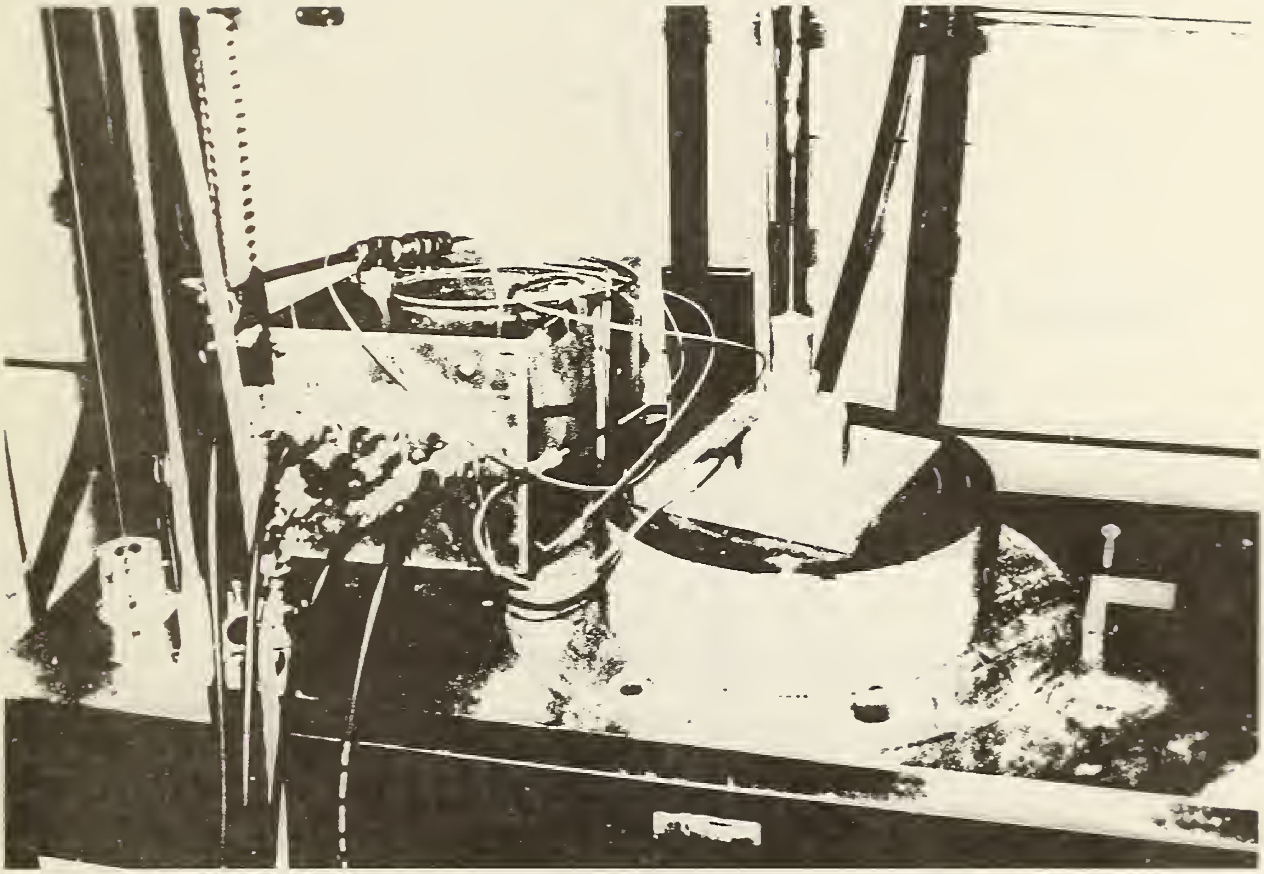

Figure 16 Close-up View of The NBS Polymer Gage Test Set-up

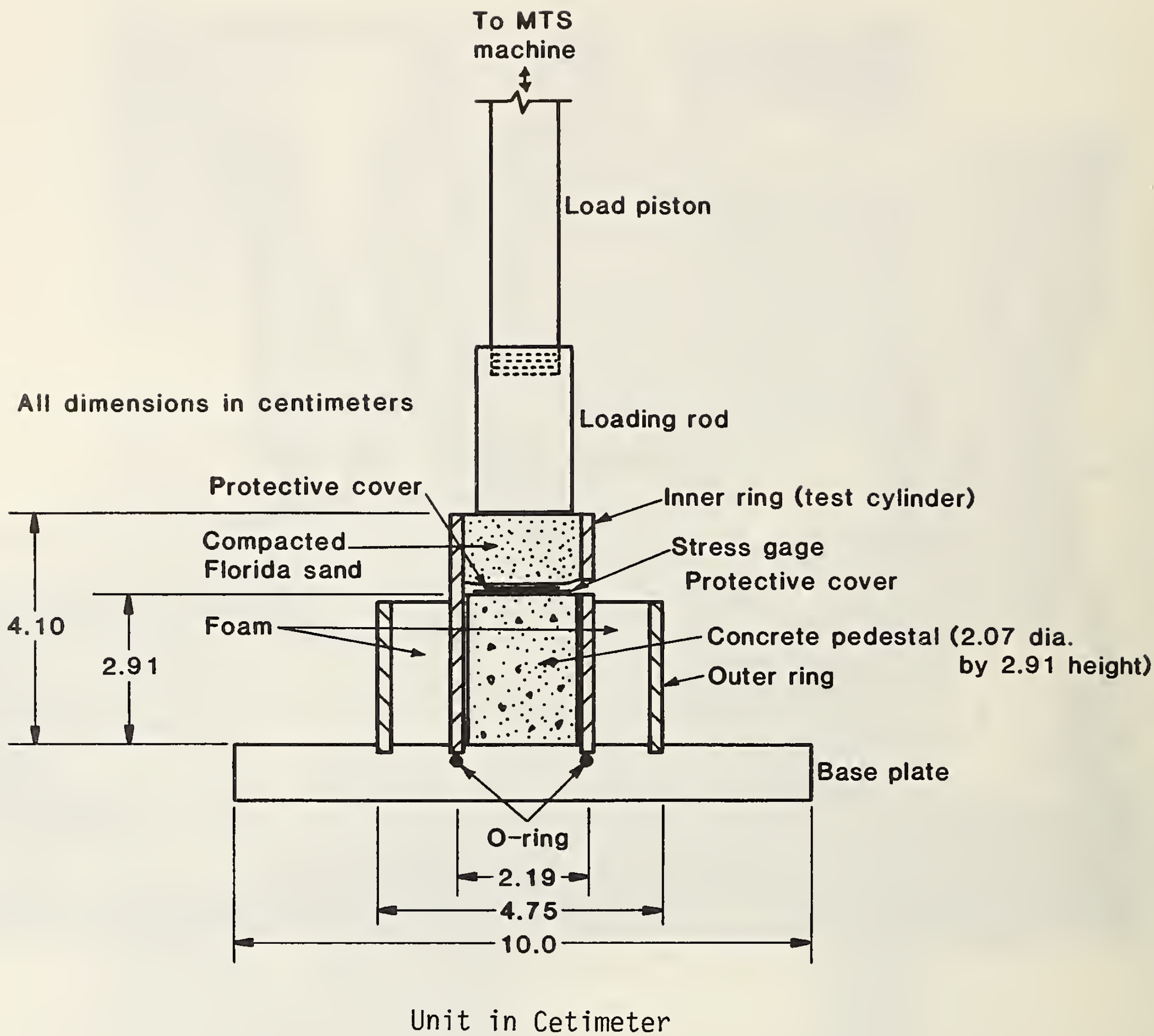

Figure 17 Schematic Drawing of The Test Cylinder and Its Accessories

RESPONSE OF POLYMER GAGE TO DYNAMIC LOAD (GAGE ON CONCRETE PEDESTAL AND BURIED IN SOIL) Test 14, Run 12

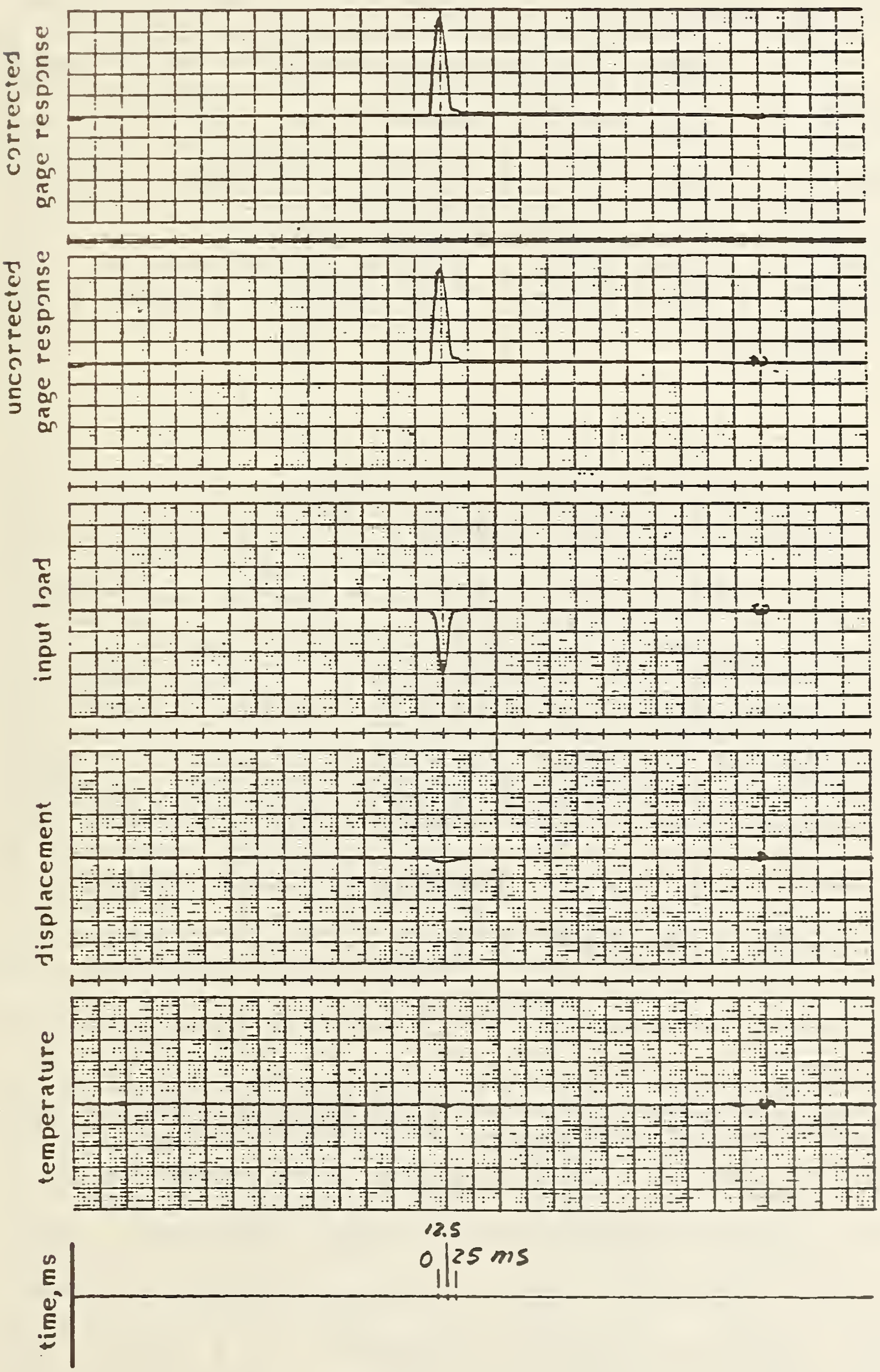

Figure 18 Typical Strip Chart Output from Impact Load Testing of the NBS Polymer Gage

4. PRESENTATION, INTERPRETATION, AND DISCUSSION OF TEST RESULTS

Results from all the tests listed in table 1 are given in figures 19 through 33. All of these figures were presented in the same format to establish the relationship between input stress in psi (calculated from the load trace recorded on channel 3 of the strip chart recorder) and corrected output of the polymer gage in volts (calculated from the voltage trace shown on channel 1 of the strip chart recorder).

Tests 12, 13, and 14 were conducted to evaluate the effect of test cylinder insulation on gage response and their results are given in figure 19. Tests 12 and 13 were run without insulation whereas Test 14 was carried out by insulating the inside of the test cylinder with duct tape. AF Gage #31 is a Type B gage and no additional protective covering was used in testing. Figure 19 shows that no difference in gage response resulted from the insulation of the test cylinder. Subsequent tests other than Tests 15 and 16 were conducted without insulating the test cylinder.

Gage response using bentonite layers as a protective covering are shown in figures 20 and 21. Both figures also serve as good examples for the loading sequence in each test specimen. Each point represents one particular impact load application and each curve shows the loading-unloading segments of a test. No reloading was carried out in these four tests; however,it was carried out in the rest of the test program. Results shown in figures 20 and 21 indicate the sensitive nature of gage response as a function of input stress when the bentonite material is used for gage protection. A loop can be traced following the loading-unloading sequence in each individual test. A possible explanation for this observed phenomenon is that the voltage measured from the gage during initial loading may be envisioned as a gross measure of the gage response to point loads due to the particulate nature of the dry bentonite soil used as the protective cover. Only after the bentonite layers have been tightly compacted to provide uniform contact with the gage surface can the measured gage response be considered to properly represent the level of stress on the gage surface (i.e., during the unloading segment of the curve). By examining the characteristics of the curves shown in both figures 20 and 21, we may conclude once again that test cylinder insulation has no effect on the gage response.

We concluded from figures 20 and 21 that the use of thin bentonite soil for gage protection is not acceptable and other types of protective measures should be explored. In fact, the use of a bentonite layer is also not practical for field application even if laboratory test results turned out to be acceptable. Figures 22 and 23 present test results using photo negative films as a protective covering. All five tests were conducted by placing the gage on a concrete pedestal backfilled with Florida sand. Gage AF #30 is a Type B gage which uses aluminum as its electrode while the electrode for Gage AF #43 is indium. Another difference in the data presented in these two figures is that in tests 22, 24, and 25, silicone grease was used in between the gage and its protective covering. Although there is a small degree of scatter in the data developed from these tests, a linear relationship between the input stress and the corrected gage output can be established for both data sets as shown in the figures. The use of silicone grease to lubricate the interfaces apparently has no effect on improving the test results.

Favorable results from the tests using photo negative films to protect gage surfaces led to the final gage design of gage Types D and E. Four gages, Gages PC #49, #54, #64, and #58, were tested to determine the calibration factors for their use in field testing. The first three gages are Type D gages and the last one is a Type E gage. Results of Gage PC #49 testing are shown in figure 24. The gage was placed on a concrete pedestal in all four tests. Tests 28, 29, and 30 were conducted using a 3 foot cable whereas Test 43 was conducted using a 150 foot long cable. It should also be noted that the gage was delaminated between one polycarbonate sheet and the PVDF layer at the end of Test 30. The gage was re-epoxyed and tested again as Test 43 to detect whether this repair process would cause any change in gage response. We were very encouraged to observe from figure 23 that neither the cable length nor the re-epoxy process of the gage has any effect on the gage response, i.e., a linear relationship can still be established from all the data points obtained from all four tests. This finding can be further substantiated by the plot of figure 25 showing the results of Gage PC #54 testing with and without the use of the 150 foot cable.

An important test variable that had to be investigated is whether the response of a gage placed in a free field condition would be different from that of the gage placed against a rigid concrete surface and covered by soil. Figures 26 and 27 plotted from the results of Gages PC #64 and #58 testing, respectively, provide the answer to this question. It can be seen that for the same load setting dialed in through the MTS test machine, a much greater stress was developed in the specimen when the concrete pedestal was present, resulting in a much higher gage response. In general, the stress generated in the presence of a concrete pedestal is about 2.5 times of that without a pedestal. Nevertheless, all data points are falling into a narrow band and a linear relationship between the input stress and the corrected gage output can be retained. This finding is very important because it means that it is possible to test the gage under one condition in the laboratory and the relationship established from that can be satisfactorily used to determine the magnitude of stress for the other case. The linear relationship established in both figures 26 and 27 also demonstrates that an increase of the thickness of the polycarbonate sheets from 0.125 mm in Gage PC #64 to 0.250 mm in Gage PC #58 does not invalidate this linear correlation. However, our assessment is that the Type D gage design which uses a 0.125 mm polycarbonate sheet offers sufficient ruggedness to withstand impact stresses up to 2000 psi achieved in the test program. Observing the gage surfaces after testing of the Type D gages indicates that only minor degrees of indentation were noticed on the gage surface, therefore, there is no need to increase the thickness of the protective covering unless higher impact load testing planned in the future dictates the change.

Results of the impact load tests conducted on four gages at various frequencies ranging from 5 to 50 Hz are given in figures 28 through 31. These figures demonstrate the validity of the established linear relationship between the two variables of interest, which are not affected by the magnitude of frequency or the impact load used in testing.

Figure 32 summarizes the test results given in figures 24 through 27. The calibrated results for these four gages are tabulated in the figure in two different units, i.e., volt/psi and pC/psi, to facilitate their use in the field, depending on the type of instruments used for data acquisition.

Finally, results of four tests conducted on Gage PC #62, which is a Type D gage, are given in figure 33 to illustrate the occasional non-linear nature of the gage response. The test numbers are given in accordance with the sequence of testing. Note that, for all four specimens tested using the same gage, the gage/stress sensitivity was reduced slightly after each specimen testing. Also, a straight line can be drawn for the data points from each specimen testing for all data points above about 400 psi. Below 400 psi, the gage showed non-linear response, i.e., all data from the four specimens tested merged toward the origin. The reasons for exhibiting this non-linearity is unclear. This matter should be investigated in future studies.

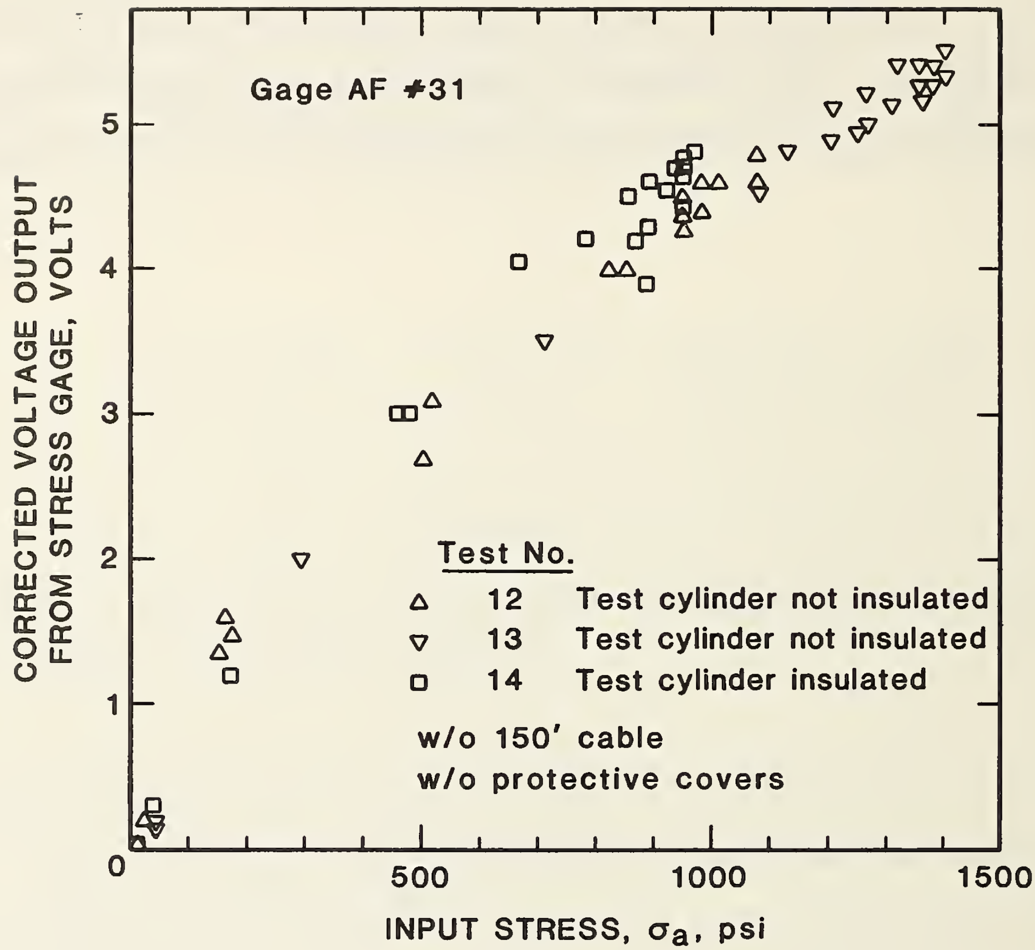

Figure 19 NBS Polymer Gage Test Results - Effect of Test Cylinder Insulation

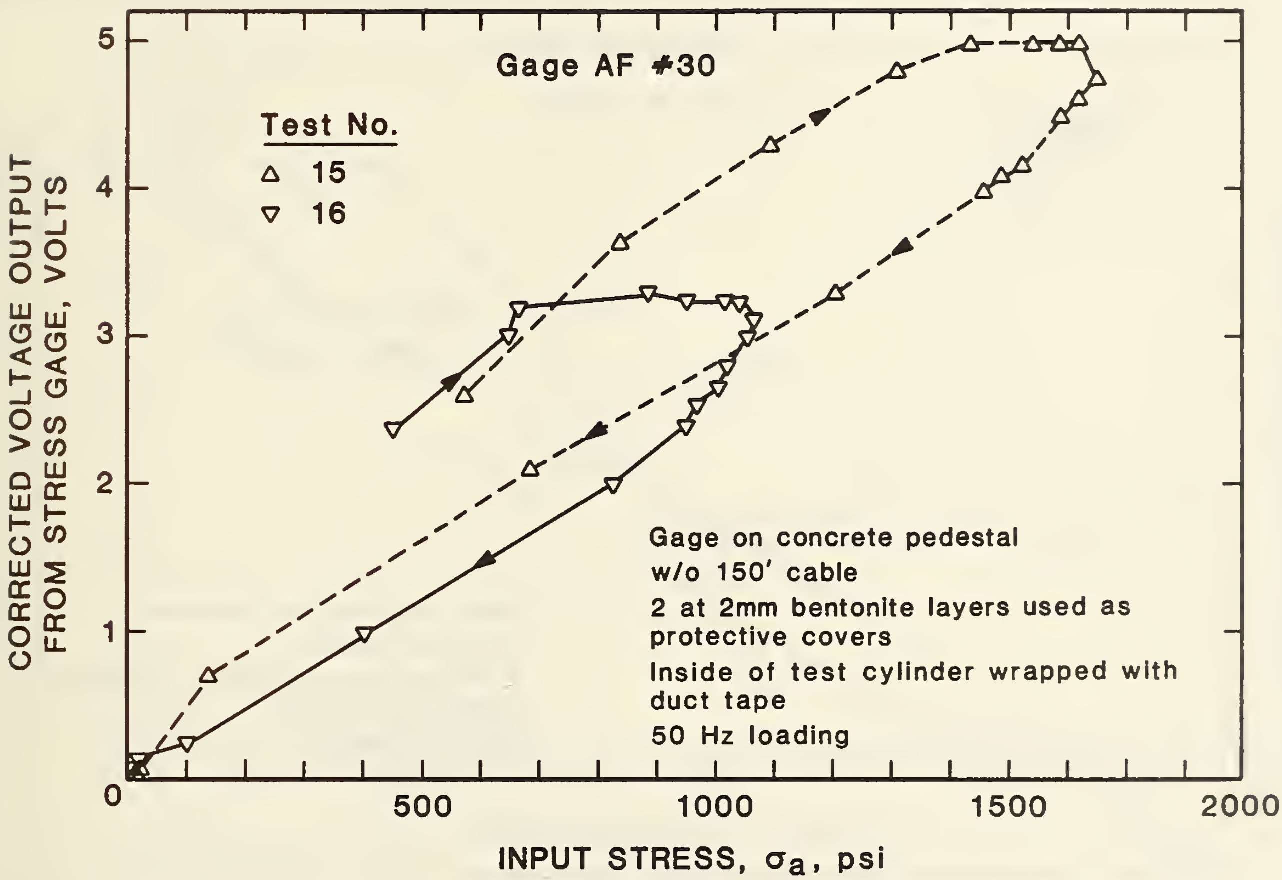

Figure 20 NBS Polymer Gage Test Results -- Bentonite Layers Used as a Protective Covering with The Test Cylinder Insulated

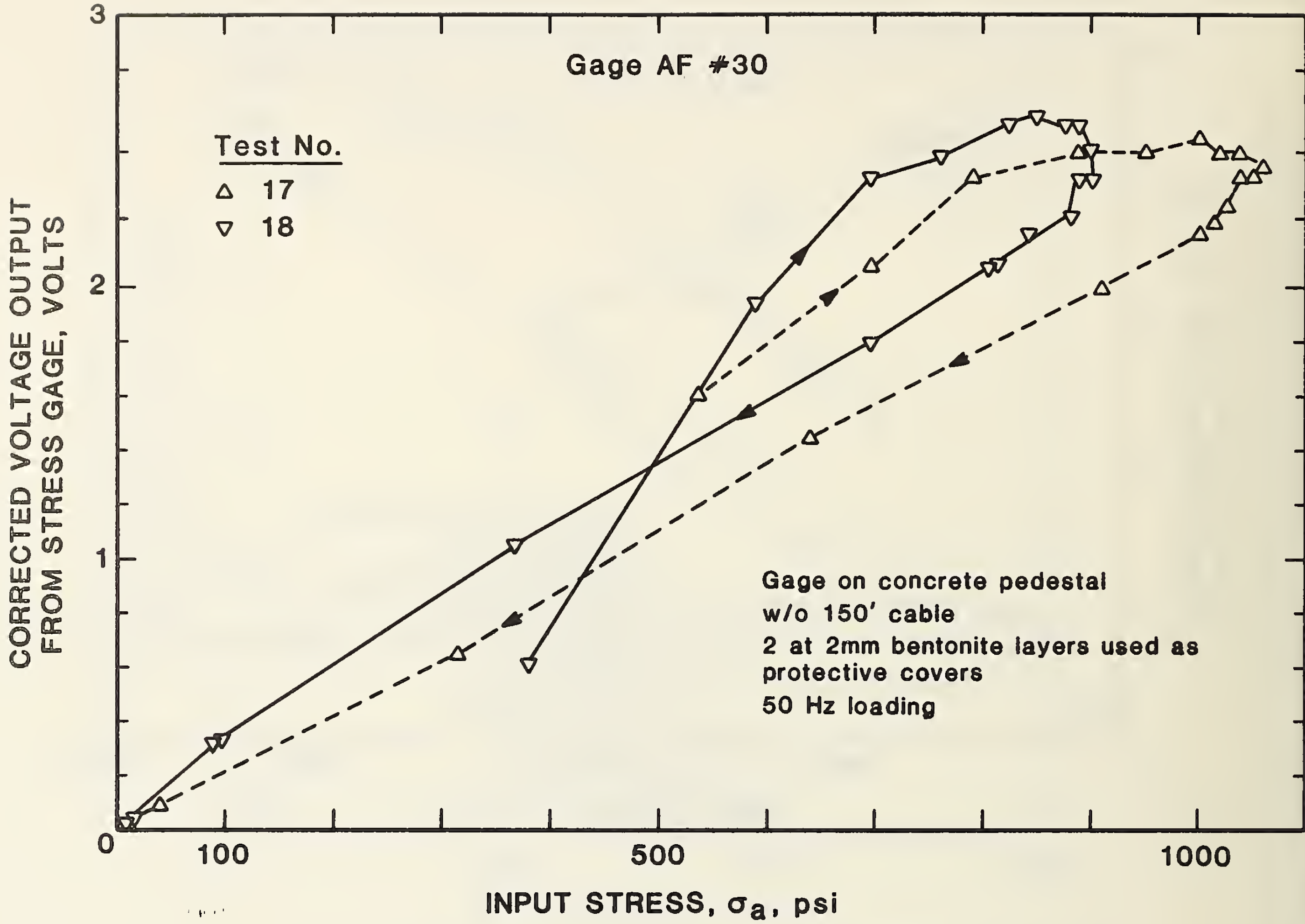

Figure 21 NBS Polymer Gage Test Results - Bentonite Layers Used as a Protective Covering with The Test Cylinder Not Insulated

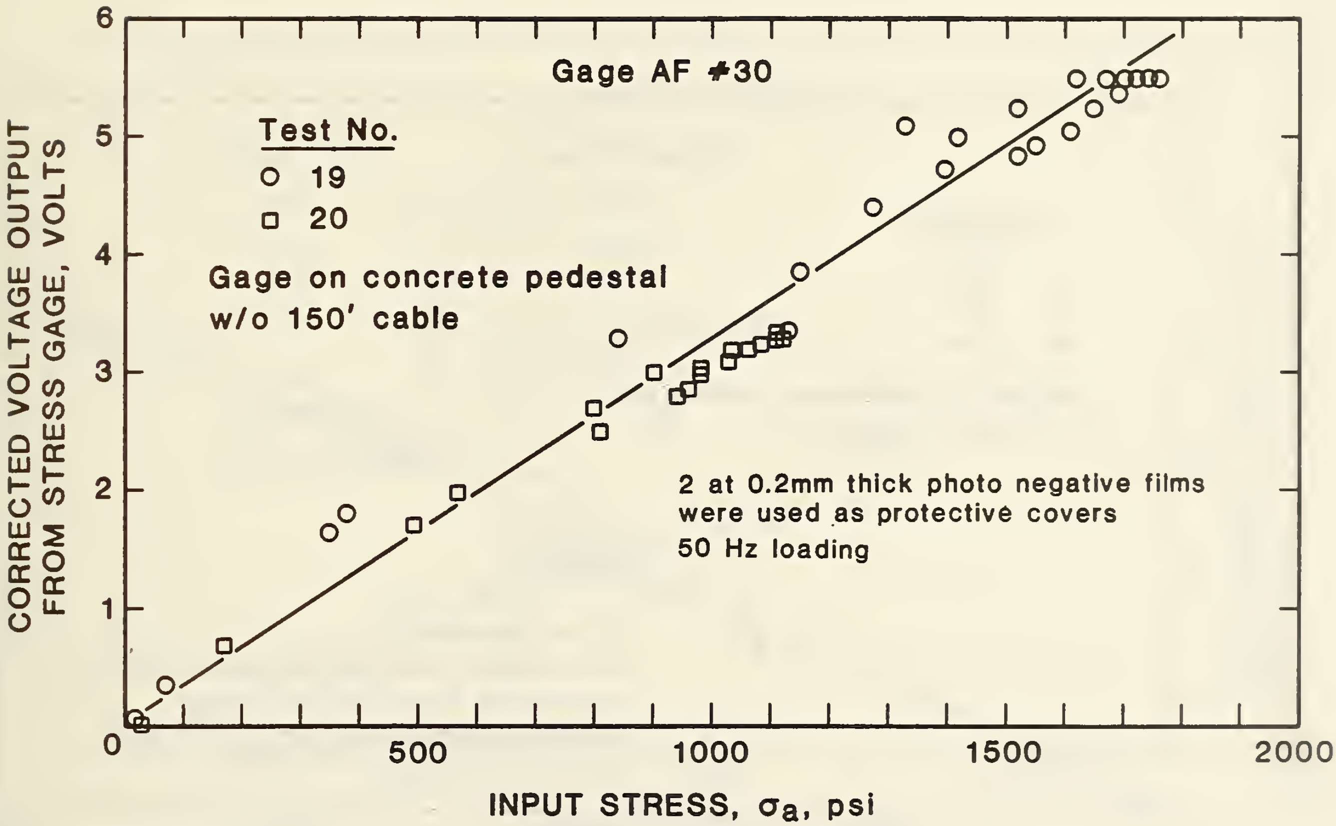

Figure 22 NBS Polymer Gage Test Results - Photo Negative Films Used as Protective Covers

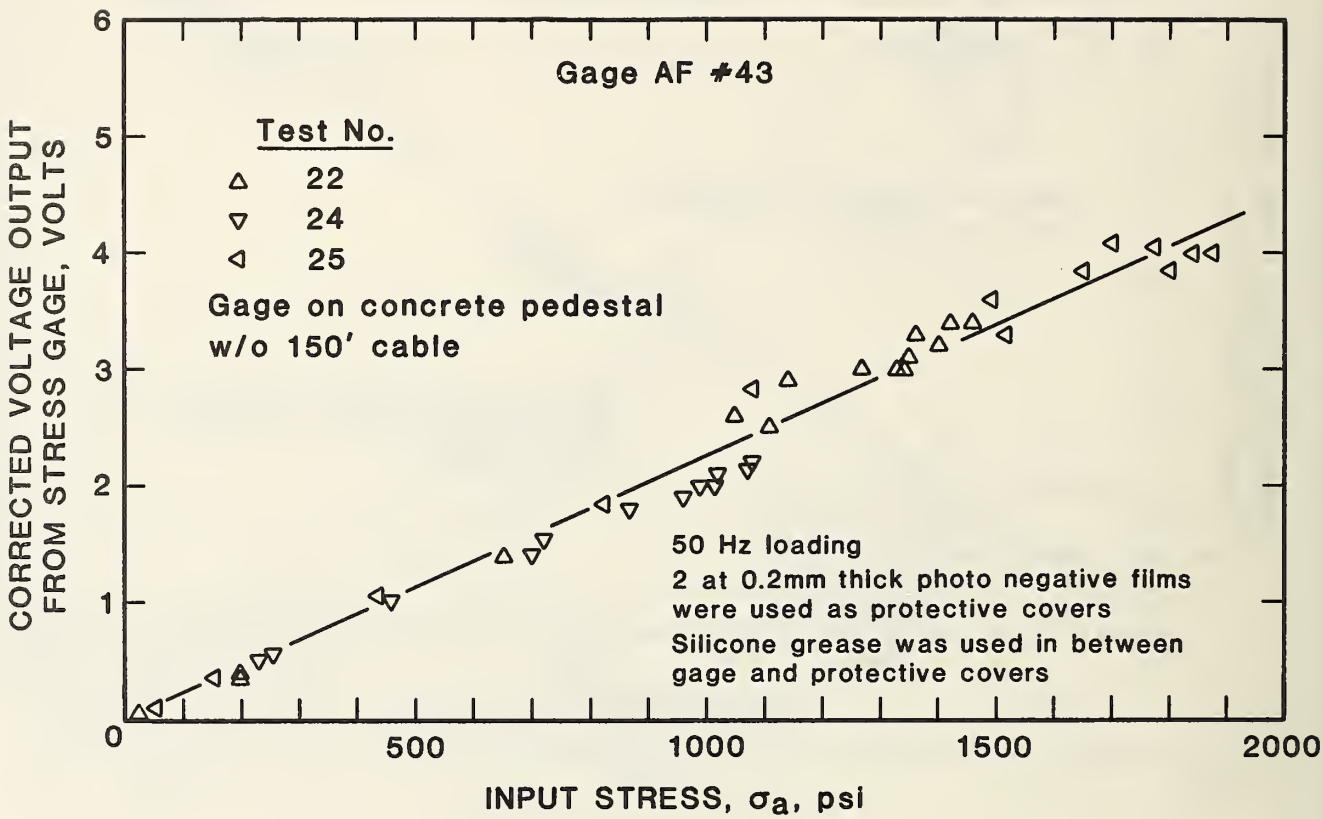

Figure 23 NBS Polymer Gage Test Results - Photo Negative Films Used as Protective Covers

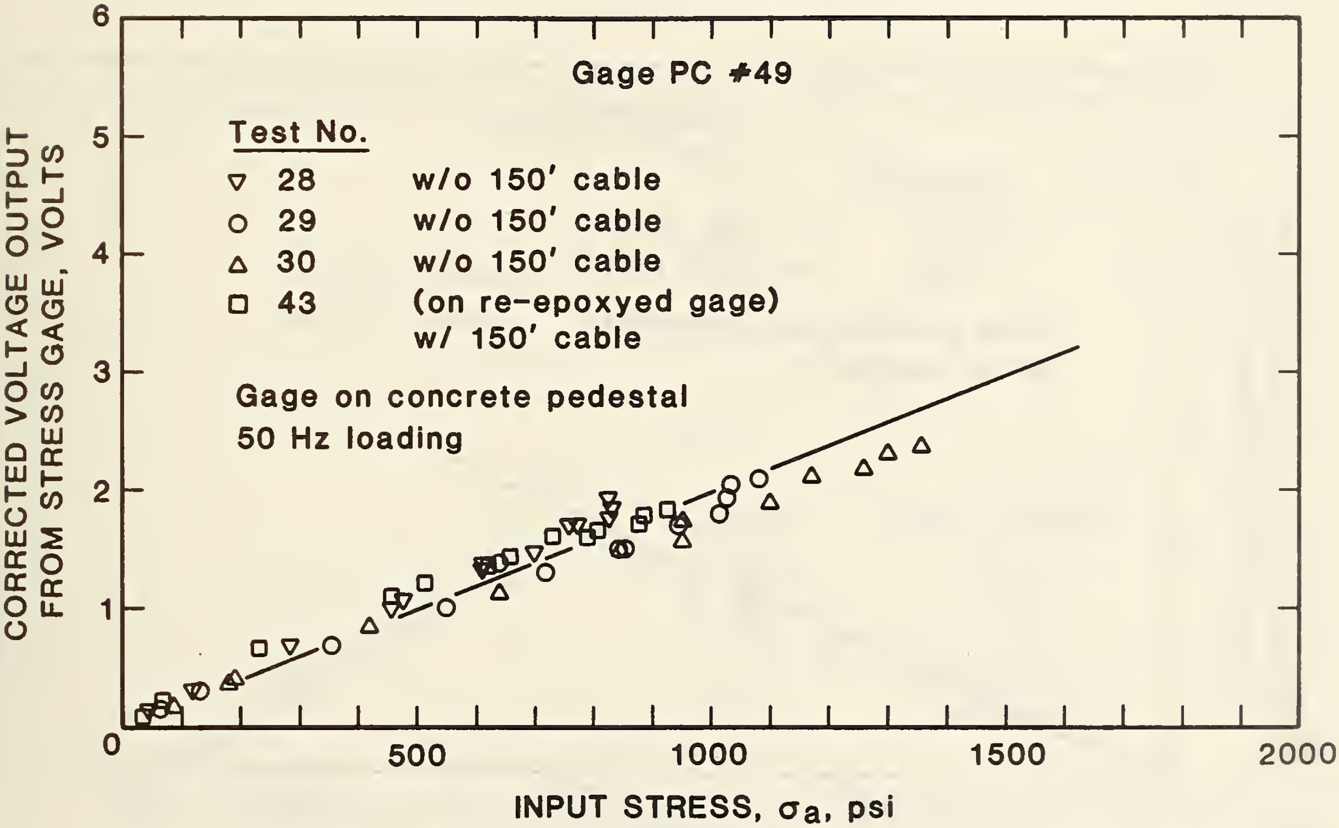

Figure 24 NBS Polymer Gage Test Results - Effect of Cable Length

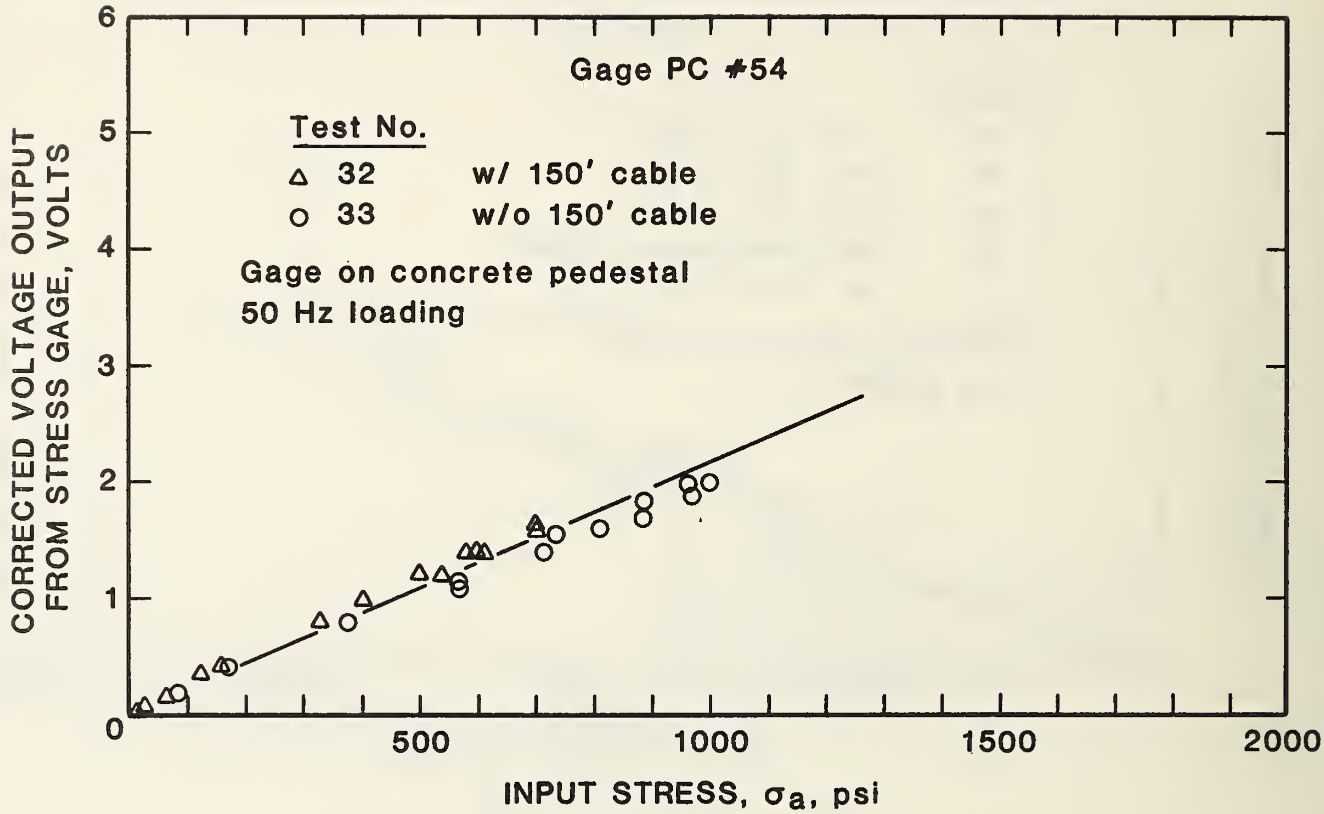

Figure 25 NBS Polymer Gage Test Results - Effect of Cable Length

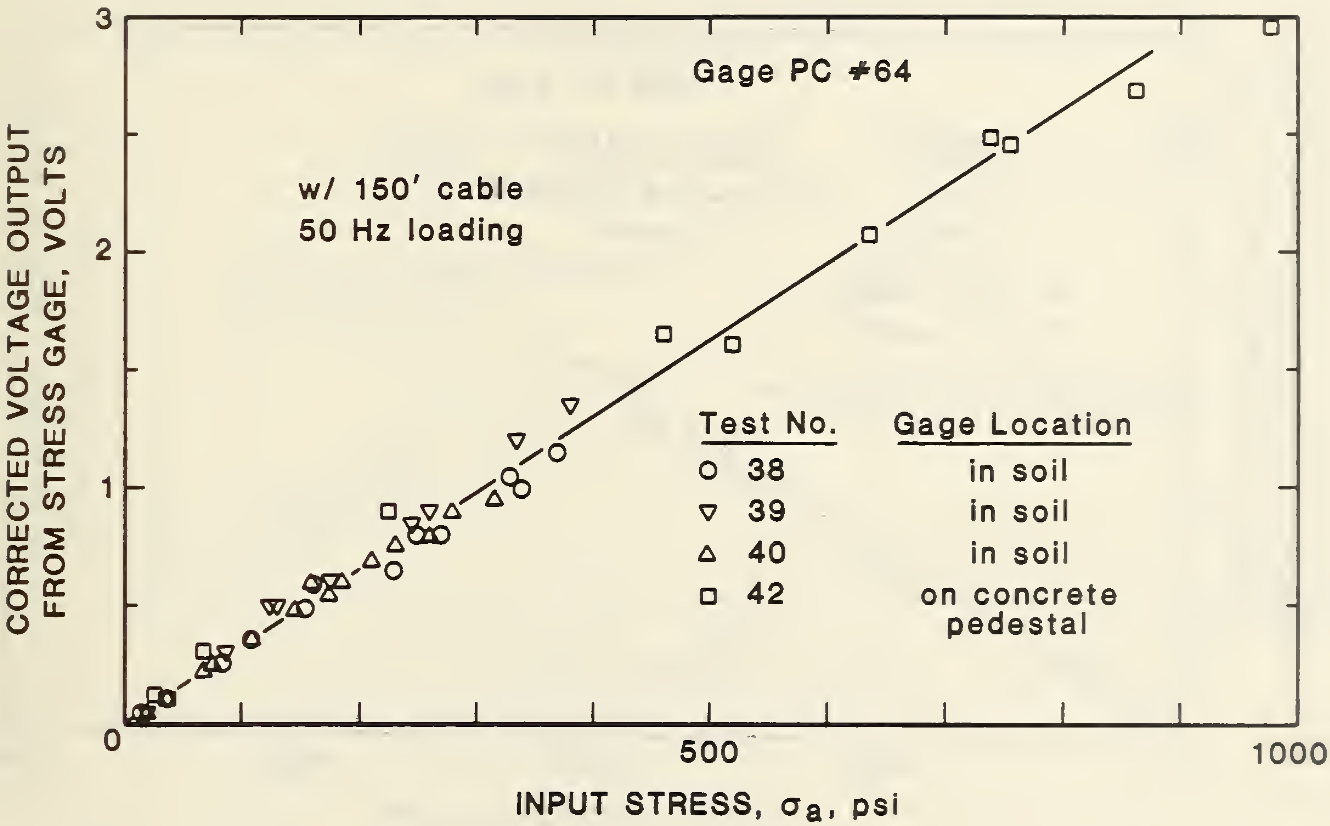

Figure 26 NBS Polymer Gage Test Results - Effect of Gage Location

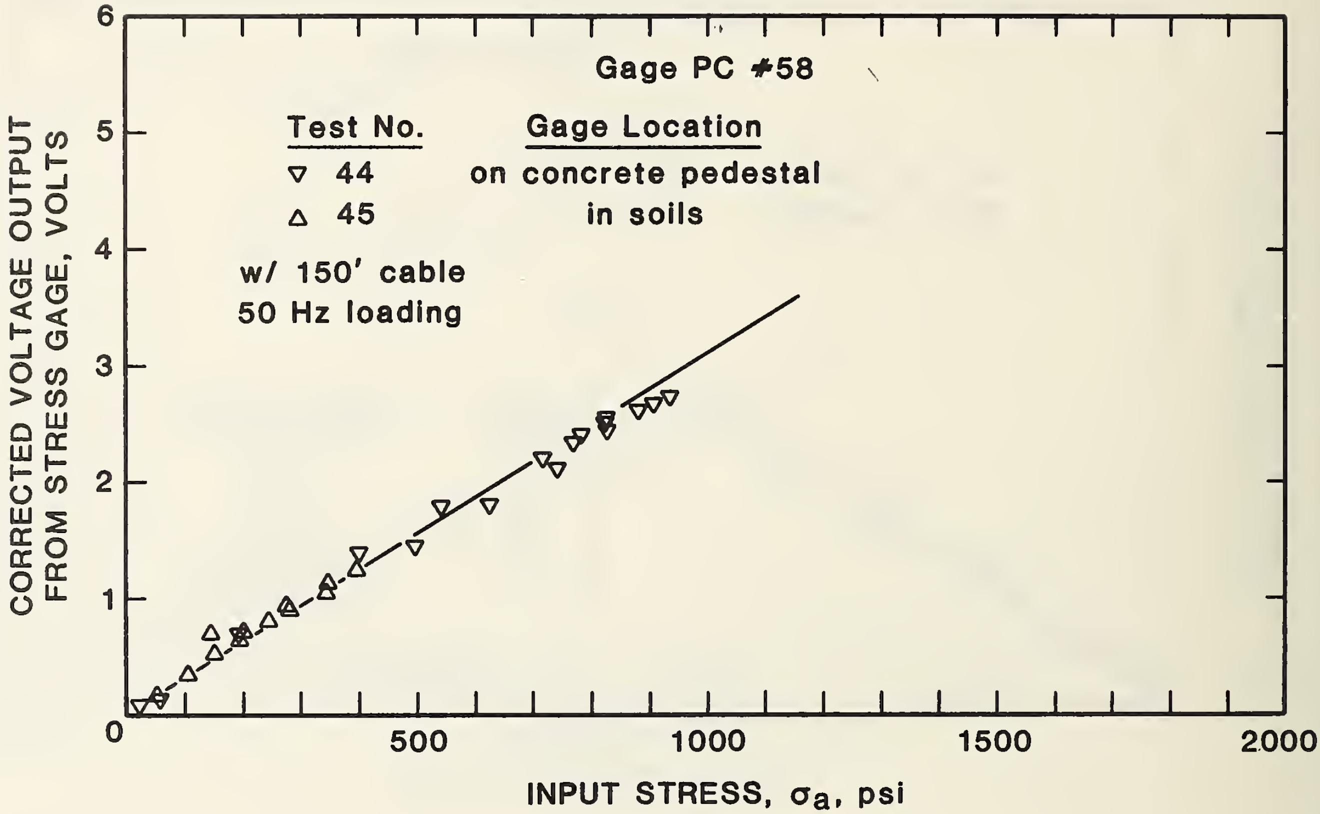

Figure 27 NBS Polymer Gage Test Results - Effect of Gage Location

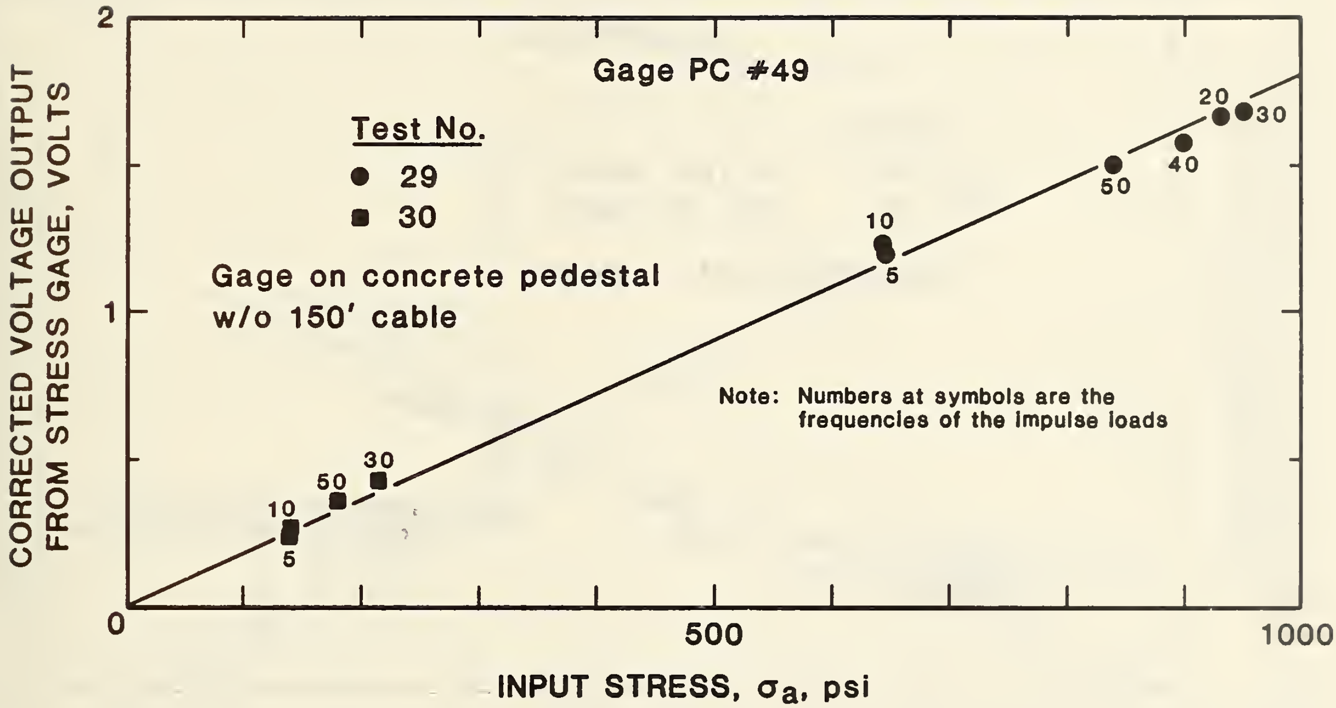

Figure 28 NBS Polymer Gage Test Results - Effect of Frequency, Gage PC #49

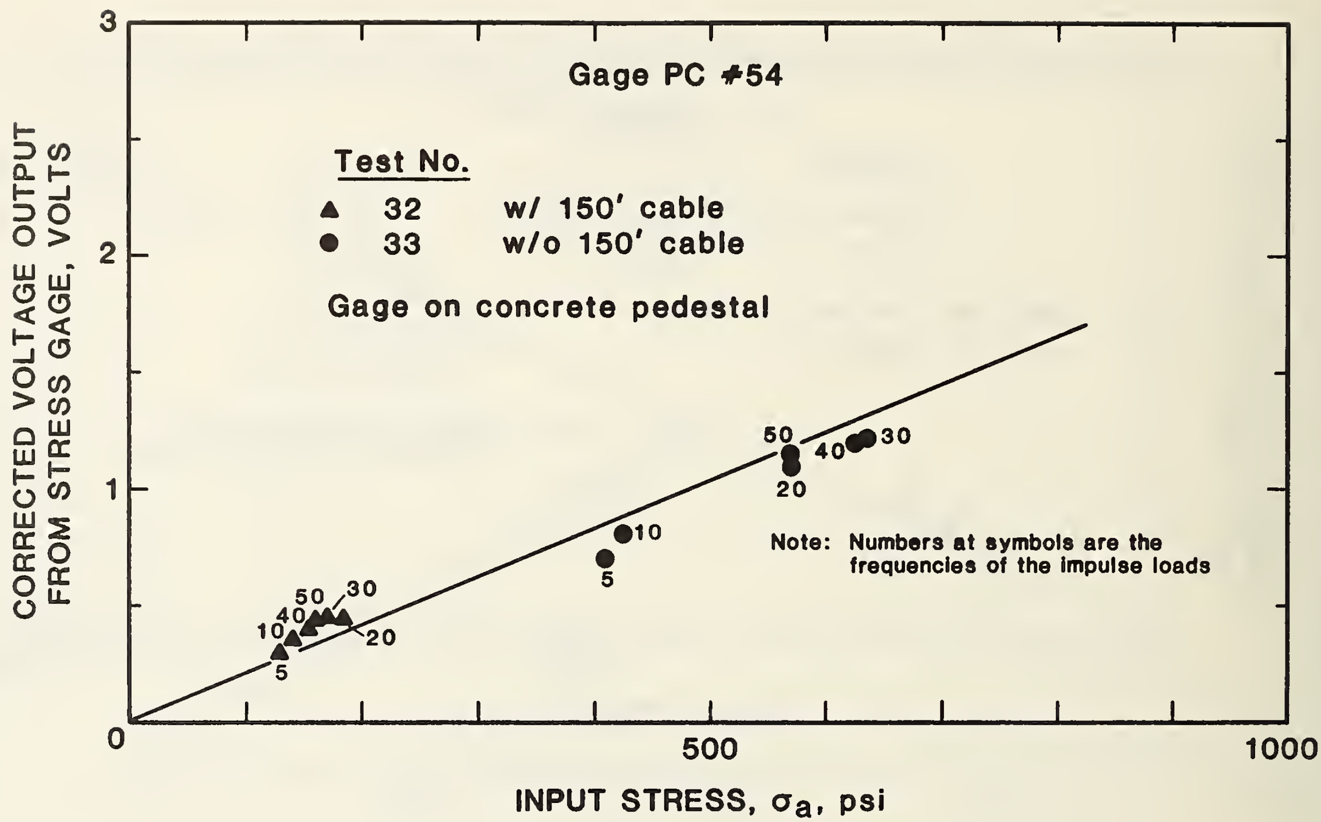

Figure 29 NBS Polymer Gage Test Results - Effect of Frequency, Gage PC #54

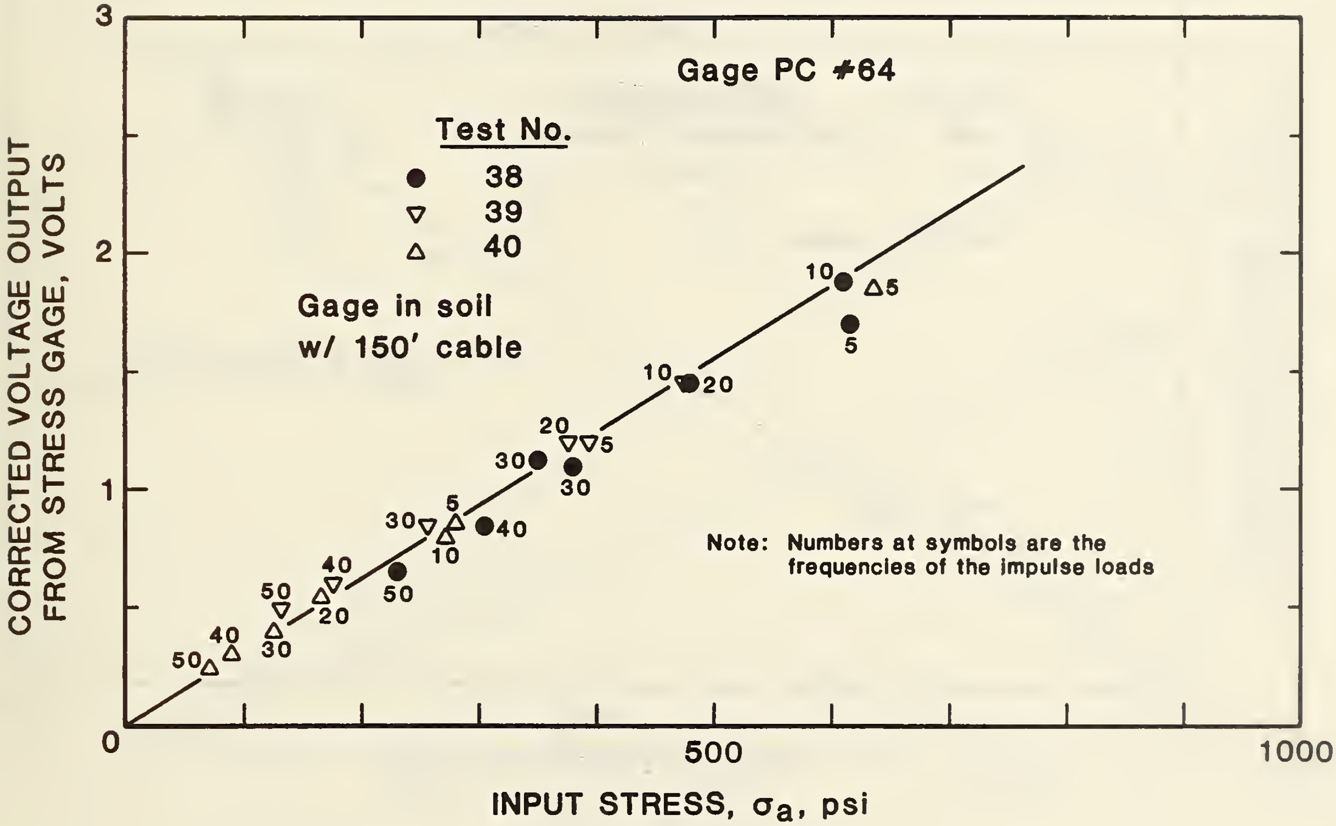

Figure 30 NBS Polymer Gage Test Results - Effect of Frequency, Gage PC #64

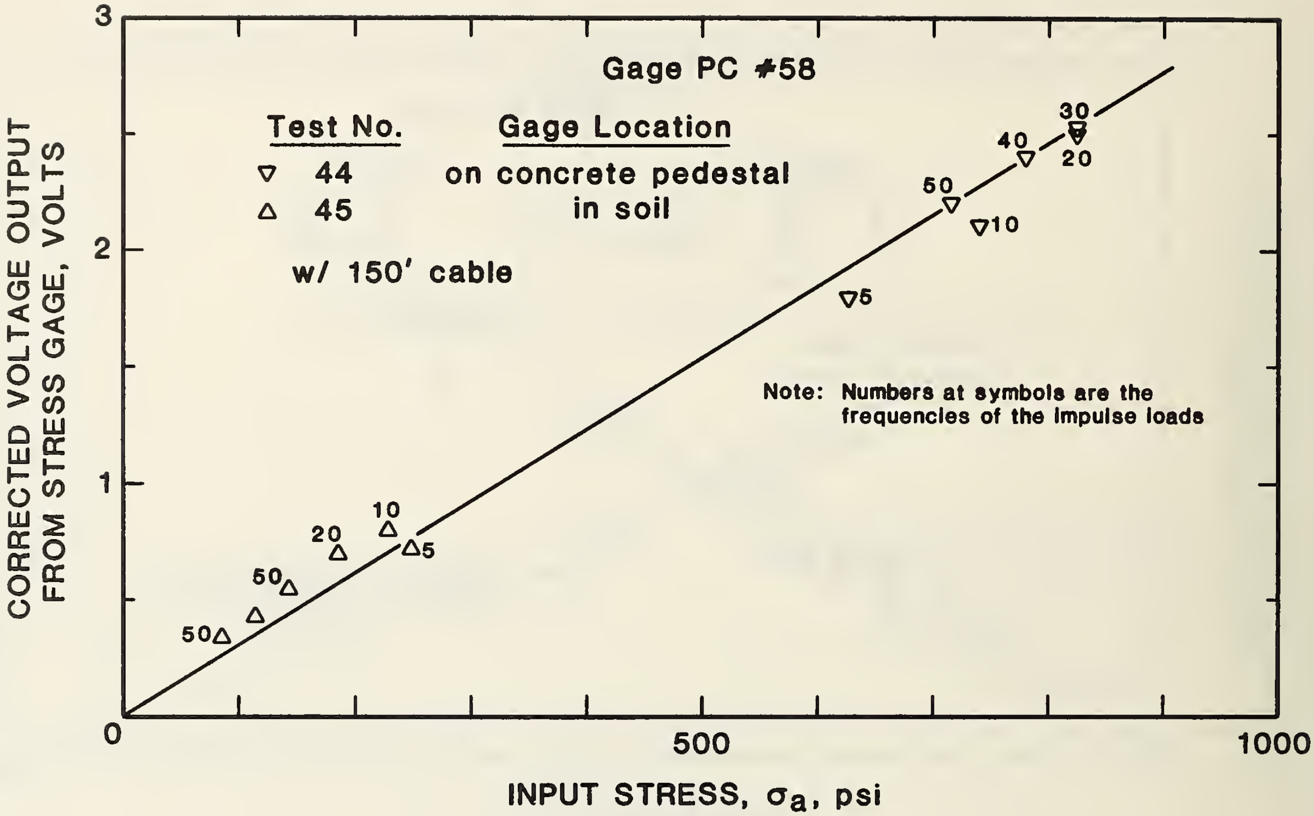

Figure 31 NBS Polymer Gage Test Results - Effect of Frequency, Gage PC #58

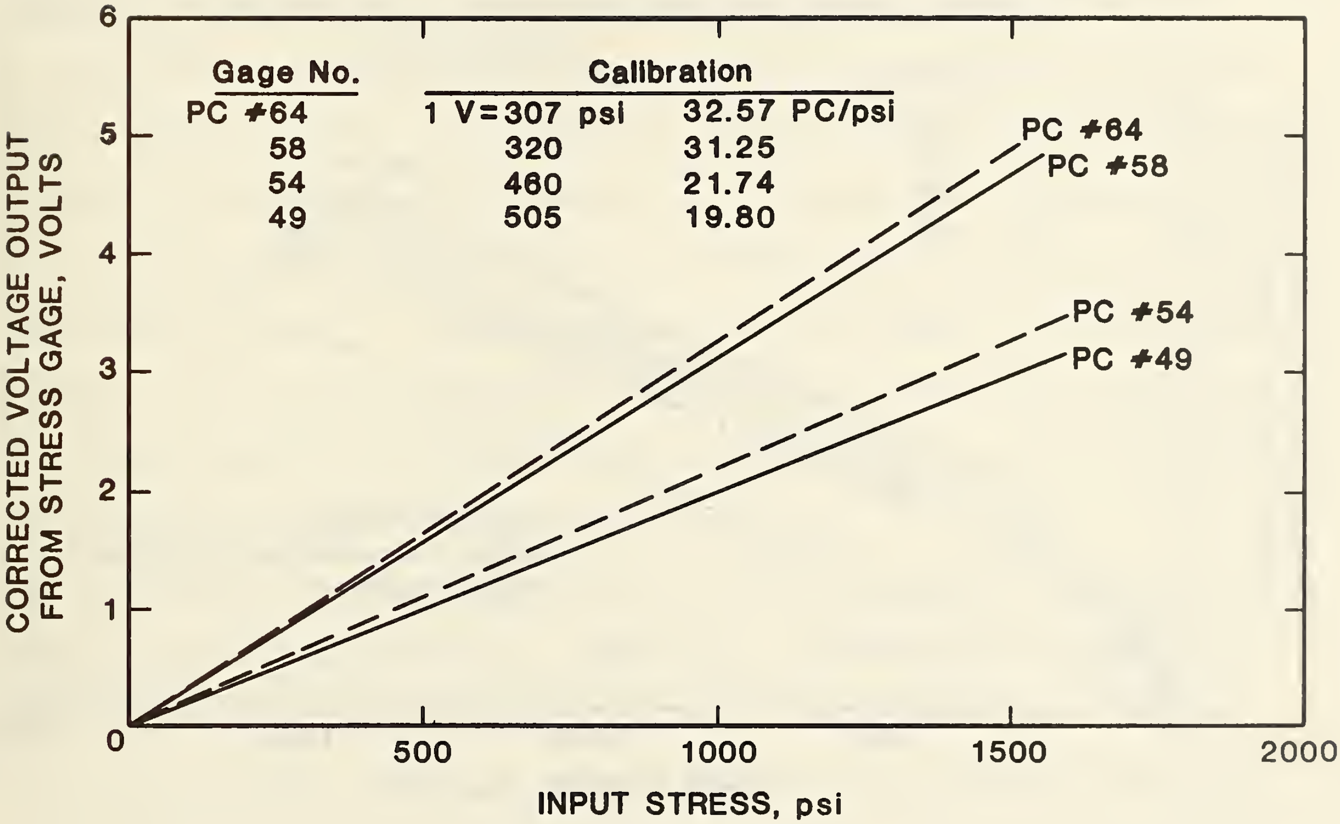

Figure 32 Summary of NBS Polymer Gages Calibrated for Field Testing

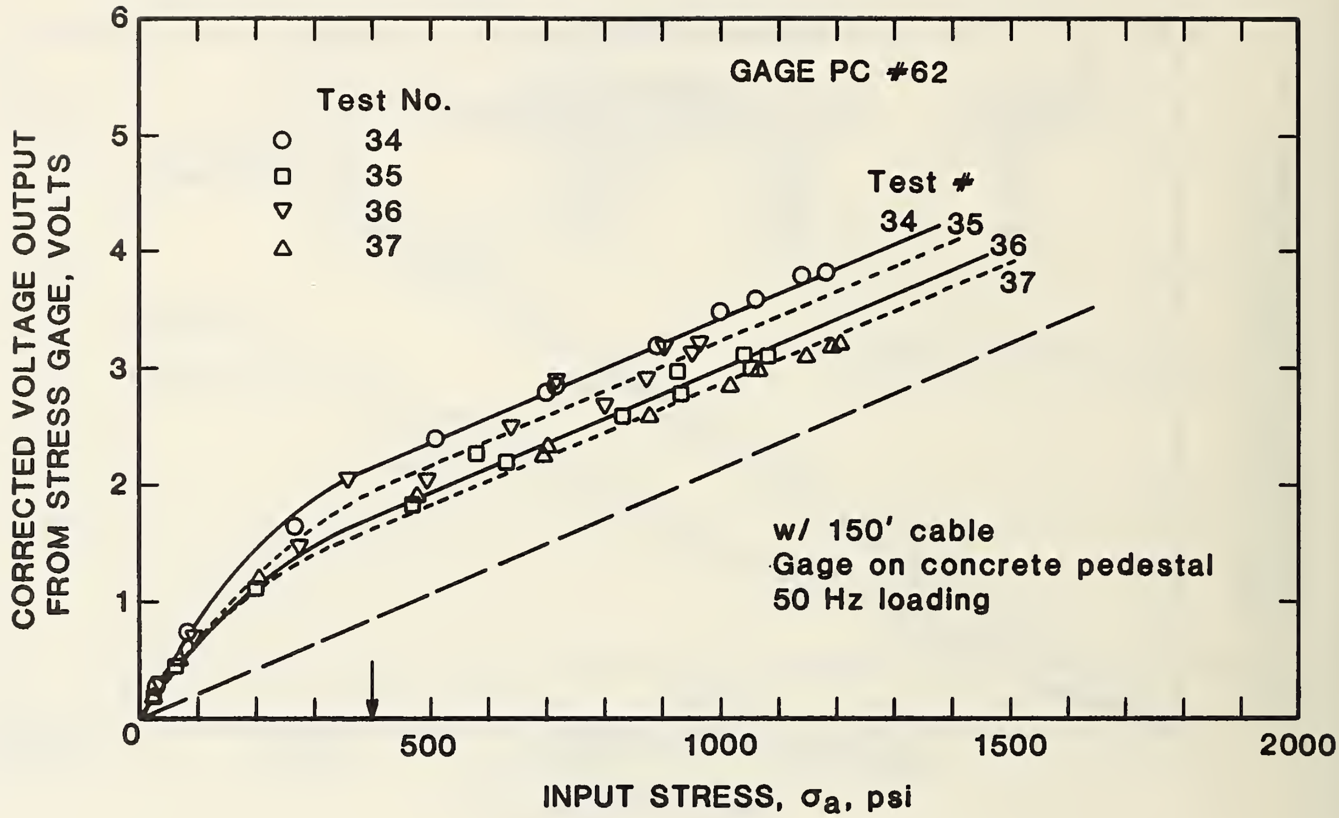

Figure 33 Non-linear Characteristics of The Gage Exhibited During The Testing of Gage PC #62

5. SUMMARY AND CONCLUSIONS

The following summary and conclusions can be drawn from the development and testing of the NBS polymer gage program:

a. The gage, which is made of two thin sheets of PVDF material, a thermocouple, and two thin polycarbonate sheets for gage surface protection, has been successfully developed to measure reliably dynamic pressures up to 2000 psi due to impact loads.

b. The gage, in its present design, has an aspect ratio of 0.024 and a modulus ratio of at least 35, which offers excellent dimensional and physical requirements for accurate stress measurement.

c. The nature of the gage design further offers the flexibility and feasibility to build gages with any aspect ratio and any shape required for specific applications. Numerous areas of gage application in geotechnical engineering have been identified to measure stresses due to dynamic loading.

d. Pyroelectric characteristics of the gage material have also been studied thoroughly to develop a temperature compensation amplifier to correct the gage signal. The temperature compensation is necessary when the gage is used for air pressure measurement due to blasting. However, test results show that this correction is not required when the gage is used to measure dynamic soil stresses since the temperature rise is very small. This leads to the conclusion that an NBS polymer gage without the embedded thermocouple can be equally effective in measuring dynamic soil stresses.

e. The present gage design evolved from an extensive test program in the Geotechnical Engineering Laboratory. Test variables includedin the program were: test cylinder insulation;use of long co-axial cable; gage location, i.e. whether the gage was placed on a concrete pedestal or buried in soil; four gage types; frequency of applied impact load; and seven different measures used for gage protection. The impact load consisted of a half cycle inverted sine waveform generated through an MTS load machine. Gage response to input load through a loading-unloading-reloading cycle was studied. A linear relationship between the input stress and the corrected gage response can be established from these test results as shown in figures 22 through 31. Specific findings from the test results with respect to each variable are given as follows:

1) Insulation of the test cylinder to prevent heat dissipation from the test specimen where the gage was embedded has resulted in no effect on the gage response.

2) Tests conducted with a 3 foot co-axial cable and 150 foot co-axial cable have yielded the same results. This means that the length of cable, which is usually in the order of several hundreds of feet in field application, should not affect the use of this gage for proper stress measurement.

3) Surfaces of the gage definitely need proper protection. Test results showed that the use of bentonite layers as a protective measure are not acceptable as indicated from the plots given in figures 20 and 21. The use of thin bentonite layers in field application was also judged not to be feasible.

4) Other types of protective covering such as stainless steel shims and hardened steel shims were also tested and were found to

be unsatisfactory for gage design.

5) The use of photo negative films as the protective cover resulted in good gage response measurement which led to the development of using polycarbonate sheets in the final design.

6) In the final gage design, polycarbonate sheets of two different thicknesses were used. Test results showed that a linear relationship can be established for both cases.

7) The linear relationship between input stress and corrected gage output holds for the gage whether it is placed on a concrete pedestal and backfilled by soil, or embedded in soil to simulate a free field condition. Therefore, the gage needs only to be tested under either condition to establish the relationship.

8) Frequencies of impact loads applied to the specimen were varied from 5 to 50 Hz, with the majority of the tests conducted under 50 Hz loading. The results indicated that frequency has no effect on the gage response, as shown in figures 28 through 31.

9) One gage was retested after re-epoxying a delamination which occurred between the PVDF sheet and the polycarbonate sheet. The test results indicated that the repair process does not affect the gage response as shown in figure 24.

f. Results of the gage calibration can be summarized in a figure such as that given in figure 32, which provides the calibration factors in units of volt/psi or pC/psi to facilitate the use of the gage for field application.

6. RECOMMENDED FUTURE STUDIES

A number of areas have been identified as a result of the present research and development program with regard to the NBS polymer gage. Additional studies are warranted to further refine the gage for its intended use. These areas are given as follows:

a. Effect of soil type: Due to the scheduled field test program, only the sandy soil from Eglin Air Force Base, Florida, where the field work was scheduled, was used in testing. Other types of soils including clay, silt, and silty sand, should be used to determine whether the NBS gage is sensitive to soil type.

b. Effect of soil moisture content: Florida sand was tested in its natural condition as it was received. The soil was slightly moist with its natural moisture content being about 6 percent. It is quite conceivable that gages may be placed in various moisture conditions including the saturated condition in its field application. Thus, laboratory testing of the gage by placing the gage in soil with various amounts of moisture should be conducted to evaluate the gage response.

c. Effect of initial placement density: Soil specimens with densities ranging from very loose to very dense should be prepared along with different gage embedments to study whether the gage would respond differently with respect to the placed soil density.

d. Rise time of impact load: Rise time in field blast tests are anticipated to be in the of order of 1 ms, which is faster than the frequency of the input impact load signal provided through the use of the MTS load machine. Tests should be conducted to evaluate the gage response under a faster input signal.

e. High pressure gage testing: A maximum soil stress up to 2000 psi was accomplished in the present program. Gage testing and calibration for higher pressure measurements, e.g., to 10,000 psi, should be developed. The tasks for this work should include development of test apparatus, test procedure, and proper protective coverings. It may also require a shot tube test set up to develop the higher pressure at a faster rise time. NBS at present does not have shot tube test equipment that can be used to accomplish this goal.

f. The flexibility in the polymer gage design with respect to its dimension and shape makes this gage particularly attractive for use to determine dynamic stress buildup and distribution in a centrifuge test environment. The gage can be miniaturized to a convenient dimension and placed in a soil bucket with almost no addition of weight to the soil mass. Many aspects of this miniaturization process will need systematic study, including gage fabrication and shielding, gage connection to the readout system, and a super fast data acquisition and reduction system through the slip-rings to accomodate the extremely fast rise time during a centrifuge blast test set up.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Polymer gages developed by the National Bureau of Standards (NBS) have been tested extensively in the NBS Geotechnical Engineering Laboratory to evaluate their capability and reliability for use in determining dynamic soil stresses generated by blast loadings. Penetration of soil grains into the gage surface was found to be the major concern and a major effort was undertaken to develop the most appropriate protective covering. Gages were dynamically loaded to develop their corresponding calibration curves. The test results indicate that the gage provides a linear relationship between the input stress and the gage output over the stress range tested. The calibrated linear relationship is not affected by the gage location, i.e., whether in soil or on a concrete pedestal; the thickness of the protective covering; the frequency of the impact load; and the length of the co-axial cable used in testing.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Blasting; Dynamic; Gage; Instrumentation; Measurement; Polymer; Soil; Stress

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