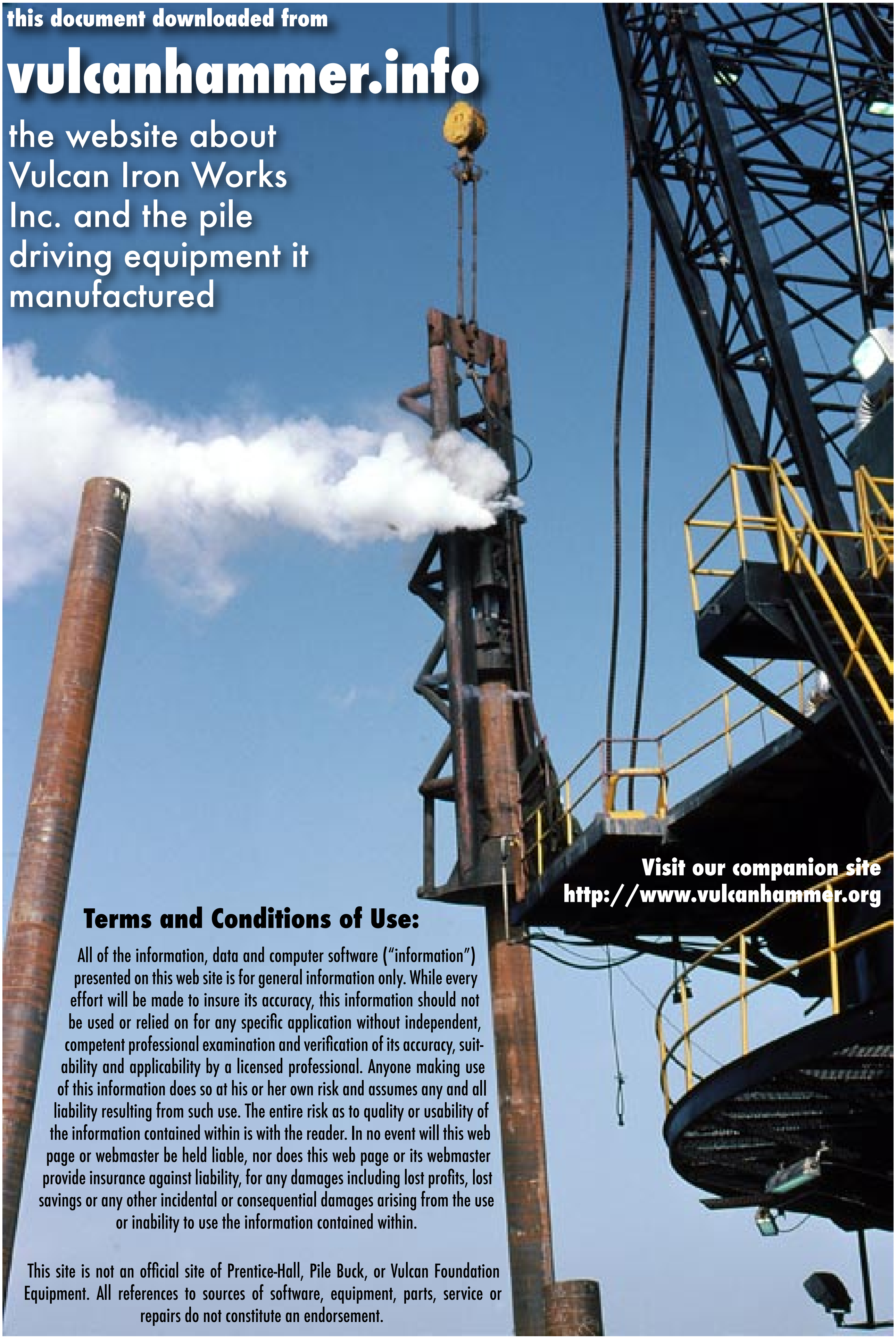

FIELD INSTRUMENTATION FOR PILES

by

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FOREWORD

Instrumentation for use in piling is probably subjected to some of the most severe environmental conditions the average practicing engineer will ever encounter. Impact stresses to 100,000 psi, accelerations of 1,000 g's, and the need for absolute waterproofing to permit long-term measurements are but a few of the problems encountered. The consequences of this environment become obvious when the large sums of money needed to fund experimental piling programs are compared with the limited amount of data obtained. Nevertheless, the necessity to supplement, support, and verify our ever increasing methods of analysis with experimental data has caused rapid expansion in the use of instrumented piles.

INTRODUCTION

Until about 1960, a majority of the data taken centered around pile displacements during driving. The equipment was usually quite simple, for example, a transit for recording the average penetration per blow, paper taped to the driven pile and marked with a pencil moving horizontally to record temporary and permanent set of the pile per blow, etc. This data was, of course, for use in pile driving formulas, of which over 400 have been proposed[(1)*], in an attempt to predict the pile's bearing capacity. However, with such an array of variables known to affect the problem, it is no wonder that little confidence was placed in the results. Even though an extensive amount of data might be taken, every equation available neglected numerous important

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*Numerical superscripts refer to corresponding items in the References.

parameters, and the complexity of the problem was so great that elaborate instrumentation was seldom considered necessary. Nevertheless, ambitious projects were regularly funded in an attempt to at least determine all the experimental values needed for a specific area or state. An excellent example of this was the recent experimental study sponsored by the Michigan State Highway Commission(2), which was probably the most extensive (and expensive) experimental pile program to date. The investigators hoped to take data on a majority of the piles, driving hammers, and soil conditions commonly encountered in the State of Michigan, and, after solving numerous instrumentation problems, were highly successful in this attempt. Only by reading the report can the volume of data taken be appreciated, but it was tremendous to say the least. Even so, their work was highly criticized by persons who objected that the number of problems analyzed were still in fact statistically insignificant and in no way warranted their conclusions or recommendations(3).

This same program illustrated that major instrumentation problems can occur regardless of the efforts made to prevent them. However, their work should prove invaluable to future researchers, since not only final solutions were given--the many problems, failures, and difficulties encountered are also fully reported. For example, the load cells and accelerometers used in the driving operations were constant sources of trouble. The placement of these instruments and the driving assembly employed are illustrated in Figure 1, and will be discussed later.

A surge of interest in the instrumentation and field testing of piles was generated in 1960 when E. A. L. Smith formulated and published the first truly general and mathematically correct analysis for the problem of pile driving(1). For the first time, questions about driving stresses, what hammer is needed to to drive a given pile, and even its bearing capacity could be answered. However, the numerous variables influencing the problem could no longer be ignored. They were required by the proposed analysis. Thus great quantities of experimental data were suddenly needed on everything from driving hammers right down to the soil itself.

Immediately after the appearance of Smith's paper in 1960, the Texas Highway Department, through Texas A&M University, initiated an extensive research program to experimentally determine input data needed by Smith's method of analysis (generally referred to as the wave equation). The experience and recommended procedures mentioned in this report resulted largely from these programs as well as from research presently funded by the U. S. Bureau of Public Roads and private sources.

It is interesting to note that once the needed input data was determined experimentally, Smith's wave equation solution began to prove itself as one of the most powerful methods of analysis available to the foundation engineer. An although there are still questions to be answered, the wave equation has already proved capable of answering such questions as whether the stresses induced in the pile during driving will be excessive(9), (10), can a given hammer drive a pile to the required penetration, and if not, what hammer should be used(11), pile bearing capacity(5), (12), and many others. The Texas Highway Department was so impressed by the reduction in pile breakage that the wave equation was used to modify the State's pile driving specifications.

INSTRUMENTATION SELECTION

Because of the large number of variables which influence the problem, pile instrumentation necessarily involves many different types of instrumentation.

However, a majority of these variables involve the measurement of

1. internal pile forces,
2. applied and resisting forces,
3. displacements,
4. accelerations,
5. velocities, and
6. pressures.

Normally, equipment selection will be greatly influenced by when the measurements are to be made. For example, measurements will commonly be made during:

1. fabrication of the pile,
2. transportation and handling,
3. during driving,
4. immediately after driving,
5. during long-term testing, and
6. during service.

Fortunately, except for the third stage listed above, each involves only low frequency phenomena. This greatly simplifies the choice of equipment since special high frequency response instrumentation will be necessary only if measurements are to be taken during the driving operation.

Figures 2 and 3 are presented to illustrate the types of instrumentation commonly employed during driving and during static tests.

Performance Considerations

In the selection of instrumentation for piles, several factors must be considered. In approximate order of importance, these factors include:

1. the accuracy of the unit,
2. its durability, or resistance to failure,
3. its influence on the measured system,
4. simplicity of operation under field conditions,
5. ease of installation,
6. readily available maintenance,
7. auxiliary equipment necessary for operation,
8. cost, and
9. salvage value.

It is probable that the first three items are of vital importance, and that even the slightest compromise in any one of them will drastically reduce the chance of obtaining useful data.

The significance of items 1 and 2 above are obvious. As an example of the importance of item 3, a study using the wave equation showed that in many cases, the mass of the instrumentation utilized throughout the Michigan Pile Study (see Figure 1) affected the results more than 40 percent(4). Obviously there is little purpose in trying to determine any parameter experimentally if the equipment employed changes the value being measured.

INTERNAL PILE FORCES

The instrumentation most commonly used to obtain data regarding the first of the variables mentioned above is the strain gauge. However, because of the uncommon environment in which it must survive, the choice of gauge, method of installation, and its subsequent protection from impact damage and moisture failure are critical.

Concrete Piles

Selection of gauges. Although standard strain gauges are often used, there are a number of gauges manufactured especially for use in concrete. These 'special' gauges will often out-perform standard gauges, and in many cases are even less expensive.

Probably the best known gauge for use in concrete is Baldwin's Valore gauge, model AS-9-S6, shown in Figure 4, and pictured in Illustration 2. This gauge consists of a standard Constantan wire gauge wrapped in a 1-mil Valore-Brass foil envelope. It is extremely flexible and delicate and must be carefully protected to prevent damage while pouring or vibrating the concrete in the forms. In 1967 the Texas Transportation Institute installed several hundred of these gauges in piles on various projects but had quite limited success(5), (6). Moisture leakage was thought to have caused the failures, but whatever the reason, the trouble consistently caused the loss of at least one test point along every pile, and in many instances every gauge was lost. Although some good driving stress data was obtained, the number of gauge failures greatly increased during the long-term load tests.

A second type of gauge, illustrated in Figure 4, was used to instrument the remaining piles. This was a polyester mold gauge manufactured by the Tokyo Sokki Kenkyujo Co., Ltd., of Japan, and consisted of a standard 300 ohm gauge hermetically sealed between two thin polyester blocks. This encapsulation completely waterproofs both the gauge and lead wires, and provides an extremely tough protective shell which simplified installation greatly since there was no need to protect the gauge against placement or vibration of the concrete. The faces of the gauge are coated with a sand grit to insure proper bond with the concrete whereas the foil-encased gauge was susceptible to bond failure. These gauges proved completely reliable in every respect, and no further failures were experienced, even though many of the piles were driven far below the water line and were not load-tested for months. To date, not a single gauge failure has been noted.

Although these gauges were quite inexpensive, their performance proved totally reliable. As shown in Illustration 1, several types of gauges are available, including both 2- and 3-axis rosettes.

Probably the most interesting of the special gauges is the vibrating wire strain gauge shown in Figure 5. One such gauge, distributed by Geo-measurements Southwest of Arlington, Texas, is shown in Illustration 3.

In this case the applied strain gauge changes the tension in a fine vibrating wire, thereby changing its natural frequency, which is translated into strain. Although special readout equipment is required, and the gauge is relatively large, its long-term stability makes it highly useful in many situations.

Possibly the most highly moisture resistant gauge available is manufactured by the Structural Behavior Engineering Labs, Inc., of Phoenix, Arizona. Termed the "Stressmeter," it consists of a 4-foot section of deformed A-432 steel reinforcing bar, turned down to accept placement of a full 4-arm bridge. The gauge is illustrated in Figure 6. The transducer is completely waterproofed and no special handling is necessary during transportation or installation. The strain gauges are attached to the bar by resistance welding, insuring a strong bond and continued performance in presence of shock and vibration. By welding the gauge to the metal it thereby becomes an integral part of the test structure, rather than a cemented addition to it.

Since these gauges are specially made to order, they are relatively expensive. However, this also gives them a number of advantages, including the following:

1. Can be made to measure low and high concrete stresses or forces.

2. Can be curved to conform to structural shape.

3. Can be lengthened and multiple-gauged along their length for installation in areas of rapidly changing static or dynamic stress.

4. Can be shortened for measurements in tight and confined areas.

The characteristics of each of the previously mentioned 'special' gauges are summarized and compared in Table 1.

Interior installation of gauges. As mentioned previously, problems inherent with the use of strain gauges are magnified when they are used under field conditions, the greatest of which is probably moistureproofing the system. The method shown in Figure 7 is recommended for use at all splice points. It has proved entirely reliable and highly superior to other methods attempted by the authors during the past 10 years[5].

The method of installation is also important, as was discovered early in 1962 during a research project conducted at Texas A&M[6]. Figure 8 shows a sketch of a typical gauge point installation used in this study. Since the gauge connections and lead wires were to be cast in the pile, adequate moisture protection during manufacture of the pile was imperative. The entire system also had to be protected from moisture until the pile was driven, and subsequently from the time of driving until the static load test could be run. The gauges also had to be installed in such a manner that they would not be damaged during the manufacture of the pile. It was found that the polyester mold gauge used required no additional waterproofing, and that it was

TABLE 1. CHARACTERISTICS OF STRAIN GAUGES FOR USE IN CONCRETE

	Baldwin Brass Foil Gauge	S.B.E.L. "Stressmeter"	Vibrating Wire Gauge	Polyester Mold Gauge
1) Accuracy	Excellent	Excellent	Excellent	Excellent
2) Durability -				
Moisture Resistance	Poor	Excellent	Excellent	Excellent
Resistance to Mechanical Impact	Poor	Excellent	Excellent	Excellent
Resistance to Bond Failure	Good	Excellent	Excellent	Excellent
3) Influence on System	None	Low	Some	Low
4) Simplicity of Operation	Excellent	Excellent	Good	Excellent
5) Maintenance	(a)	(a)	(b)	(a)
6) Ease of Installation	Fair	Good	Fair	Excellent
7) Auxiliary Equipment	Standard	Standard	Special	Standard
8) Cost per Gauge	$15.00(c)	$102.50(d)	$115.00 (d)	$3.00(c)
9) Availability	Excellent	Good	Good	Poor
10) Salvage	None	None	Possible(b)	None
11) Application				
Static	Yes	Yes	Yes	Yes
Dynamic	Yes	Yes	No	Yes

(a) Not feasible.
(b) Feasible if gauge can be retrieved from test specimen.
(c) Four units required for full 4-arm bridge.
(d) Only one unit required.

sufficiently strong to withstand the placing and vibrating of the concrete without being damaged.

In earlier projects at Texas A&M, each gauge point was pre-fabricated in the laboratory, and consisted of a completely waterproofed module including the gauge bridge, main lead wires, and surface connectors. This module scheme permitted fast field installation with a minimum of interference in the field to the pile fabricator. Each module could also be tested, zeroed, balanced, etc., before leaving for the job site. This module is shown in Illustration 4.

The main lead cables were laid along the upper surface of the pile and secured to the reinforcing strands at frequent intervals with plastic tape as shown in Figure 9. Care must be taken to insure that the main lead cables are not placed in one bundle but are spread uniformly across the surface. Otherwise, considerable crosstalk between channels may result. At the head of the pile the main lead cables are bundled and wrapped with plastic tape to form a common exit. Approximately 5 feet of lead cable was left exposed at the head of the pile, the connections having earlier been completely waterproofed by potting with RTV silicone rubber as illustrated in Figure 9. This potting compound proved completely reliable and was easily cut off the connectors immediately prior to testing. After testing, the connectors were again potted for future tests.

The gauges should be loosely attached with light tape or wire to the prestressing strands or reinforcing bars as shown in Illustration 5. Sufficient space between the gauge and bar should be left to allow the grout to completely surround the gauge.

As noted in Figure 9, the lead wires extending from the pile should be kept as short as practical, since very long leads are highly subject to damage during handling and transportation of the pile. Extremely long leads are also a great temptation to workmen needing a length of rope, or some hook-up wire for their stereo or extra telephone at home.

Exterior installation of gauges. In some cases the pile to be tested has already been fabricated. This obviously prevents the use of embedded gauges, forcing the use of surface gauges. The use of surface gauges is normally less desirable because both the gauges and wiring are fully exposed, thereby requiring either more elaborate protection or extreme caution during handling, transportation, and testing of the pile. Illustrations 6 and 7 show how polyester mold gauges were recently used to determine the importance of stresses induced during the handling and transportation of piles(7). In each case a full 4-arm bridge was employed, with the mold gauges simply bonded to the pile surface with epoxy. No waterproofing of the gauges was necessary and the only preparation of the pile was the removal of any loose surface scale with a stiff wire brush.

Steel Piles-Gauge Selection and Installation

The use of strain gauges on a steel pile poses many of the same problems mentioned for concrete piles. However, in the case of steel piles, mechanical protection for the gauges and wiring must always be provided to prevent the soil, and hammer impact, from destroying the gauges or tearing out the wiring. Also, the choice of adhesive to resist dynamic stresses, and the waterproofing compounds employed should be carefully considered. Fortunately, gauge manufacturers are fully able to provide sufficient information on which to base the selection. Recent tests by the Texas Transportation Institute(8) happened to employ Micro-Measurement gauges, C-2 epoxy, and Gaugecoat 5 waterproofing compound, from which excellent data was obtained. Because the pile tested was a pipe pile, the instrumentation was installed through access ports which were later welded back in place. Asbestos wrapping was used to protect the lead cables as the pile was welded together.

LOAD CELLS

As was noted earlier, the load cell used in the Michigan Pile Study often affected the problem significantly because of its size. However, the tremendous loads generated beneath the driving hammer would not permit a reduction in its size, as was noted in the Michigan Report[2]. However, the use of the load cell was not absolutely essential, since strain gauges could have been mounted directly beneath the head of the pile, acting in effect as a load cell. This obviously would be far more expensive, and calibration might have caused problems, but all facts considered, the author would strongly recommend gauging the pile head rather than using any equipment which so drastically influenced the variables being measured.

DISPLACEMENT TRANSDUCERS

Probably the most common method for recording dynamic pile displacements is to run a pencil horizontally across a sheet of paper fastened to the pile, a method which is still frequently used. However, if an accurate time base is needed, more elaborate equipment must be employed.

Although research personnel at Texas A&M tried many different displacement transducers, including linear wire-wound resistance gauges as well as optical tracking cameras, the only satisfactory field method discovered thus far employed a linear variable displacement transducer, or L.V.D.T.

The L.V.D.T. is basically a transformer, with primary and secondary windings coupled by a free-floating cylindrical core of magnetic material moving through the center of the instrument. The unit has many advantages, including:

1. it will not "bottom out" if an excessive deflection is applied, when connected as shown in Figure 10,

2. there is but one moving part and wear is minimal, and

3. there are no sliding electrical contacts such as in wirewound resistance gauges.

The only real disadvantage used to be a limited stroke range (2 to 3 inches), but new equipment has constantly appeared with increased ranges. Crescent East, Inc., of El Monte, California, makes a heavy duty model with a linear range of 16 inches (Model HC-2B-16).

It should be noted that the Michigan Pile Study also tried a number of unsuccessful devices for determining pile deflection, and they also concluded that the L.V.D.T. was superior[2].

PRESSURE TRANSDUCERS

Probably the most important factor in selecting a pressure transducer for measuring soil pore water pressure is the ability to withstand the high accelerations during driving. In recent tests by the Texas Transportation Institute[8], pore water pressure measurements were obtained with Consolidated Electrodynamics Corporation Type 4-326 pressure transducers. Important design features included corrosion resistant housings, 0-100 psi gauge ranges, and the ability to withstand a 1000-g half sine wave pulse for one millisecond without damage. The pressure transducers were mated to the pile wall as shown in Figure 11. The transducer support was necessary to protect the instrument from breakage through bending during driving. Porous bronze plates were employed to prevent the entry of foreign material into the transducer diaphragm chamber. In order to lower the response time of the instrument, the pressure transducer was filled with water before the protective porous bronze plates were fastened in position with epoxy. The pile was transported with the porous bronze plates oriented upward and sealed to prevent loss of water from the transducer through seepage and evaporation.

Upon arrival at the test site the installation was checked and the bronze plates moistened again as an added precaution. A thin layer of clay was applied to the porous bronze plates to minimize loss of contained water by seepage, and the pile was hoisted to a vertical position and driven. These precautions were taken in order to lower the response line of the instruments to the extent that pressure measurements recorded, other than those due to shock waves during driving, were considered to be those existing in the soil, even during rapid pressure fluctuations.

Although the pressure transducers used in this study were bonded-gauge with a single range (0-100 psi), the use of a variable reluctance, multiple-range transducer such as the Pace P-3D might be less expensive. The pressure range of a variable reluctance pressure transducer, unlike bonded gauge types, is determined by the thickness of a special plate bolted between two pressure sensing elements. Furthermore, the range of the transducer can be changed by merely purchasing a new (and relatively inexpensive) plate from the manufacturer.

However, regardless of the transducer selected, it will probably require an external bracket support to withstand the driving stresses involved.

ACCELEROMETERS

The selection of an accelerometer to withstand the environment of pile driving is quite simple. Actually, it is probable that any of the known manufacturers can supply an accelerometer which will prove satisfactory, except for the following:

1. The mounting studs are invariably weak. This results in rapid loosening of the accelerometer, which must be bolted down tight for useful readings, and often even complete failure of the mounting stud.

2. The lead wires to the accelerometer are either microscopic in size, or the electrical connector is made of extremely weak material.

In either case, it is usually anyone's guess as to whether the lead wires or the whole accelerometer will be the first to break off. This same problem was encountered in the Michigan Pile Study(2), and no solution was reported.

Of the several types of accelerometers available, the piezo-electric type is probably superior as far as resistance to internal damage, having proven far more durable than the bonded strain-gauge type. Typical of the piezo-electric accelerometers, and most commonly used for pile instrumentation by the authors is the Endevco mocel 2211C.

Special care should be excercised when mounting accelerometers to insure that the mounting base itself is extremely rigid, having a much higher natural frequency of vibration than that being measured. Otherwise the vibrations of the base may well obscure the data being measured.

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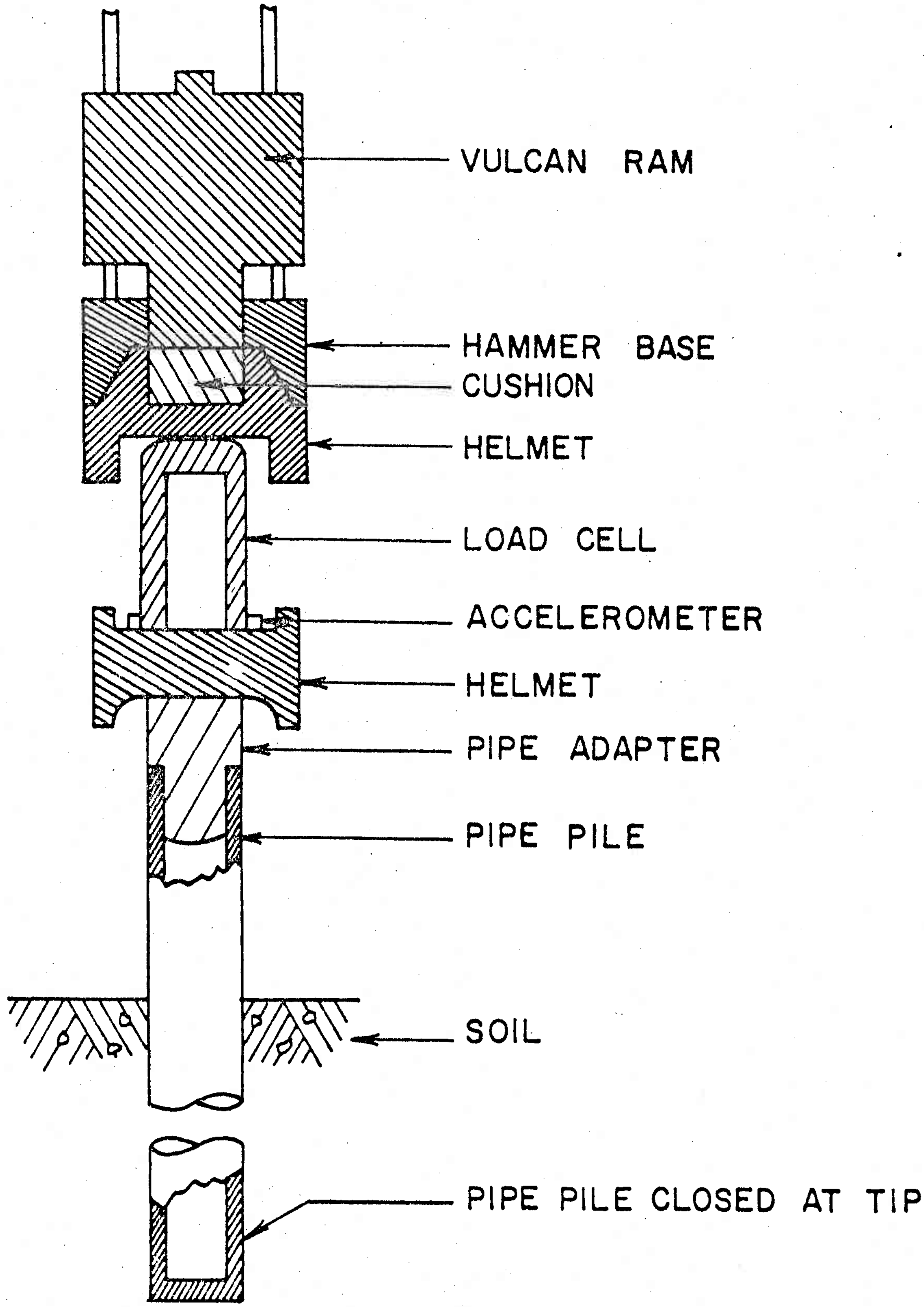


Figure 1. Driving Assembly Used in the Michigan Pile Study

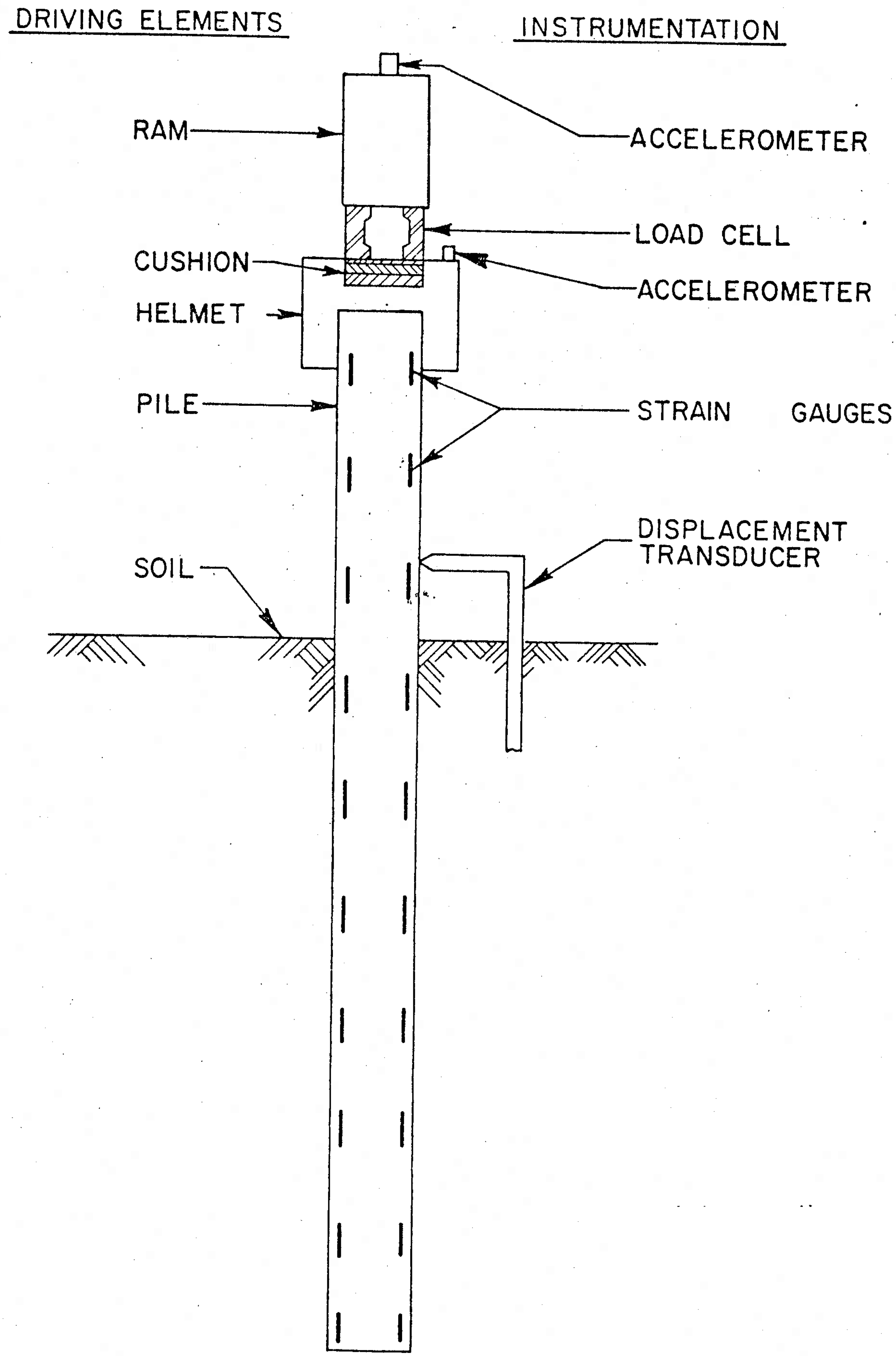


FIGURE 2. POSSIBLE MEASUREMENTS DURING DRIVING

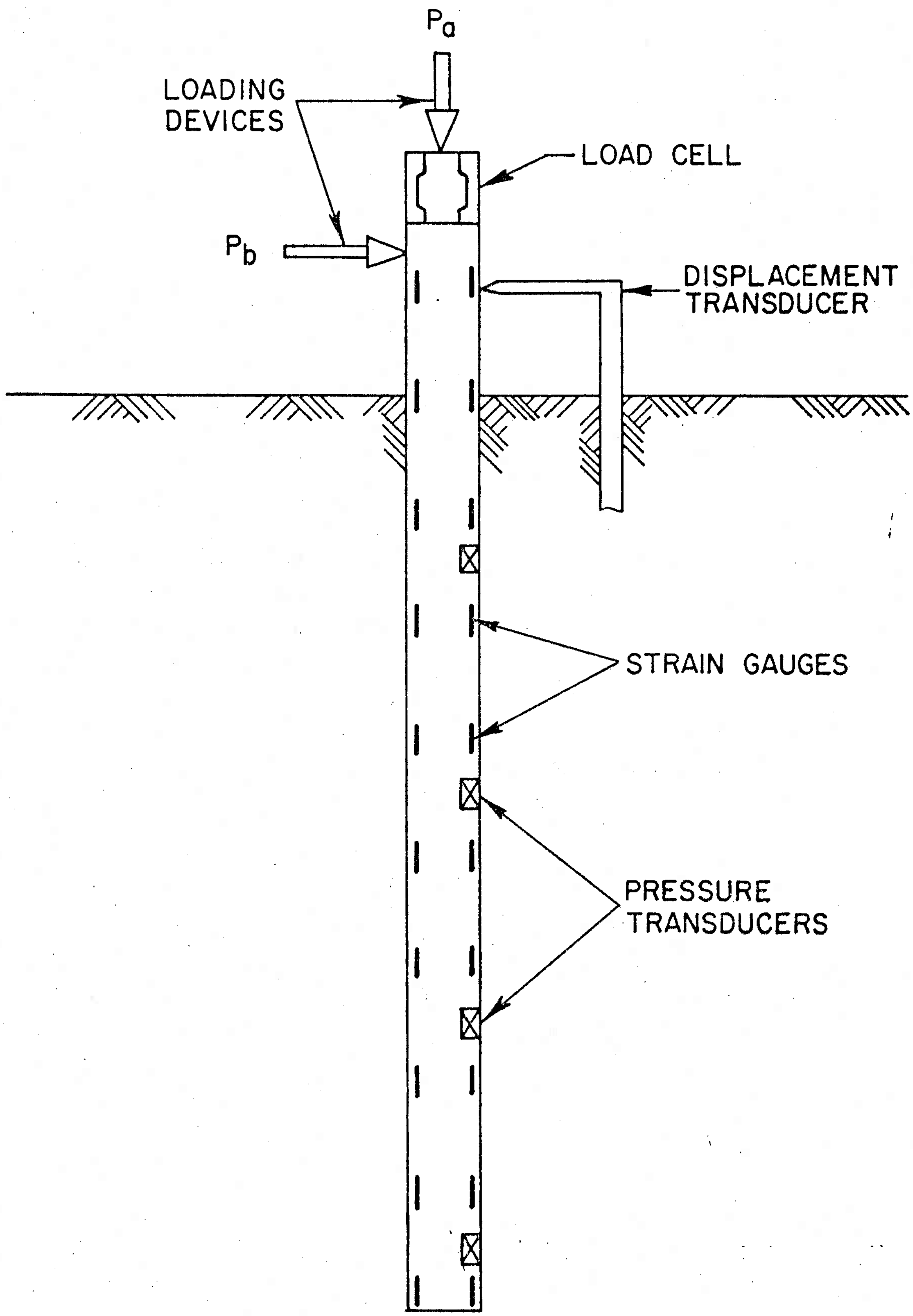


FIGURE 3. POSSIBLE MEASUREMENTS DURING STATIC TESTING

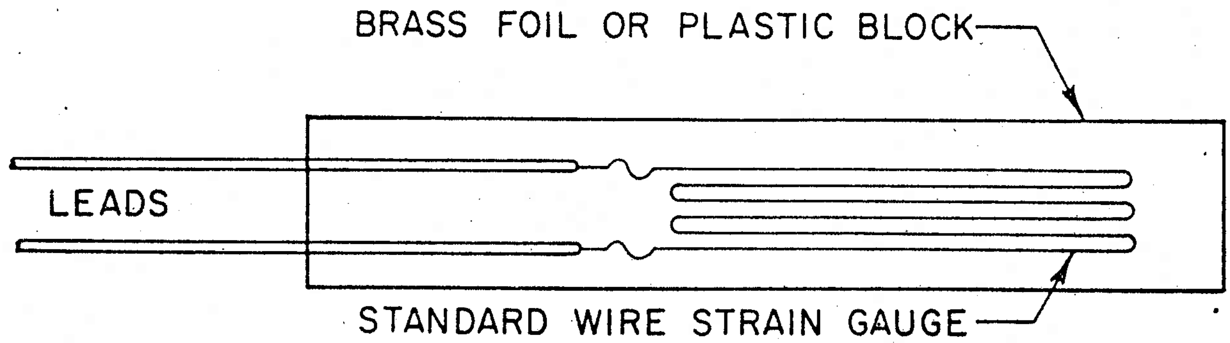


FIGURE 4. CONCRETE IMBEDMENT GAUGE

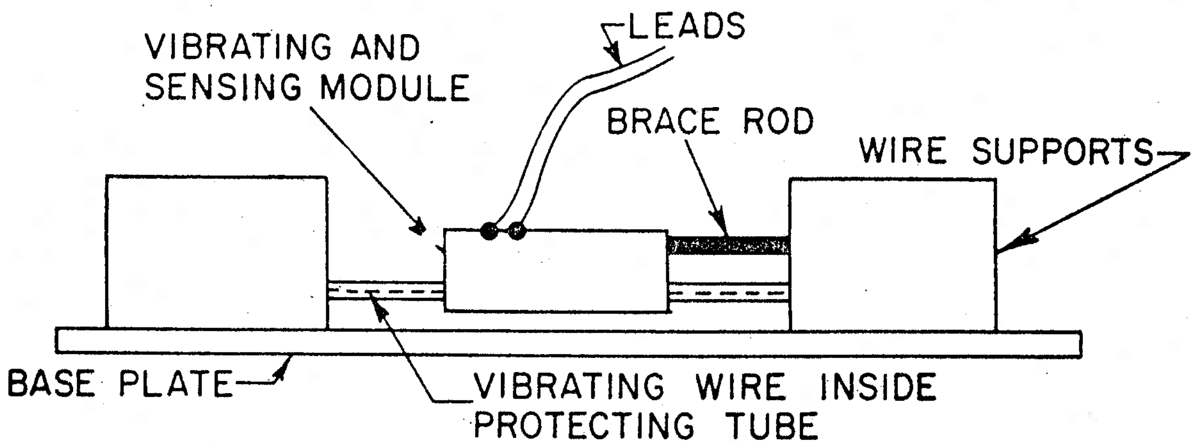


FIGURE 5. VIBRATING WIRE STRAIN GAUGE

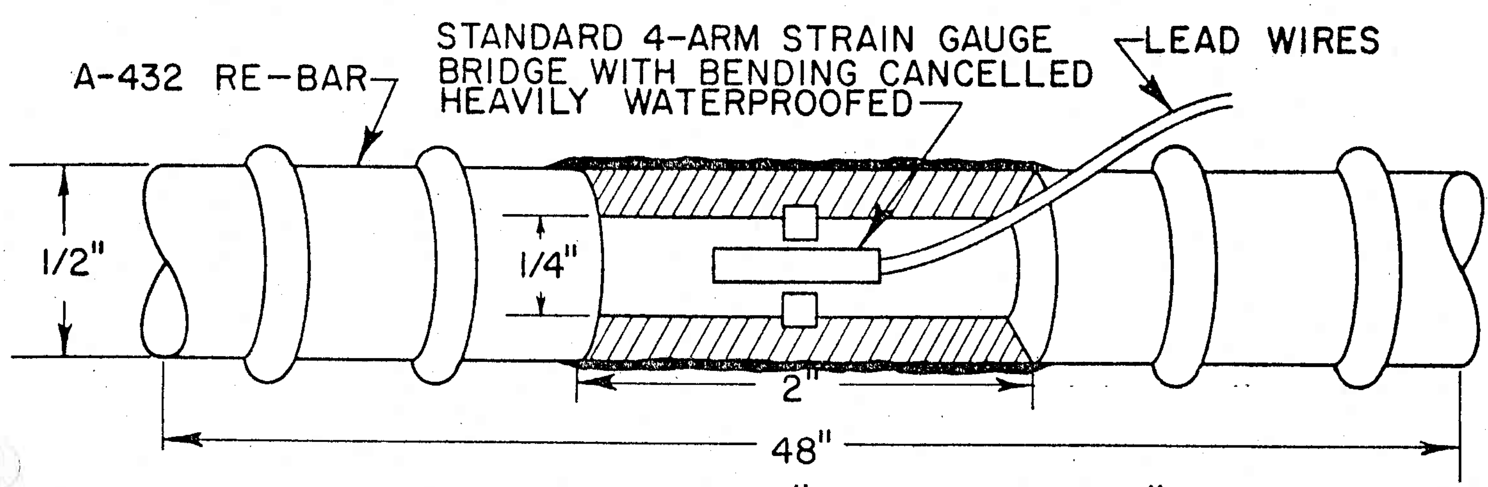
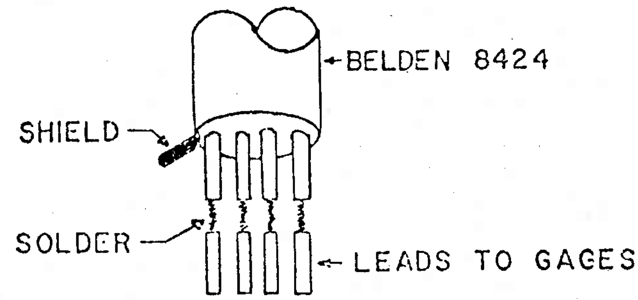
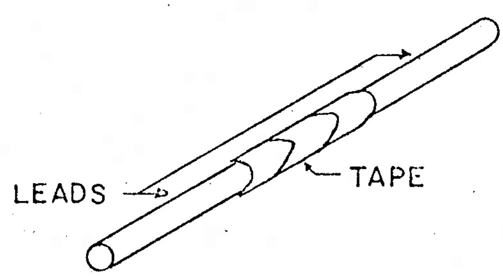


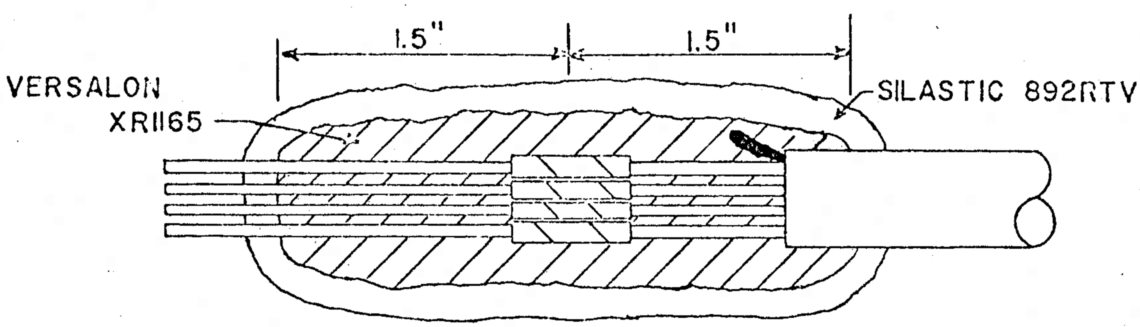
FIGURE 6. "STRESSMETER"



STEP 1: SOLDER CONNECTIONS



STEP 2: WRAP WITH ELECTRIC TAPE



Step 3: Coat entire connection with Versalon XR 1165 (Polyamide Resin) Termo-setting Plastic (General Mills,2627 Kipling St., Houston, Texas) and Silastic 892RTV adhesive/sealant (Dow-Corning Co.)

Figure 7. Moisture Proofing Lead Wires

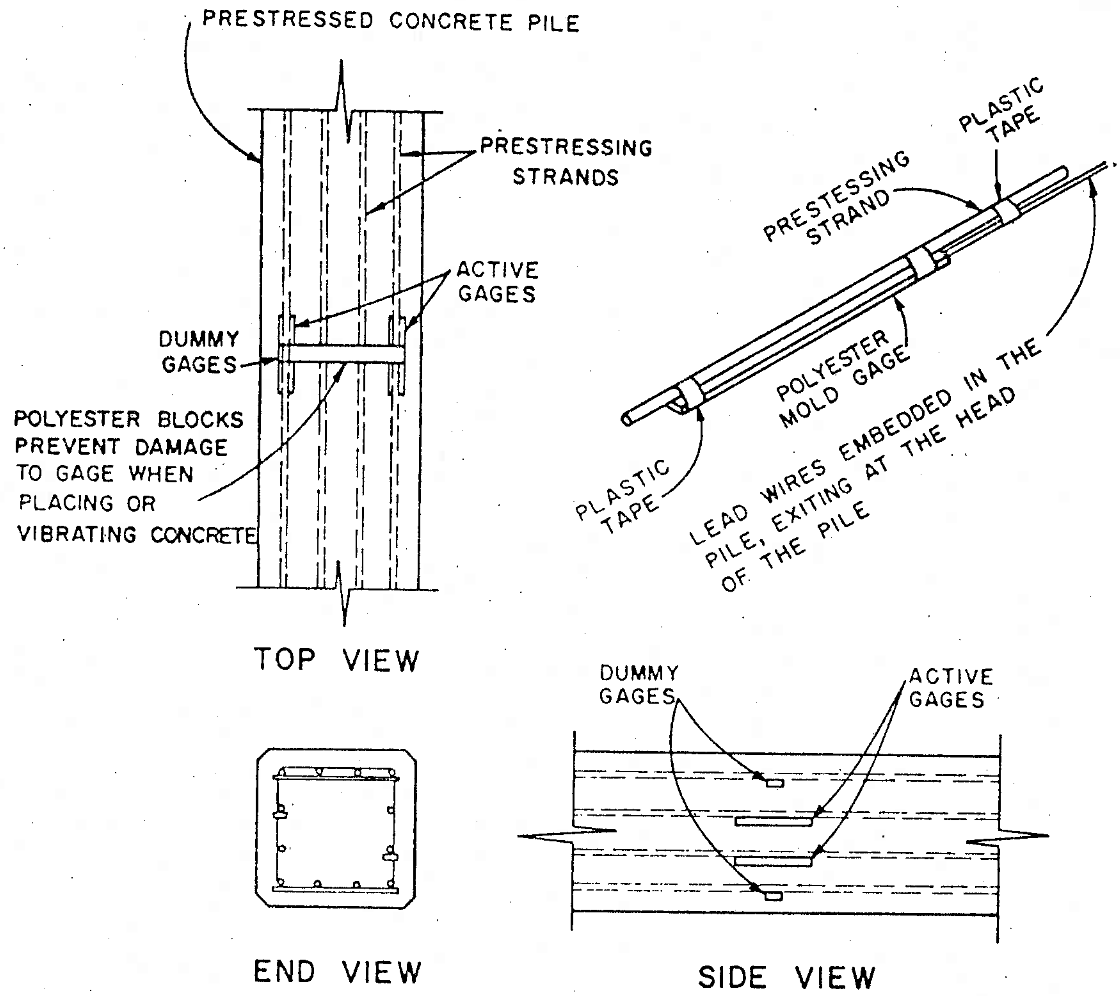


Figure 8. Typical Gauge Installation

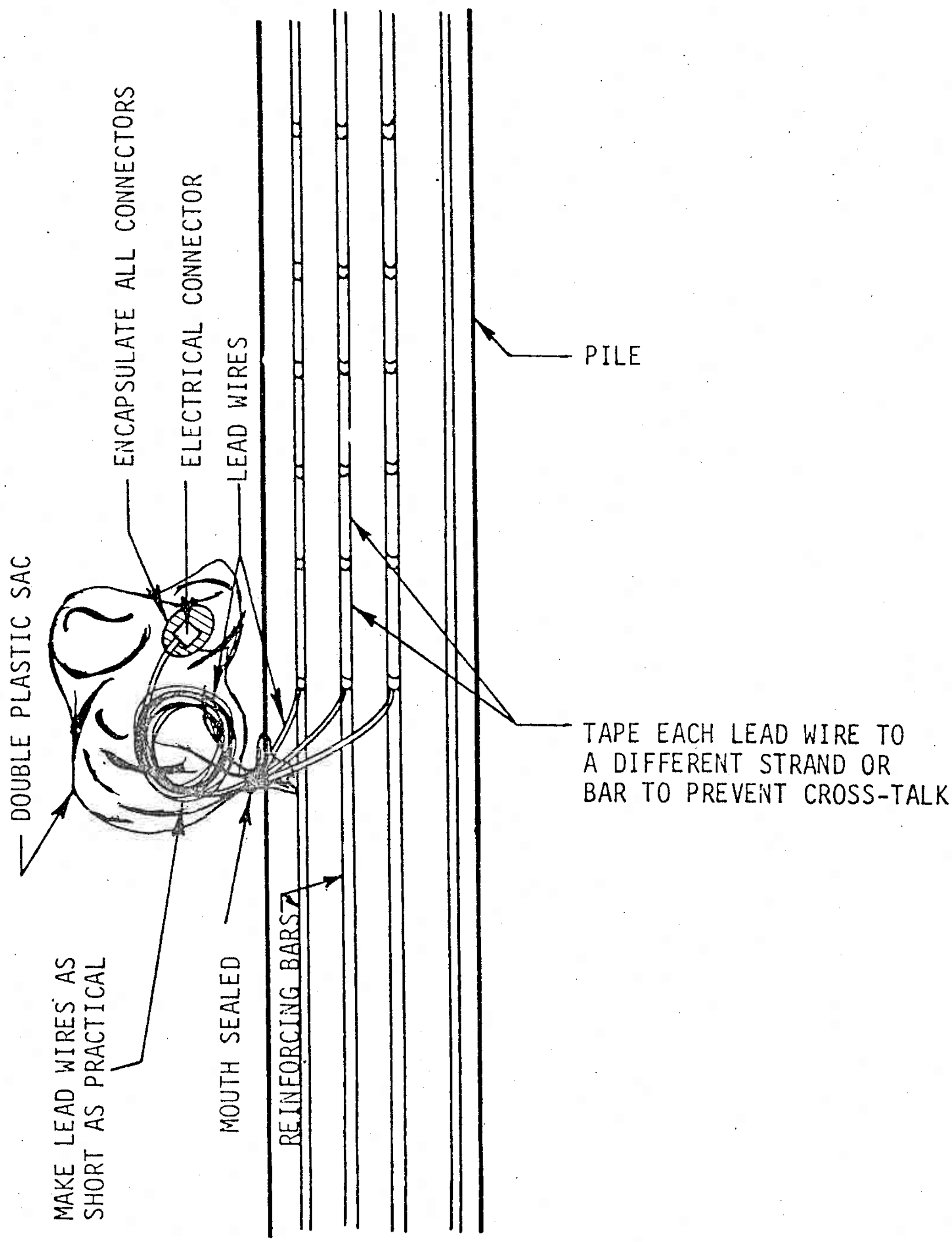


Figure 9. Wiring Placement and Protection for Concrete Piles

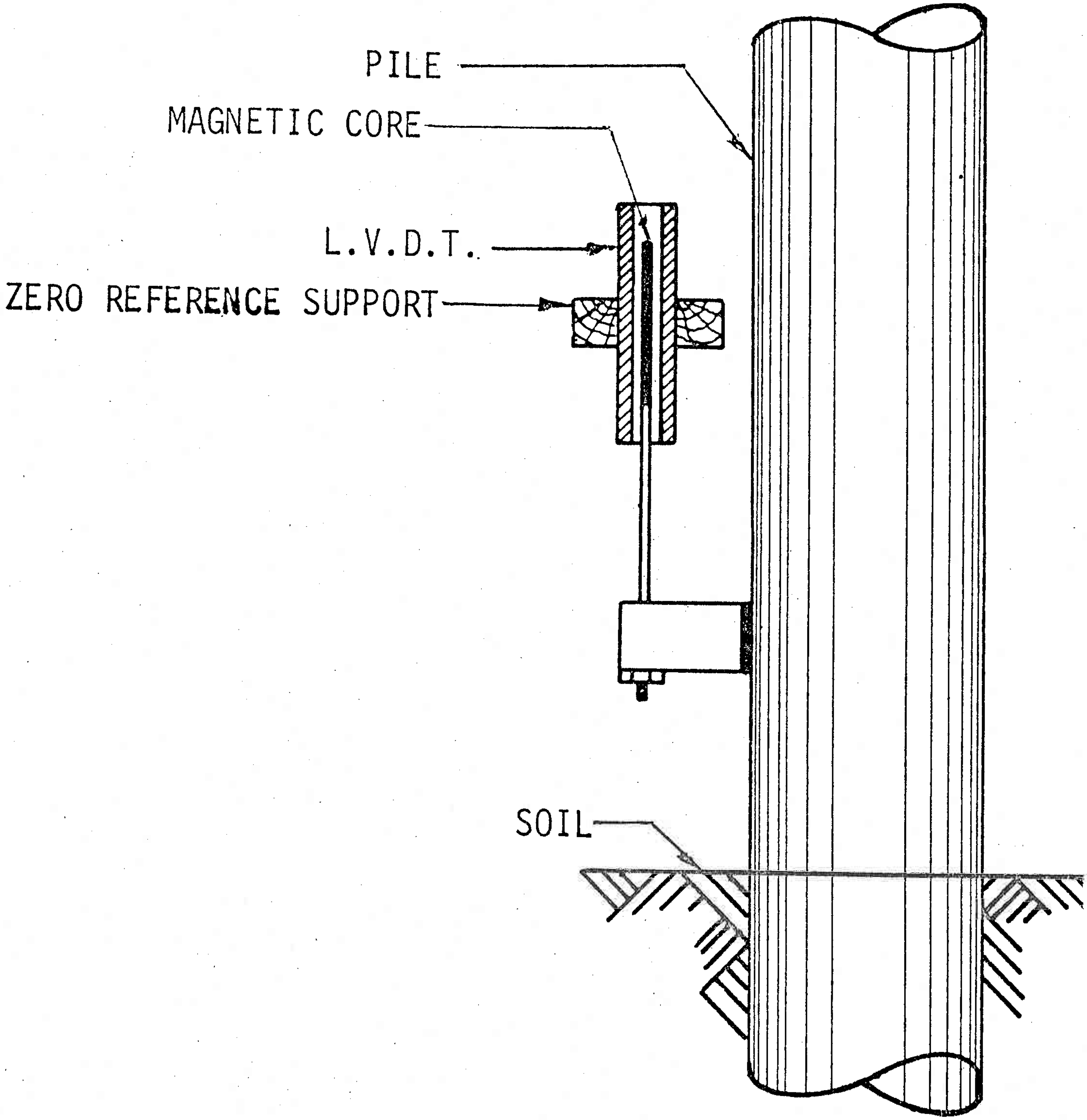


Figure 10. Linear Variable Displacement Transducer

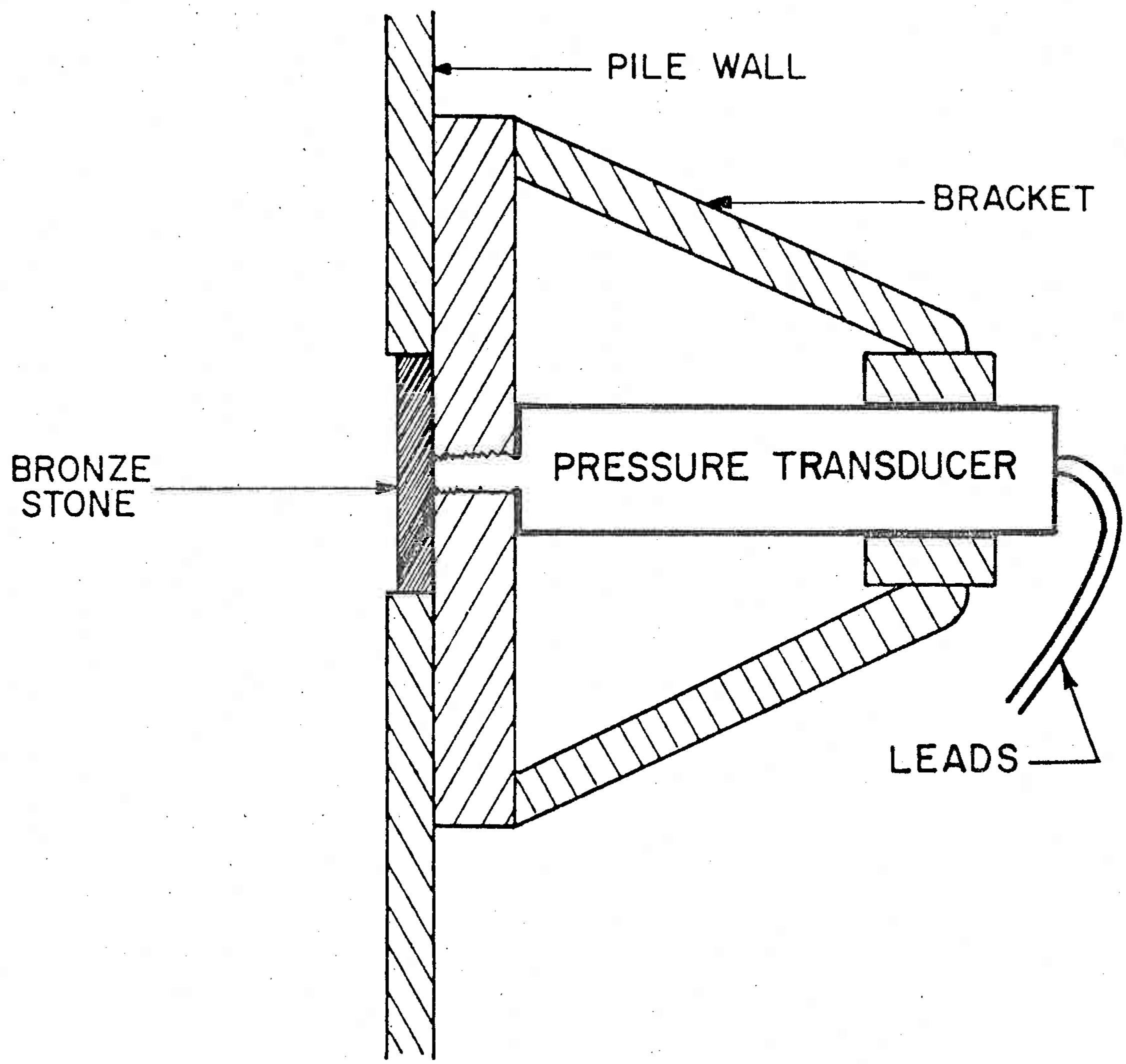


Figure 11. Pressure Transducer Installation

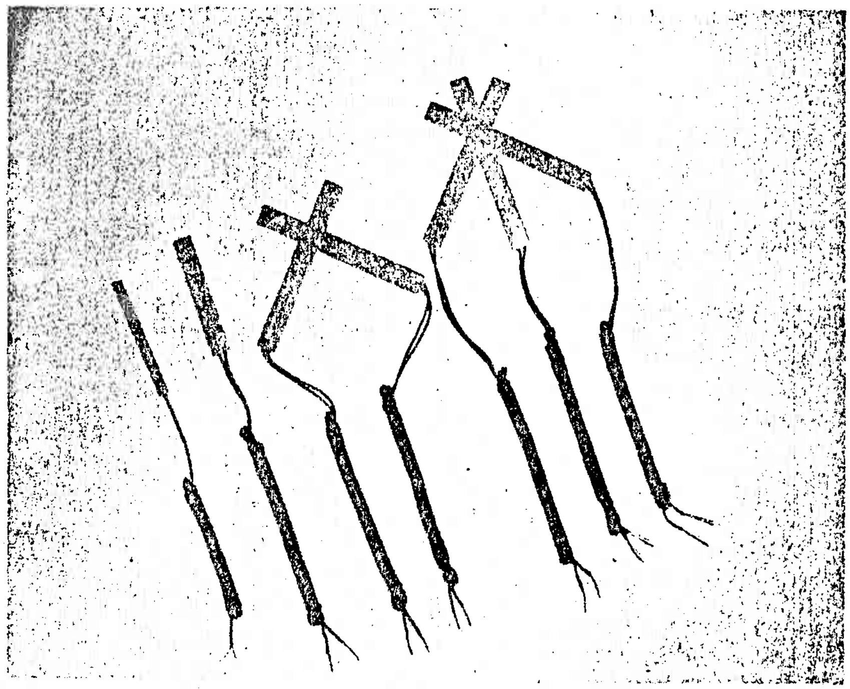


Illustration 1. Polyester Mold Gauges

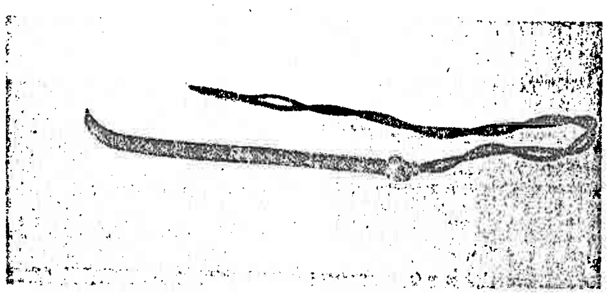


Illustration 2. Brass Foil Envelope Gauge

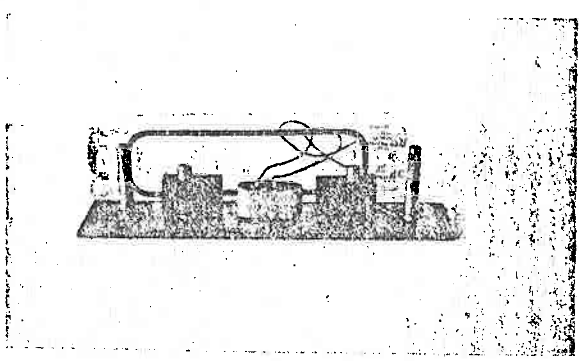


Illustration 3. Vibrating Wire Strain Gauge

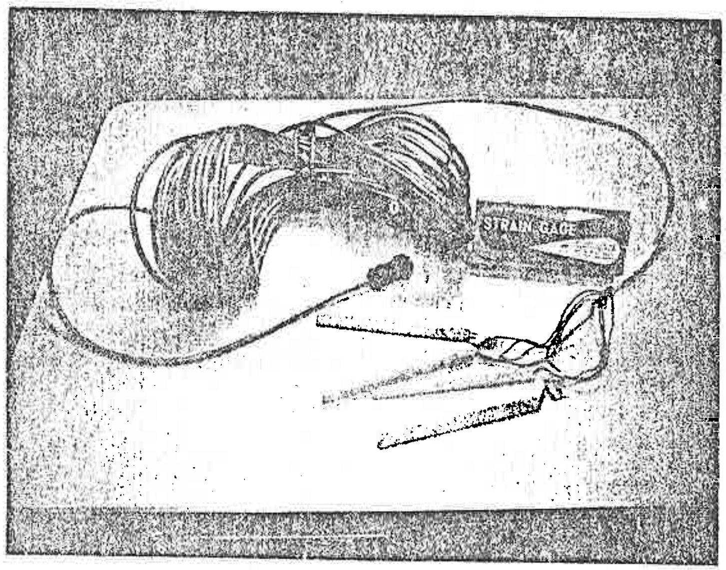


Illustration 4. Prefabricated Gauge Point
Ready for Installation in Pile

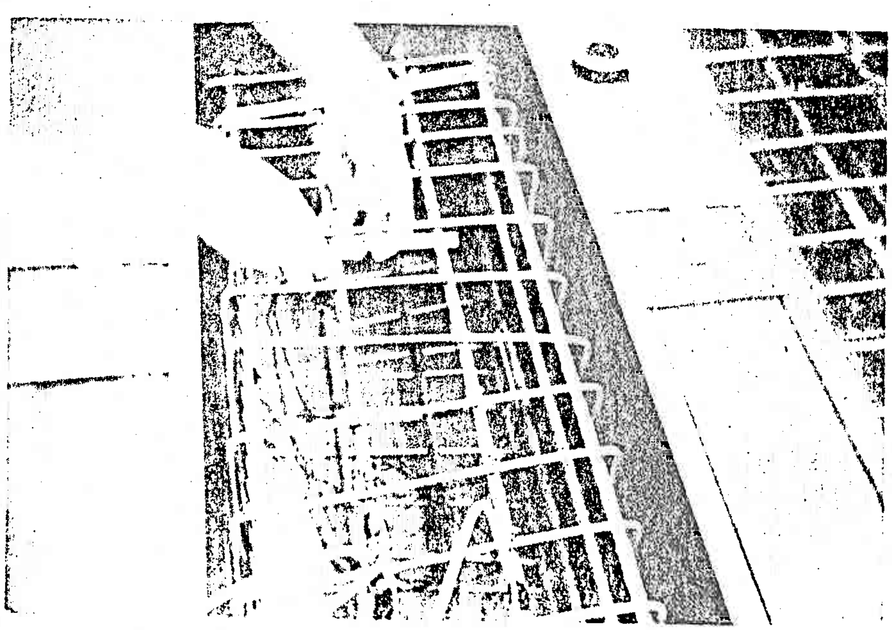


Illustration 5. Installation of Embedded Gauges

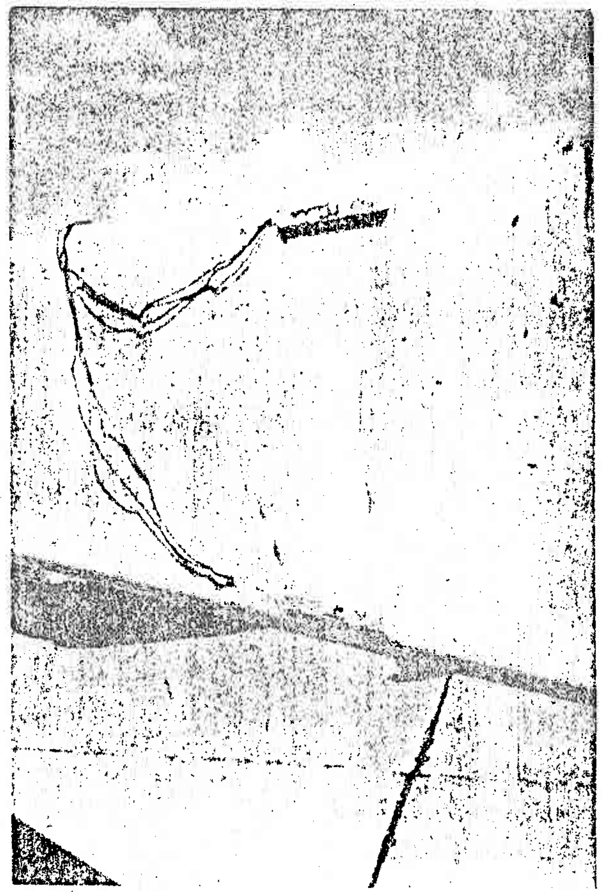


Illustration 6.   Mold Gauges Mounted on Surface of Pile

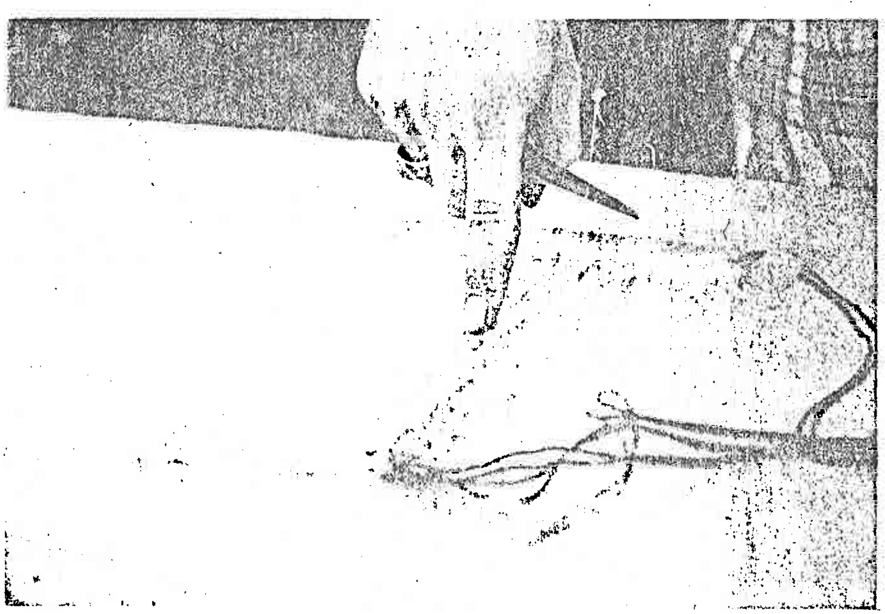


Illustration 7.   Full 4-Arm Bridge Mounted on Surface of Pile