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STATIC MEASUREMENTS OF PILE BEHAVIOR
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During the past decade engineers and contractors have increasingly recognized the need for research in the area of pile foundations. This is evidenced by the quantity of papers on the subject appearing in the literature. Theories regarding pile behavior are becoming more refined as are analyses of measurements made on pile foundations. In many instances precision in the analysis of measurements greatly exceeds the precision with which the measurements were made. It is obvious that many researchers are not aware of the errors inherent in the methods of measurement that have been commonly used or do not recognize certain features of pile measurements as being sources of error. A review of the mistakes that have been made in measurements of pile behavior will serve as background for stating the requirements for proper instrumentation.

TYPICAL PILE LOAD TEST

The pile load test in which measurements of the load-settlement relationship at the top of the pile are made is probably the most common test made on pile foundations. Tests of this type were originally conceived and utilized to verify that a pile's ultimate capacity was at least twice the design load. Errors of 5% to 10% in the measurement of both load and settlement were seldom of consequence. Errors of such magnitude can occur as will be described below. Unfortunately, tests of this type are being analyzed with very refined theories involving load-settlement relationships without due regard for the errors involved.

Load Measurement—For the type of loading arrangement wherein a load is balanced on a pile, the magnitude of load depends on both the volume and density of the material utilized to make up the load. It is probable that loads of this type are known within an error of 5% and certainly within 10%. If the load is balanced on the test pile a truly constant load is attained even if the absolute magnitude of the load is not known. Where a hydraulic ram is used to apply load to a pile, neither the magnitude of the load nor its constancy is likely to be known within an error of 5% and perhaps 10%. This can be true even though the ram and the gage have been calibrated.

In Figure 1 a hydraulic ram is shown schematically applying a load caused by internal hydraulic pressure measured by a bourdon gage. It is possible to calibrate a bourdon gage with a considerable degree of accuracy. The theory usually applied is that the load at the top of the ram is equal to the pressure measured by a bourdon gage. Some engineers accept this theory and require only that the gage be calibrated. Other engineers require that the ram and the gage be calibrated as a unit. The advantage of calibrating as a unit is supposed to be that the effect of ram friction occurring along the sides of the ram (primarily at the location of the seal) can be taken into account. Calibrations of the latter type can be an exercise in futility, as will be described below.

In a laboratory calibration of a hydraulic ram the conditions are nearly ideal. For example, the base of the ram is usually level in a testing machine and the ram is aligned vertically. Further, a spherical bearing is usually seated against the top of the ram and serves to decrease any eccentricities that may have arisen. It is possible to obtain two different calibrations for the ram depending on whether the ram is used to load the testing machine, or if the testing machine is used to load the ram. In the first case the pump is actuated to bring the ram up against the head of the testing machine, thus causing the testing machine to record load. In this case the ram friction decreases the actual ram load below the theoretical output of the ram (area x pressure). In the second case the load on top of the ram is somewhat greater than the theoretical load because of reversal of ram friction when it is forced downward. The difference between the two calibrations is equal to twice the ram friction. In many instances calibrations that are actually used in the field were obtained by loading the ram with the testing machine, whereas the ram is actuated to load the pile in an actual test; thus, the wrong calibration is utilized.

A further source of error that is not generally recognized is that in the field the ram is seldom aligned perfectly with the pile. Also, the head of the ram seldom makes perfect contact with the reaction beam. As a consequence, eccentric loading almost always occurs. The eccentric loading in turn causes a misalignment of the ram in the ram housing, thus increasing the potential for ram friction in a manner that is neither known nor calibrated in the laboratory. Therefore it is possible not only to use the wrong calibration from the laboratory, but also to introduce an error that does not occur in the laboratory, namely, tilting of the ram in the ram housing.

It is possible to alleviate ram misalignment in the field very easily. A spherical bearing similar to the one used in most testing machines can simply be placed between the ram and the reaction beam. Some hydraulic rams already have such a spherical seat built into them. The use of a spherical seat is to be encouraged and in the writer's opinion should be required by specification.

Another problem with hydraulic rams is that of maintaining a constant load. It is possible for the hydraulic pressure either to be raised or lowered without producing the corresponding theoretical

Reference:
effect on the actual load output of the ram. Thus it is not known whether or not a static load is being maintained on the pile. A practical way of circumventing this problem is to insert a load cell between the spherical bearing and the reaction beam. The load cell may be a steel bar instrumented with SR4 strain gages or it might simply be a proving ring. The writer has found the SR4 strain gage load cell to be most convenient for this purpose. Further, load cells have made it possible to determine the magnitude of error in load measurement by the hydraulic method. The errors are generally less than 5%, but instances of errors as high as 10% to 20% have been observed.

It should be clear that if the true load history on a pile is to be known it is necessary to use an independent load measuring system along with a spherical bearing. If the test data are to be used for research purposes there is no excuse for performing the test otherwise considering the widespread availability and low cost of appropriate equipment.

Deflection Measurement—Measurements of the deflections of pile heads are commonly made with unsatisfactory techniques. It is not necessary to introduce new equipment for measurement of pile head deflection, it is only necessary to apply proper technique with the equipment now commonly used. For example, in the case of dial indicators it is obvious that when two dials are used they must be located on a diameter of the pile cross-section and placed at equal radial distances. Then the two dial readings can be averaged to obtain the deflection of the center of the pile cross-section. This requirement is ordinarily met, but the necessary associated details for a successful measuring system are often ignored.

There are two choices for attaching the dial: (1) It can be attached to the pile and a reaction plate placed on the reaction beam, or (2) It can be attached to the reaction beam and a reaction plate attached to the pile. For this discussion it will be assumed that the dials are attached to the reaction beam and that the tips of the dials rest against a reaction plate that is attached to the pile. One of the most common errors in technique is to let the dial stems rest on the cantilever projection of the plate that is commonly placed between the pile and the ram (see Fig. 1). It is possible and probable that inelastic deformations take place at the contact of the plate with the pile; in addition, warping of the plate can occur due to the application of concentrated stresses. Thus possibilities for unknowns are introduced for which there is no excuse. It is a simple matter to attach brackets directly to the sides of the pile that extend beyond the edge of the ram so that dial stem reaction plates can be attached to them.

Another detail of some importance is that the dial indicators be placed truly vertical (assuming that the pile is vertical). Equally important is orientation of the dial stem reaction plates in a truly horizontal plane. For this purpose the writer uses stainless steel discs with a ground surface. With the stem truly vertical and the reaction plate truly horizontal it is possible for a slight translation of either the pile or the dial reaction beam to occur without causing a change in the dial reading. It is fairly common in pile load tests for the pile head to translate horizontally by varying amounts. In a very poor test setup the translation may amount to an inch or more. In a good load test setup the translation may be no more than 1/8 of an inch. Translation occurs usually because of misalignment of: (1) the reaction beam, (2) the hydraulic ram, and (3) either the pile or the dial reaction beam. Then the test pile may not be truly vertical as driven. Horizontal movements are most prevalent where the test equipment does not include a spherical bearing.

With the techniques described above it is seen that two dial indicators can be utilized to obtain the settlement of a pile head. Commonly, three or even four dial indicators are used. In any event, it is merely necessary that the dials be equally spaced around the pile and be at equal radial distances so that the dial readings can be averaged to obtain the settlement of the center of the pile cross-section.

Commonly dial indicators with a sensitivity of 0.001 in. per division are used. Occasionally engineers have specified dials with a sensitivity of 0.0001 in. per division. The latter is simply too sensitive to be of any value in a pile testing program; their use usually causes more confusion that enlightenment. Quite often a load test will involve gross deflections exceeding 1 in., and on long heavily loaded piles the deflection may even exceed 2 in. Therefore, dial indicators with a minimum travel of 2 in. are recommended.

Another matter of technique involving dial indicators is the manner in which the dial reaction beam is itself supported. Support is usually obtained by driving two stakes in the ground at some specified distance from both the test pile and the reaction piles. Then a reaction beam is fastened to the two stakes by a variety of methods. Two problems are then introduced: (1) the possibility of vertical movement of the stakes due to proximity to the test pile and the reaction piles that are being loaded, and (2) motions in the dial reaction frame because of temperature changes.

Ordinarily the dial indicator reaction frame stakes are located at least five pile butt diameters away from both the test pile and the reaction piles. A spacing of 10 diameters away from both reaction piles and test piles is preferred. Such distances are usually obtainable in a practical manner. However, recent theoretical contributions to the stresses and displacements in the pile-soil system due to the loading of a pile lead to the conclusion that reaction stakes should be at least 30 feet away from the test pile. This would be a very stringent requirement if in actual practice the behavior is actually observed in practice. To date none of the authors of such theoretical papers have presented any actual evidence to support their theoretical conclusions. Further, the writer has used surveying techniques to obtain the settlement of reaction stakes in actual pile load tests in hopes of finding evidence that would support such
After pile butt load and settlement the next most commonly used method of measuring pile head settlement involves surveying techniques. The level instrument should be referenced to a bench mark located at least 10 pile butt diameters away from both the test pile and the reaction piles, and preferably at a greater distance. Two observations of pile head settlement should be made on brackets or arms attached directly to the pile, not to the plate between the pile and the hydraulic ram. The brackets should be on a diameter of the pile cross-section and spaced at equal radial distances, just as for the dial indicators and the wire-scale-mirror systems. The two readings so obtained should be averaged to obtain the settlement of the center of the pile cross-section. Proper surveying techniques yield approximately the same resolution as the wire-scale-mirror system.

The foregoing discussion is also applicable to tension tests on piles. A third commonly used method of measuring pile head settlement involves the load transfer test data. After pile butt load and settlement the next theoretical work; the attempts have been futile. Nevertheless it should remain an open question as to whether the theoretical predictions are realized. The writer recommends that a survey instrument be used to check for settlement of reaction stakes in future load tests so that data can be accumulated on this subject. The bench mark should be at least 50 ft. away from both the test piles and the reaction piles.

A dial reaction frame consisting of two steel stakes driven into the ground to which the reaction beam is welded is essentially a rigid frame structure. The writer has personally observed dial changes due to both ambient temperature changes and to differential temperature changes in such reaction frame setups. Differential temperature changes come about because of sunlight or other heat sources acting on one part of the reaction frame and not on the remainder. This can be corrected by completely shading the reaction frame setup; however, the dial indicators will still be sensitive to changes in ambient temperature. Special details have been introduced to reduce temperature change problems, such as roller supports for the ends of the reaction beams instead of welding them to the reaction stakes. Normally, however, dial indicators are most useful for determining deflection-time relationships when a new load increment is added to a pile, but only for a period of perhaps 30 to 60 minutes. Pile head deflections on the order of several thousandths of an inch, either up or down, measured on a long-term basis are likely to be totally fictitious. Accurate measurement of long-term settlement behavior with the use of dial indicators requires temperature stability and/or special details.

The details of tensioning the wire in a wire-scale-mirror system are important. Commonly, a weight is attached to the wire which in turn passes over a pulley. The stability of this technique is open to serious question. The writer has plucked the wire in such systems (as one would pluck a guitar string) to test for return of the wire to its original position, usually without success. A more satisfactory system involves a turnbuckle along with tying the ends of the wire to the reaction stakes. The wire in such a system will return to its original position if disturbed.

The readings from a pair of wire-scale-mirror systems can be averaged to obtain a deflection of the center of the pile cross-section, as recommended for dial indicators. Where both dials and wire-scale-mirror systems are used, they should give the same results. Although the wire-scale-mirror system has a lower resolution than the dial indicators it is still sufficiently precise for many research purposes. Further, a very significant advantage of the wire-scale-mirror system is freedom from temperature effects making it quite useful for long-term measurements. The writer has personally observed instances where both dial indicators and wire-scale-mirror systems were used on a pile that was held under a truly constant load as measured by a load cell. By observing only the dial indicators one got the impression that the pile was moving into the ground as the temperature decreased and that it rose out of the ground when the temperature increased, even though the load was constant. However, the indicated movement of the pile head was zero based on data from the wire-scale-mirror system.

Another commonly used and highly successful method of measuring pile head settlement is the wire-scale-mirror system. The system consists simply of a scale attached to a mirror which in turn is attached to the side of a pile. A piano wire is then strung horizontally across the scale and mirror, but just clear of it. By sighting across the wire and into the mirror until the extra image of the wire is eliminated (elimination of parallax) a direct reading can be obtained on the scale. Commonly used scale is 6 inches long and divided in 50ths of an inch; resolution of 100th of an inch is easily obtained. Many of the detail requirements for the successful use of this system are the same as those cited for dial indicators. It is necessary that at least two such systems be used and located on a diameter of the pile cross-section and at equal radial distances. The writer ordinarily uses two dial indicators and two wire-scale-mirror systems at right angles to each other. The wire-scale-mirror systems should be attached to the pile either directly or on brackets welded to the pile; they should not be attached to the plate between the pile and the hydraulic ram. Further, the mirrors should be vertical and the wires nearly horizontal. Location of the reaction stakes for the wires should be at least 10 diameters away from both test pile and the reaction piles; even greater distances are practically obtainable with this system.

LOAD TRANSFER TEST DATA

After pile butt load and settlement the next most common measurements are those of settlement or strain at various positions along the embedded portions of piles. Such measurements are most commonly made with the use of tell-tales or, as they are sometimes called, strain rods. These consist simply of a rod attached to some point on the embedded portion of the pile, but otherwise...
free to move in a casing such that a measurement at the pile head relative to a fixed reference, or relative to the pile head itself, provides a measurement of the movement of that point on the pile. Another commonly used tool is the electric resistance strain gage in a variety of forms.

Load transfer information is obtained from strain rods by using the difference in settlement between two gage points to determine an average strain in the pile cross-section. This strain is then used along with the properties of the section, either assumed or measured, to obtain load in the pile. The electric resistance strain gages in their various forms actually determine strain at the gage location. This in turn is used with the known or measured properties of the pile section to determine load at the gage location. With both types of measuring systems it is necessary that the properties of the pile cross-section be known on the basis of test, or by assumption of Young's modulus. Actual load calibration of an instrumented pile is preferable.

In long term pile tests involving timber on concrete, the strains that are measured are likely to be a function of changes in the pile material itself as well as movement of the pile relative to the soil. Thus, long term measurements made on piles consisting of timber and concrete represent composite behavior of pile and soil rather than a measurement of the pile relative to the soil. By contrast, steel pile cross-sections are stable with respect to creep and changes in modulus, and can provide long term information on changes in soil support conditions. Note, however, that long term measurements also depend on stability of the instrumentation system itself. Such stability is reasonably assured with the use of strain rods, but may not occur with the use of electrical systems. An advantage of measurements on the embedded portion of the pile is that temperature stability is attained. However, water leakage problems can be rather severe. Great care must be exercised in the details of an electrical instrumentation system to obtain successful long term measurements.

Much of the load transfer test data that is available in the literature is in error because of an oversight in interpretation of the test data. The oversight is that zero readings are taken after the pile is in the ground on the assumption that the pile contains no residual loads. Reports of measurements usually deal only with the load changes that occur once the pile is in place. The significance of the error has been pointed out by Hunter and Davisson with respect to instrumented test piles from the Arkansas River Project. In one instance approximately 50 tons of residual load remained at the pile tip after driving. It was not possible to correlate load transfer data from compression and tension test results without accounting for the residual load in the pile. In this instance the piles were driven entirely in sand. In other soil profiles involving weak soil materials, the skin friction acting on the pile during driving is so low that relatively insignificant residual loads are produced. An example of such a case is the test data presented by Prof. Blessey at this conference. He did not encounter any difficulty in analyzing his data on the basis of the assumption that zero residual loads were in the pile after driving.

With the use of tell-tales or strain rods it is not possible to determine residual loads in the piles because there is no choice but to establish zero readings after the pile is in the ground. However, electric resistance strain gage techniques make possible obtaining a complete load history on the pile starting from the time of gage application on the pile. If a complete history is maintained on each gage location from the time it is instrumented, through the time it is set up in the leads ready for driving, after it is driven, and during load testing, it should be possible to have complete compatibility of loads and deformations. To date this has been performed in only a minority of the load transfer investigations. Progress in research based on pile foundation measurements can be made only if complete strain histories are obtained on all gage locations, and truly stable instrumentation systems and pile cross-sections are used for long-term investigations.

LATERAL LOAD TESTS

Most of the comments made above with respect to load and deflection measurements in standard load tests apply also to lateral load tests. In particular, the spherical bearing is virtually a necessity because a lateral load test inherently involves rotation of the head of the pile. The spherical bearing will allow rotation to proceed without development of distortions in the test setup.

Rotation of the pile head is usually an item of interest, and may be measured by taking deflection measurements normal to the pile axis at two locations; the difference between the readings is a measure of the change in slope. Measurements may also be made with a sensitive level bubble, and by use of a slope measuring device operated along the pile axis. Rather unsatisfactory correlations between theory and experiment have occurred with respect to rotation of pile heads; this is probably caused by unsatisfactory measuring techniques. The use of dial indicators is subject to question because of the nature of the deformations involved in the vicinity of the tips of the dial indicators. The writer believes that a sensitive level bubble or other slope measuring device is preferable. One other possible source of error in slope measurement is local distortions at the pile head caused by the application of a concentrated load at the pile head. The load transfer detail should be designed to minimize this distortion. The use of a spherical bearing will tend to diminish distortions of this type.

Measurements along the axis of the pile usually consist of slope or strain. A slope measuring device will give slope versus embedded length of the pile; this can be integrated to obtain deflection, and differentiated and coupled with the properties of the pile cross-section to obtain bending moment versus depth. Most of the slope measuring devices available at this time give very good results on
Strain readings at various points along the embedded portion of the pile can be coupled with the properties of the pile cross-section to determine bending moment. It is highly desirable that instrumentation of this type be calibrated in a bending test before the pile is placed in the ground. Further, the same comments given for the standard load test apply also for the lateral load test, namely, that a complete stress history should be kept on all gage stations from the time the pile is gaged until the test is completed.

For a routine lateral load test a measurement of load and deflection at the ground surface is usually adequate. Measurements of slope at the ground surface can be added to such a test with a minimum of additional effort. Where somewhat more information is desired a slope measuring device may be used along the axis of the pile to provide more detailed information with respect to depth. For research purposes the resolution obtainable from strain gage devices is highly desirable.

**DYNAMIC TESTS**

Although this paper is concerned with static measurements of pile behavior, there are instances where both static and dynamic studies are performed and for which the same instrumentation is used. For example, an SR4 load cell used to measure static load in the head of a pile can also be used for dynamic measurements although there will be an effect on the measurements due to the mass of the load cell itself. The dial indicators used for static measurements are clearly unsatisfactory for dynamic measurements. The dial indicator can be replaced with an LVDT (linear variable differential transformer). For measurements along the length of a pile go-tales or strain rods are not satisfactory for dynamic tests, but most of the electric resistance strain gages are satisfactory. To the writer's knowledge there is no satisfactory method of measuring dynamic rotation of the pile.

A method of eliminating the effect of mass of the load cell is to instrument the head of the pile itself and eliminate the load cell. The pile is then calibrated by use of a load cell either before or after the dynamic tests. An example of this procedure is given in Ref. 1.

Data recording for static tests is normally accomplished with paper and pencil. However, when equipment with dynamic test capabilities is utilized the data usually can be taken by means of an oscilloscope, an oscillograph, or a magnetic tape recorder. The writer makes use of all three techniques whenever a test is performed involving dynamic data. The oscillograph is used to observe a particular event without limitations on frequency response. Further, the oscilloscope is a general purpose tool useful for monitoring the behavior of all parts of the recording system. Oscillographs utilizing light sensitive paper are somewhat limited in frequency response, but are usually capable of giving resolution to the types of data obtained in dynamic pile tests. The almost instant availability of the test record makes it possible to know that the desired test data is in fact being obtained. The best method of recording dynamic test data, however, is by use of an FM magnetic tape recorder because it has both static and dynamic capabilities to frequency responses much higher than those necessary for the type of data usually encountered in dynamic pile tests.

A significant advantage of the tape recorder is that the data can be replayed innumerable times, and by adjustment of tape speed the time base of the data can be extended so that a record such as acceleration versus time can be studied in minute detail. Another advantage of the tape recorder is that the data is available innumerable times in analog form. The data can be processed in analog form (for example integration of an acceleration record) and then slowed down so that it may be printed out with an ink writing recorder, or the data may be digitized for output by any of the digital means that are available. One channel of the tape recorder can also be used for voice recording of events that are important to the data. Another significant advantage is that sufficient frequency response is available at tape speeds low enough that all data for a dynamic test can be recorded. This is superior to the common practice of taking samples on an oscillograph, or an even smaller number of samples with an oscilloscope equipped with a camera.

**SUMMARY**

Recent interest in the design and construction of pile foundations has led to a great number of measurements on the behavior of piles. Many of the reported test programs have been performed with satisfactory instrumentation equipment coupled with unfortunately poor techniques and unrealistic analyses. The errors involved in pile load testing have been examined herein and criteria for obtaining accurate data have been delineated. Important additions to the equipment normally used to perform standard pile load tests are a load cell for independent measurement of load, and a spherical bearing for reduction of eccentricities caused by the normal out-of-tolerance conditions found in field work.

In the analysis of load transfer data along a pile it is necessary to know whether or not residual loads existed in the pile after it was driven. Further, it must be recognized that short term loading and long term loading can involve different physical phenomena. Steel piles with stable instrumentation systems can be used for long time tests, whereas concrete and timber piles will usually creep under load and such strains become an inherent part of the test data even though the test was originally conceived to determine the behavior of the soil, not the pile material itself.

**REFERENCES**


Fig. 1 Hydraulic ram on test pile