Instrumentation for Tests of Piles Subjected to Axial Loading

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Load tests of piles under axial loading are performed for two purposes: to prove a particular design and to gain information to allow a redesign. Instrumentation needed for evaluation of proof loading can be placed above ground. To obtain information for redesign, data must be obtained on the manner in which load is transferred in both end bearing and skin friction; therefore, instrumentation must be placed along the length of the pile. The importance of providing the appropriate instrumentation for proof testing is obvious, and failure to do so can lead to serious consequences. However, the far more challenging problem and the potentially more significant one is to select the proper instrumentation for determining the load transfer in skin friction and end bearing as discussed herein. Significant contributions are being made in the development of innovative techniques for these measurements. Recent advances in modeling show the value of determining the unit load transfer, f_z, as a function of axial pile movement, w_z, at points along a pile and unit end bearing, q_B, as a function of tip movement, w_B. The design of piles under axial loading in the near future will be based on predicted f_z–w_z and q_B–w_B curves. Investigation of the integrity and deformation behavior of axially loaded piles by use of dynamic tests (stress wave measurements) is gaining credence. Instrumentation for such testing can be rather complex, but essentially all instrumentation is composed of off-the-shelf items that are readily available. Generally, testing is performed at very small strains. However, the restriking of driven piles, or the use of special equipment to impact cast-in-place piles, is becoming more common, although instrumentation, such as the pile-driving analyzer, for such applications is more custom-made.

Two types of tests are run to obtain the behavior of piles subjected to axial loading: a proof test to learn if the design that was preselected is satisfactory and a test to obtain information for redesign. The instrumentation for the first of these tests is specified by the standards of the American Society for Testing and Materials (*1*) and is not discussed further. The instrumentation for the second type of test is nonstandard, is of considerable importance, and is discussed briefly in this paper. In addition, instrumentation and interpretation of stress wave tests (dynamic testing) to evaluate pile integrity and deformation behavior are presented.

An analytical model for the pile-soil system must be selected before instrumentation for load testing is selected. Therefore, a brief description of several analytical models is first presented. The variety of instrumentation that is available for load testing is then discussed. Finally, a discussion of the interpretation methods of the test results and the benefits of performing instrumented tests is presented.

The discussion on static load testing is followed by a discussion of instrumentation for integrity testing. As with static load testing of piles, the selection of instrumentation for integrity testing depends on the analytical model used to analyze the results. Methods based on stress wave propagation are most often employed in integrity testing. Therefore, these methods are discussed, and the associated instrumentation and analyses are presented.

MODELS FOR AN AXIALLY LOADED PILE

The pile and the supporting soil can be modeled as a continuum by use of the finite element method, or the models that are shown in the following paragraphs may be used. Selection of a model before selecting instrumentation and performing field tests is essential. The engineer should make use of information on soil properties, pile geometry, construction procedures, instrumentation, and loading arrangement to perform preliminary analyses of the expected results of the load-test program. The accuracy, sensitivity, and ruggedness of the instrumentation can be judged and modifications made if necessary. Selection of appropriate models for both dynamic and static loading and the use of the models in preliminary analyses are essential before making a final decision on instrumentation.

The well-known model of a pile under dynamic loading (pile driving) by Smith (*2*) is shown in Figure 1. The pile is modeled by a series of masses separated by linear springs. The soil is modeled by a series of nonlinear springs and dashpots. The energy of a falling weight is used, along with the nature of the appurtenances at the top of the pile, to obtain a time-dependent force. A differential equation is then solved in difference form to obtain the motion of each of the masses and the downward movement of the top of the pile. One aspect of this approach that continues to be improved is the mechanism used to describe nonlinear soil behavior and its relationship to measurable soil parameters.

Full instrumentation of a dynamically loaded pile is complex, and the usual procedure to date is to use a restricted amount of instrumentation near the top of the pile. This instrumentation allows a simplified version of the wave equation to be used to obtain the capacity of a pile, or to determine the integrity of a concrete pile, as discussed later.

If a static load is applied, the masses and dashpots in Figure 1 are of no consequence, and the pile can be modeled as shown in Figure 2 (*3*). The pile is simply replaced by a spring whose stiffness can vary from point to point along the pile. The soil is

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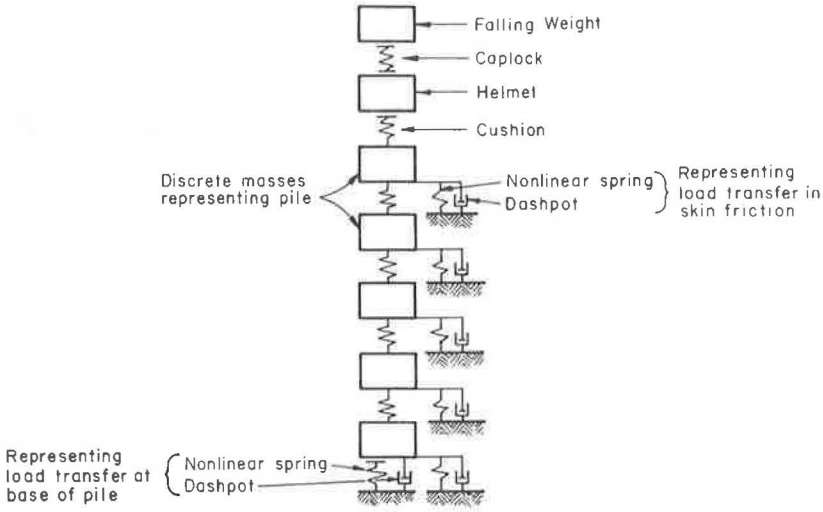


FIGURE 1 Smith model for pile driving (*2*).

replaced by a nonlinear spring and a friction block. The family of curves at the right of the figure depict a typical set of load-transfer curves for the soil.

The potential value of load-transfer curves in Figure 2 is easy to understand. The engineer can assume a downward movement, w_B, of the tip of the pile and use the curve to obtain the unit end-bearing, q_B, and, hence, obtain the load at the tip. A length of the pile above the tip can be selected, the downward movement, w_z, of the increment can be estimated, the unit load transfer in side resistance, f_z, can be obtained by using the appropriate curve, and the load taken in side resistance by the selected increment can be computed. The shortening of the selected increment can then be computed, which allows the downward movement, w_z, of the increment to be found. The procedure can be repeated until convergence is achieved for the selected tip movement. Successive increments of the pile can then be analyzed until the top is reached. The analysis will reveal a top load and a top movement. Other tip movements can be selected, the procedure repeated, and the load-settlement curve for the pile can be obtained analytically.

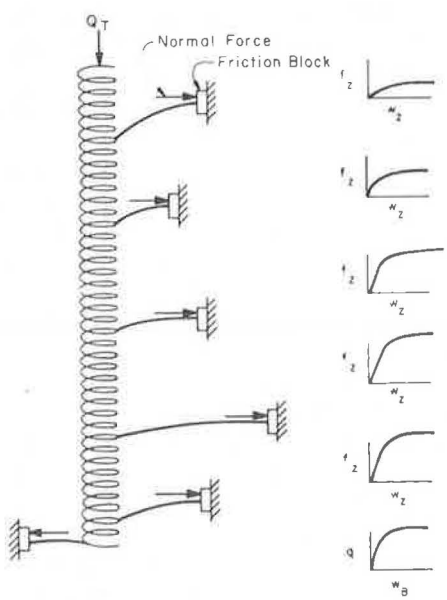


FIGURE 2 Model of pile for static loading (*3*).

Thus, if a sufficient number of tests of instrumented piles can be performed, the development of methods of predicting the load-transfer functions is possible. The ability to predict such functions with reasonable accuracy is an enormous benefit to the geotechnical engineer. Furthermore, the selection of appropriate instrumentation to obtain the load in a pile as a function of length is facilitated even if the load-transfer functions can only be approximately predicted.

Some analysts have criticized the models shown in Figures 1 and 2 because the soil is not shown as a continuum. However, as more information becomes available on load transfer, the curves can be depicted if necessary as multivalued to reflect the continuum effect.

INSTRUMENTATION FOR STATIC LOADING

The requirement of the instrumentation is to produce data showing load versus settlement for the top of the pile and a family of curves showing the distribution of load as a function of depth. It is the latter role of the instruments that is of particular interest in this paper.

The simplest form of instrumentation that will produce the load-distribution curves is the telltale or unstrained rod (*4*). The rods are inserted into tubes that extend to a series of depths along the length of the pile. The pile will shorten under an axial load and the rods will not. The amount of deformation of points along the pile can be determined by dial indicators, and a plot of the deformation as a function of depth can be made. The strain in the pile can be found from the slope of the plot, and the internal load can be found by multiplying the strain by the pile stiffness. Telltales perform well if there is a sufficient number and if the relative stiffness between pile and soil is such that there is an appropriate amount of strain in the pile.

Another method that will yield the deformation from point to point along a pile is shown in Figure 3. A French agency developed an ingenious system to be placed into a metal tube that is built into the pile (*5*). The system consists of a series of air-operated clamps that are connected by metal strips on which

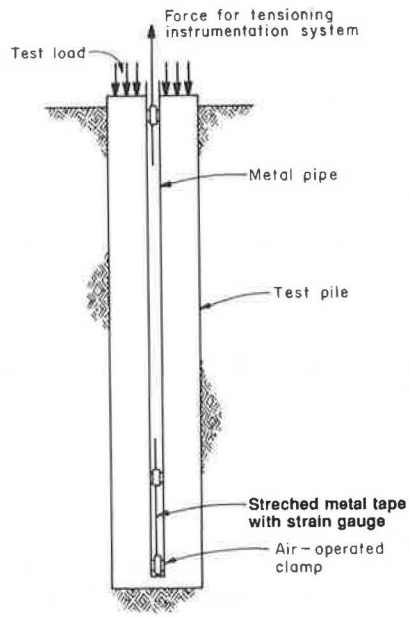


FIGURE 3 French system for instrumenting a pile for obtaining load as a function of depth.

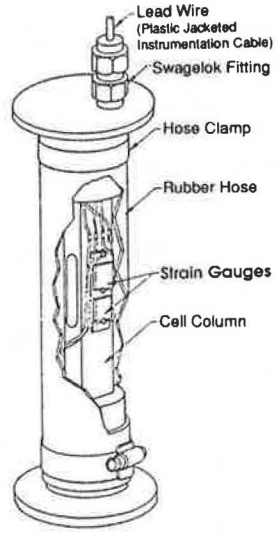


FIGURE 4 The Mustran cell.

electrical resistance strain gauges are fixed. The assembly is lowered to the bottom of the pipe after the pile has been installed, the lower clamp is actuated to fasten the assembly, a tensile force is applied to the top of the assembly to put all of the strain gauges in tension, and then the other clamps are actuated. As load is applied to the top of the pile, the strain in the gauges is reduced and the deformation can be obtained by use of a calibration curve. After the load test is completed, the air-operated clamps are released and the assembly is recovered and available for use another time. Interpretation of the data proceeds as with the use of telltales.

A load cell can be constructed for the bottom of a drilled shaft and installed before the placement of the fluid concrete. The cell consists of two stiff plates that are separated by remote-reading, load-measuring devices so that the load transmitted to the tip of the drilled shaft can be measured directly (*6*). Osterberg (*7*) has described a similar device in which the plates are separated by hydraulic fluid. This system allows fluid to be pumped into the load cell until either the end load or the side resistance is exceeded, whichever is smaller. The separation of the plates can be found from the volume of fluid that is pumped. The measurement of the movement of the bottom of the shaft by use of a telltale and the movement of the top by use of a dial gauge allow the plotting of a load-settlement curve for the tip and a load-uplift curve. Only one of the curves will be fully developed, of course. A similar system was described by Lizzi (*8*). Installation of the bottom-hole load cell should be planned carefully so that construction of the drilled shaft is not seriously delayed.

The basic device for use in obtaining the internal load in a pile is the strain gauge. Two types are in common use: the vibrating-wire and the electrical-resistance. The gauges can be fastened to the interior of a steel pipe, put inside a small channel or angle that is welded to a steel H-pile, fastened to a rebar in a precast or cast-in-place concrete pile, or used to construct a special cell such as shown in Figure 4 (*9*). The Mustran cell is constructed with electrical-resistance strain gauges and can be installed in precast concrete piles or fastened to the rebar cage of a drilled shaft. A serious problem with strain gauges is that they must be kept perfectly dry; only a few molecules of moisture will result in electrical leakage with a loss of accuracy or a complete failure. To combat the moisture problem, dry nitrogen, a desiccant, is forced through the sheath on the electrical cable leading to the Mustran cell and pressurizes the interior of the cell, thereby preventing the intrusion of moisture. Hundreds of Mustran cells have been built for use with load tests.

The strain in a pile can be found with Mustran cells, and the load can be obtained simply by multiplying the strain by the axial stiffness of the pile. The preferred procedure to obtain the value of pile stiffness is to establish a level of Mustran cells at or near the ground surface. If care is taken to ensure that the stiffness of the pile is constant with depth, or nearly so, the top level of instruments can serve as a calibration level. A curve can be developed that shows load in the pile as a function of the Mustran-cell reading. That curve can then be used to obtain the internal load at all other measurement levels that are below the ground surface.

In all of this testing, the modulus of the pile, E, is quite important in evaluating the load-test results. The modulus of steel piles can be considered quite constant and is well-known. Concrete piles and drilled shafts, on the other hand, can exhibit variability in the modulus with load level and from site to site. It is helpful, therefore, to evaluate the modulus of the pile being load tested.

The most direct way of evaluating E for a test pile is to install instrumentation in the unembedded length. This typically requires on the order of 5 to 10 ft of length for telltales or Mustran cells. Another method is to use the speed of compression waves to evaluate the small-strain modulus, E_{max}, of the concrete as discussed in the section on integrity testing. The modulus of concrete is, however, relatively nonlinear at relatively high concrete stresses. Schmertmann (*10*) recommends that the ratio of E_{static} to $E_{dynamic}$ ($E_{dynamic} = E_{max}$) on the order

of 0.84 be used in the absence of better data. He also recommends that this ratio not be used above from 0.33 to 0.5 f_c' (the unconfined compressive strength). If larger stresses are applied during the load test, other means may have to be used to account for possible significant nonlinear behavior in E, not only during the test but also along the length of the pile under a given high load.

RESULTS FROM STATIC LOADING OF AN INSTRUMENTED PILE

A set of load-distribution curves that were obtained by the use of Mustran cells is shown in Figure 5 (*11*). This test was

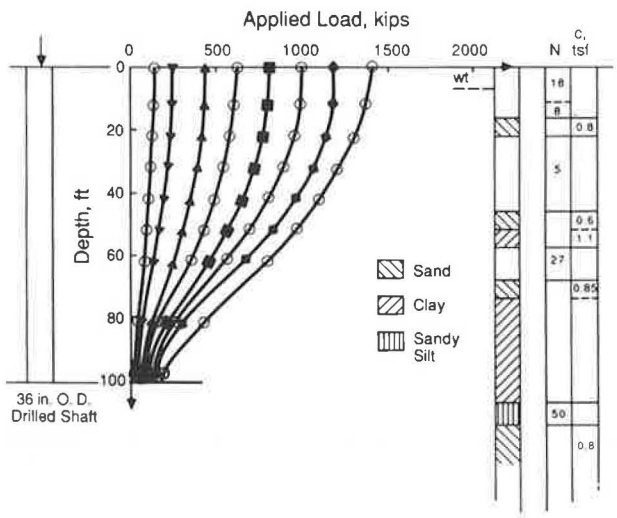


FIGURE 5 Typical set of load-distribution curves for a drilled shaft obtained from use of Mustran cells (*11*).

performed on a drilled shaft that was about 100 ft in length. Curves of this type are useful even before being interpreted to obtain detailed information on load transfer. The curves show that virtually all of the early loads were carried in skin friction, that virtually no load was removed from the pile by the top 10 ft of soil, and that the maximum load transfer in skin friction occurred at about the midheight of the drilled shaft. The last curve shows that the applied load was about 1,800 kips, that about 250 kips were carried by the tip of the drilled shaft, and that about 1,550 kips were carried in skin friction.

A detailed analysis can be made of the curves shown in Figure 5 to obtain information on transfer of load as a function of movement of the pile. The unit load transfer in skin friction, f_z, for one of the given curves in Figure 5 can be found for a particular depth, z, by using the following equation:

$$f_z = \frac{1}{C_z}\frac{dQ_{nz}}{dz} \tag{1}$$

where C_z is the circumference or perimeter of pile at depth z and Q_{nz} is the load in the pile at depth z for nth load. The corresponding downward movement, w_z, of the pile with respect to its initial position can be found by using the following equation:

$$w_z = \delta_n - \int_0^z \frac{Q_n dz}{A_z E_z} \tag{2}$$

where

δ_n = settlement of the top of the pile for the nth load,
A_z = cross-sectional area of pile as a function of z, and
E_z = modulus of elasticity of the pile as a function of z.

The value of the modulus of elasticity, E, may not be linear with the compressive stress, as discussed earlier. If so, the symbol should be written E_{qz} where q denotes the unit stress in compression in the pile.

The unit load transfer in end bearing, q_B, may be computed from the following equation:

$$q_B = \frac{Q_B}{A_B} \tag{3}$$

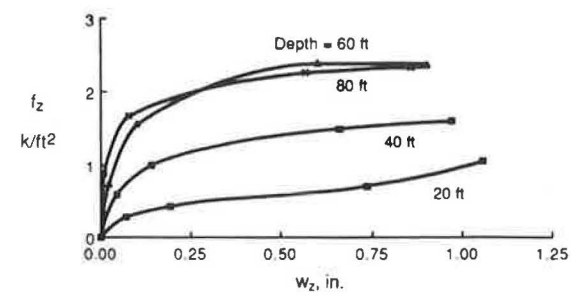
where Q_B is the load at base of the pile and A_B is the area of the base of the pile. The corresponding downward movement w_B of the base of the pile may be found from the following equation:

$$w_B = \delta_n - \int_L^0 \frac{Q_n dz}{A_z E_z} \tag{4}$$

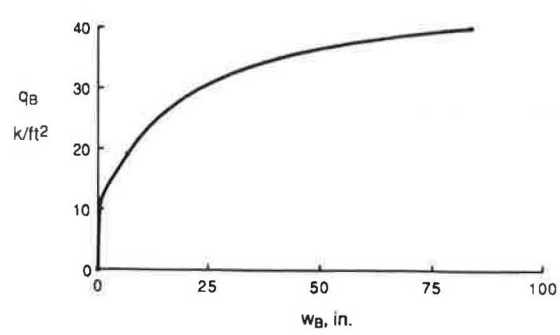
where L is the total length of the pile.

The curves shown in Figure 5 were analyzed by using Equations 1 through 4 and the results are shown in Figure 6. The curves in Figure 6 are valuable to the designer if drilled shafts of other diameters are needed at the test site. Furthermore, a collection of such data will allow correlations to be developed between soil properties and load transfer.

The application of the analytical procedure that is presented is for the results of a test of a drilled shaft (bored pile) in which



(a) Load Transfer in Skin Friction.



(b) Load Transfer in End Bearing

FIGURE 6 Load-transfer curves for test of a drilled shaft.

there were no residual loads and displacements in the pile. The analytical procedure must be modified to deal with the initial conditions in the pile. The determination of the residual loads and displacement for a driven pile requires the use of assumptions about the behavior of the pile during the last blow of the hammer or, preferably, the use of instrumentation for measurement of internal load whose zero reading does not shift as a result of pile driving.

As a further example of the value of instrumenting piles during static tests, the curves in Figures 7 and 8 are presented.

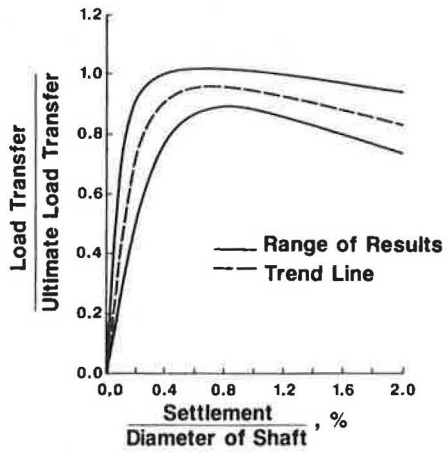


FIGURE 7 Normalized curves showing load transfer in side resistance versus settlement for drilled shafts in clay (*11*).

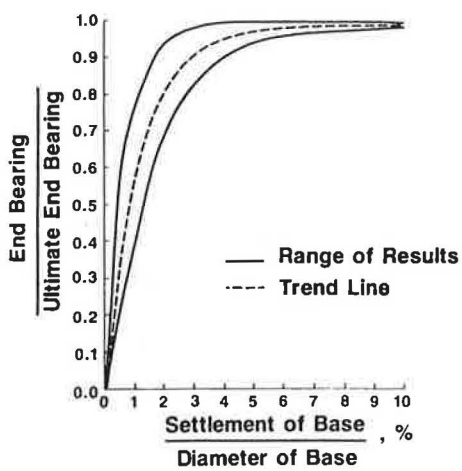


FIGURE 8 Normalized curves showing load transfer in end bearing versus settlement for drilled shafts in clay (*11*).

The curves were obtained by analyzing the results of several tests of instrumented drilled shafts that were installed in clay (*11*). It is of interest to note the difference in the scales of the abscissas for Figures 7 and 8. It is generally known that more relative settlement of the base of a pile is needed to develop a given percentage of load transfer than the relative settlement of the sides. The results from instrumented tests dramatically confirm this important point.

The procedure for using Figures 7 and 8 to get a curve that gives top load versus settlement is essentially the same as described earlier except that the entire drilled shaft is selected as a single element. The resulting curve will not likely be as accurate as if load-transfer curves were available at all points along the drilled shaft. However, the axial stiffness of drilled shafts is usually so great that the shortening of a shaft under axial load is small. The curves in Figures 7 and 8 can allow the engineer to make a reasonably accurate estimate of the settlement of a drilled shaft under a given axial load. This estimate would not have been possible if load tests of instrumented drilled shafts had not been performed.

INTEGRITY AND OTHER DYNAMIC TESTING

Two general types of integrity tests are used on drilled shafts or driven piles that have been installed: routine nondestructive tests that are considered a part of the inspection procedure and special tests in response to a suspected defect. Routine tests are performed on drilled shafts that are uninstrumented or contain some inexpensive transducers that are cast in place; these tests are not costly and thousands of them have been performed in recent years in the United States and abroad.

Special tests that are performed on drilled shafts or piles with a suspected defect, on the other hand, will normally be time-consuming and can be rather expensive. Generally such testing is undertaken only in unusual circumstances and often requires significant preparation of the members to be tested.

Some of the techniques that can be used to perform routine nondestructive tests to investigate pile integrity include the following:

- Vibrate or transiently load the pile externally and record signals with transducers at the pile head,
- Vibrate or transiently load the pile externally and record signals with transducers that are embedded in the concrete, and
- Install access tubes and use down-hole instrumentation to investigate the concrete between the access tubes.

Some of the special techniques that can be used to investigate the integrity of piles include the following:

- Use drilling and coring to investigate for cavities or contaminated concrete and to investigate the condition of the contact at the base of the pile or shaft,
- Use geophysical logging tools or video cameras in drilled or cored holes to examine the condition of the concrete,
- Perform a load test on the questionable pile, and
- Dynamically load the pile by dropping a heavy weight on the top of the pile or by using a pile-driving hammer and then employ wave-equation or impulse-response methods to compute the load capacity or stiffness.

These routine and special methods are discussed briefly in the following sections.

EXTERNAL VIBRATION OF THE PILE

Vibration with Hammer Blow—External Instrumentation Only

A procedure that is simple in concept was developed by the TNO Dynamics Laboratory in Delft, the Netherlands (*12*), and

is illustrated in Figure 9. The head of the pile is struck with a hand-held hammer. A compression wave is generated that travels down the drilled shaft, is reflected from the bottom of the shaft (or from a defect), and is picked up by an accelerometer at the top of the shaft. In operation, however, the method can require skilled operators. The signal must be processed to eliminate unwanted waveforms, and the resulting signal must be displayed rapidly for convenient analysis.

An example of an idealized result from an integrity test is shown in the inset in Figure 9. As may be noted, the time for the compression wave to travel down the shaft and back again can be read from the signal as it is displayed on the screen of an oscilloscope. With knowledge or an assumption of the compression wave velocity in concrete (V_c), the constructed length of the drilled shaft (or the distance from the top of the shaft to a defect or irregularity) can be found from the simple equivalence shown.

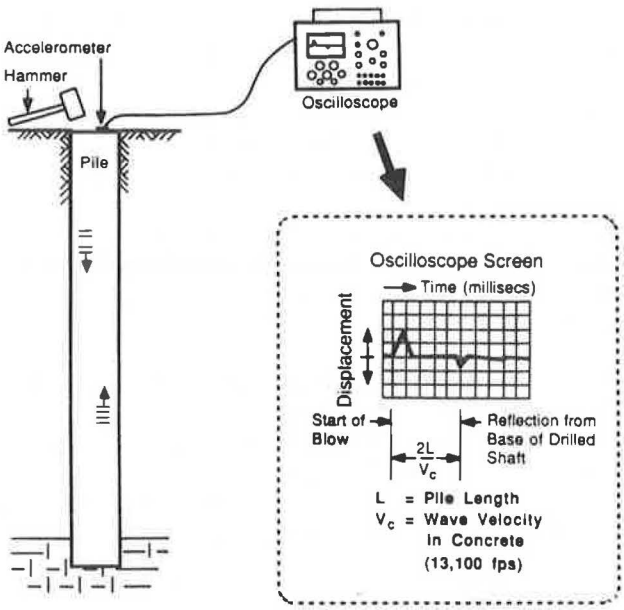


FIGURE 9 General arrangement for TNO testing method (*12*).

The advantages of the method are that a test can be performed rapidly and inexpensively. The disadvantages are that the interface bond is not investigated, that specialized equipment is necessary, and that the operators must be skilled in interpreting the waveforms that are recorded.

Vibration with Hammer Blow—Embedded Instrumentation

Investigators at The University of Texas at Austin have done studies by using the same concept as was used by TNO except that the receivers were embedded in the drilled shaft (*13, 14*). This test arrangement is illustrated in Figure 10. In addition to the embedded receivers, an accelerometer (or vertical velocity transducer) can be used at the top of the drilled shaft to provide further data.

The two receivers that are shown in the figure, plus a surface accelerometer, yield a significant amount of data. With such an

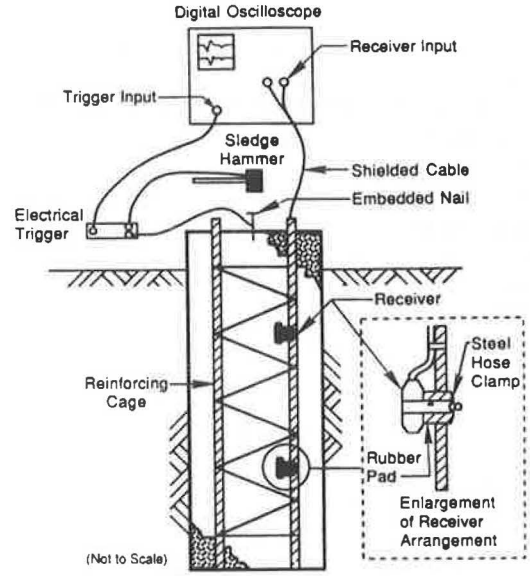


FIGURE 10 Compression wave propagation method with embedded receivers (*13*).

arrangement, direct evaluation of wave velocity, V_c, is performed and confirmation of any possible irregularities can be done by comparisons between the transducer signals. Direct evaluation of V_c allows computation of the small-strain modulus of elasticity, E_{max}, of the pile from

$$E_{max} = \frac{\gamma}{g} V_c^2 \tag{5}$$

where γ is the total unit weight of the concrete or steel and g is the acceleration of gravity.

The receivers are vertical velocity transducers (geophones) sealed in plastic cases. An electrical cable extends from the transducer case to about 10 ft beyond the top of the shaft. The transducers are relatively inexpensive (about $50 each), and the instrumentation can generally be installed rapidly with no delay in the construction process.

Typical results from a test shaft in Houston, Texas, are shown in Figure 11 (*14*). The shaft is 30 in. in diameter, 50 ft in length, and contains four embedded receivers. Evaluation of the quality of the concrete, in terms of compression wave

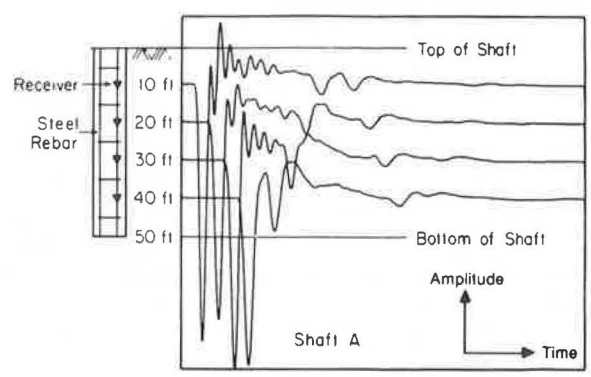


FIGURE 11 Seismic waveforms recorded with embedded receivers in a 50-ft-long sound shaft (*14*).

velocity, is illustrated in Figure 12. Although compression wave velocity cannot be directly related to concrete strength (because of mix design variations), measured P-wave velocity for a given mix design provides a relative indication of concrete quality of the shaft or pile. A suggested rating of concrete quality based on P-wave velocity is provided in Table

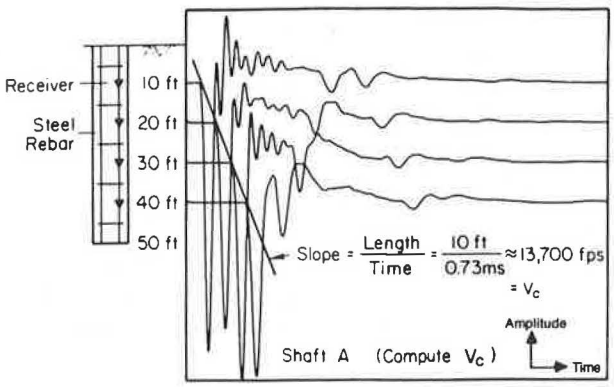


FIGURE 12 Illustration of wave velocity determination from initial arrival of compression wave monitored with embedded receivers (*14*).

TABLE 1 SUGGESTED COMPRESSION WAVE VELOCITY RATINGS FOR CONCRETE FROM ULTRASONIC TESTS (*15*)

Compression Wave Velocity		
Measured in ft/sec	Measured in m/sec	General Conditions
Above 15,000	Above 4570	Excellent
12,000–15,000	3660–4570	Good
10,000–12,000	3050–3660	Questionable
7,000–10,000	2133–3050	Poor
Below 7,000	Below 2130	Very poor

1 (*15*). The rating scale shown in Table 1 is based on ultrasonic pulse tests (high-frequency tests), which were used to measure P-wave velocity through a concrete medium. Wave propagation velocity in a rod differs from wave propagation velocity in a continuous medium of an identical material if the wavelength of the pulse is greater than the rod diameter. Since a drilled shaft or pile behaves like a rod in this testing, wave propagation velocity as determined herein will be less than the velocity measured at ultrasonic frequencies, the reduction being approximately 10 percent for a Poisson's ratio of 0.25. Therefore, velocities listed in Table 1 have been reduced by 10 percent and are presented in Table 2 so that they can be compared with wave velocities determined by this test method.

Identification of wave reflections in these records is illustrated in Figure 13. It can be seen in the figure that reflections have occurred only from the ends (top and bottom) of this straight-sided shaft. Such identification shows that the shaft contains no defects or irregularities.

Two advantages of using embedded receivers in comparison with surface receivers are that the background noise level is much reduced with embedded receivers (reducing or eliminating the need for signal processing) and any number of embedded receivers can be installed. The disadvantages of using the wave propagation method with embedded receivers are the same as those listed for wave propagation testing with external

TABLE 2 SUGGESTED COMPRESSION WAVE VELOCITY RATINGS FOR CONCRETE FROM WAVE PROPAGATION METHOD (*14*)

Compression Wave Velocity (ft/sec)	E^a (psi)	General Conditions
Above 13,500	5.90	Excellent
10,800–13,500	3.77–5.90	Good
9,000–10,800	2.62–3.77	Questionable
6,300–9,000	1.28–2.62	Poor
Below 6,300	1.28	Very poor

NOTE: Figures are assuming the wavelength is greater than two times the pile diameter.

[a]Assuming the unit weight of concrete = 150 pcf.

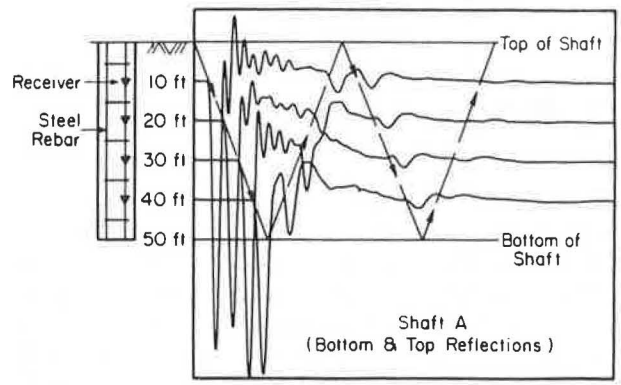


FIGURE 13 Identification of wave reflections from top and bottom of a sound shaft (*14*).

instrumentation. In addition, use of embedded receivers involves a somewhat greater cost and the decision to test must be made before construction.

Steady-State Vibration

Davis and Dunn (*16*) report that the method of forced vibration (steady-state vibration) was developed by the French Building Institute (CEBTP) in the 1960s. Preiss et al. (*17*) report that several thousand bored piles (drilled shafts) have been routinely tested with the method. The test is performed by placing an electrodynamic vibrator over a load cell in a specially prepared region at the center of the top of the shaft as shown in Figure 14 (*18*). The vibrator is driven by a sinusoidally varying current over a frequency range from about 20 to 1,000 Hz. The output from the load cell at the top of the drilled shaft is fed into a regulator that adjusts the amplitude of vibration to keep the force level constant. The vibrator force is applied to the head of the drilled shaft, and the vertical velocity at the shaft head from a velocity transducer is monitored for each measurement frequency.

The curve of V_0/F_0 is plotted as a function of frequency, where V_0 is the maximum velocity at the head of the drilled shaft and F_0 is the applied force. This plot, shown in Figure 15 (*18*), expresses the mechanical admittance or mobility of the shaft head. The frequency difference between successive resonance peaks, Δf, is equal to

$$\Delta f = V_c/2L \tag{6}$$

where L is the intact length and V_c is the compression wave velocity in the concrete (about 13,000 fps for sound concrete).

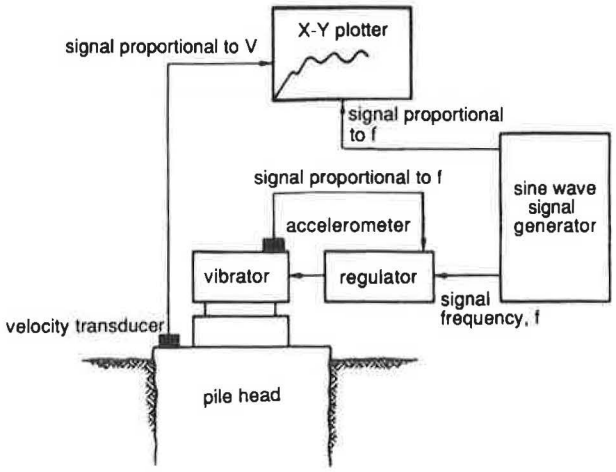


FIGURE 14 Experimental arrangement used in steady-state vibration testing (*18*).

If the shaft length is known, the quality of the concrete in the drilled shaft can be inferred from the wave velocity. One problem that can arise is that interpretation can be complicated by "noise" in the electronic monitoring systems created by variations in diameter of the drilled shaft, variations in concrete quality, variations in the stiffness of the soil around the drilled shaft, and any exposure of the top part of the drilled shaft above the ground.

In addition to predicting reflector depths, the forced vibration test also measures dynamic stiffness at the foundation head. Dynamic stiffness reflects the soil-foundation interaction conditions and may be thought of as a spring constant with units of kips per in. Identical foundation members will be much less stiff when placed in soft soil than in bedrock. Defects such as necking and soil inclusions in drilled shafts and breaks in driven piles also result in comparatively lower dynamic stiffnesses (*19*). Correspondingly, enlargements and bulbs in shafts produce comparatively higher dynamic stiffnesses.

The forced vibration test can characterize the nature of defects, such as necking or bulbing, on a comparative basis for similar foundations. Although the dynamic stiffness measured by the forced vibration test is a low-strain measurement, correlations with static stiffness at low loads in axial load tests indicate dynamic stiffness is typically one to two times the static stiffness. Such correlations have been used to make reasonable predictions of foundation settlement under working loads. However, the forced vibration test does not predict the capacity of deep foundations.

The advantages of the method are that no preselection is needed of the shafts to be tested and that an experienced operator can detect both discontinuities and major faults. The disadvantages are that more equipment and instrumentation are required than for the other methods where vibration is used and that little information can be obtained below a significantly enlarged region in the drilled shaft.

Impulse Response

Impulse-response testing is a technique in which the force of a vertical impact is compared to the vibration response of the shaft head using a spectral analyzer. Stain (*20*) reports that results and interpretation from the impulse-response or "transient dynamic response" method are in every way identical to the forced vibration method just discussed. The impulse-response method has several advantages over the forced vibration technique in that the bulky vibrator is eliminated, minimal preparation of the shaft head is required, and the impulse-response test is much faster. Consequently, the impulse-response method has now largely replaced the forced vibration technique in practice.

Equipment used to perform the impulse-response test consists of a spectral (signal) analyzer, impulse hammer (with

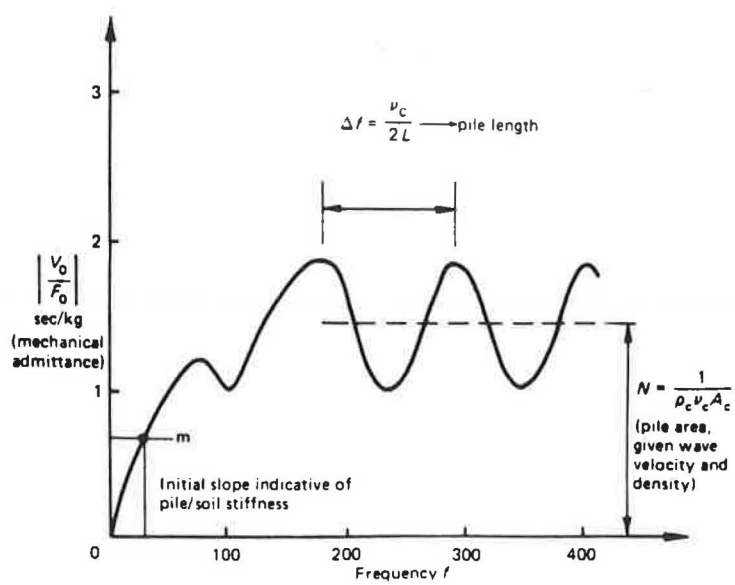


FIGURE 15 Idealized response curve for steady-state vibration testing of a drilled shaft (*18*).

built-in force transducer), and a geophone as indicated in Figure 16 (*19*). The test consists of hitting the shaft head with an impulse hammer and measuring the vibration response of the shaft head with a vertical velocity transducer (geophone). Several tests are conducted on a single pile, and the impact force and vibration response are averaged and processed with the signal analyzer to determine the dynamic response of the soil-foundation system.

Results of impulse-response tests of the sound shaft at the research site of The University of Texas (*14*) are presented in Figure 17. (Wave propagation testing of this shaft, Shaft A, has already been shown in Figures 11–13.) The test records are plots of V_0/F_0 versus frequency, or mobility plots, as discussed previously. Dynamic stiffness can be calculated from the initial straight-line portion of the plot at low frequencies or directly by integration using the signal analyzer. At low frequencies the soil and shaft move together, which permits the measurement of dynamic stiffness as a result of the soil-structure interaction effect (*19*). Resonant peaks for the shaft are also apparent in the mobility plot. An average change in frequency between the peaks of 138 Hz was calculated as illustrated. A reflector depth of 49.6 ft was calculated for the shaft as indicated on the mobility plot. The actual reflector depth (the bottom of the shaft) was 50 ft, which is in close agreement with the prediction.

In summary, the impulse-response method provides data on reflector depths and soil-foundation interaction effects. Comparative evaluation of test results can also indicate the nature of an irregularity such as a bulb or neck. The impulse-response method is much more portable and faster than its predecessor, the forced vibration method. Like the TNO stress wave method, reflections may not be identified from long slender shafts because of excessive attenuation, and reflections may also not be identified from shafts founded in competent bedrock with density and compression (stress) wave velocities that are similar to the shaft concrete. In these cases, embedment of geophones or tubes is necessary to confirm the continuity of such shafts. However, experience has shown that significant defects will produce identifiable reflections at depth in even long slender shafts, depending on the soil conditions (*21*).

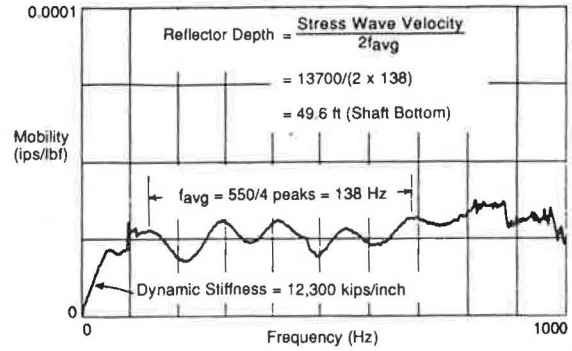


FIGURE 17 Mobility plot for Shaft A (sound shaft) shown in Figure 11 (*19*).

STATIC AND DYNAMIC LOAD TESTS OF SUSPECTED DRILLED SHAFTS

In some instances, the only positive way to prove the integrity or behavior of a particular deep foundation is to perform a static load test. However, only in unusual instances is such a procedure economically feasible for drilled shafts. The assembly of the loading equipment would, in most instances, be more expensive than the replacement of the questionable shaft.

A general exception exists where a drilled shaft is designed for a relatively light load and where existing drilled shafts in

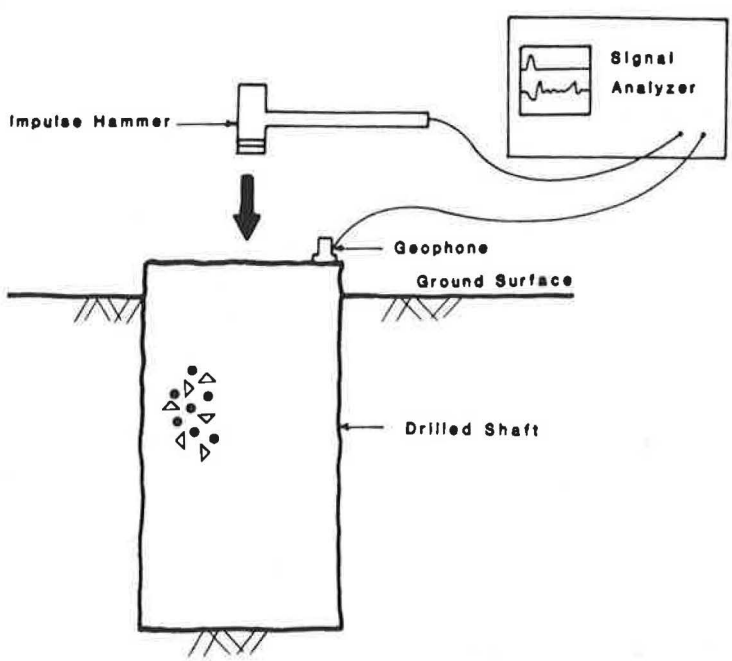


FIGURE 16 Experimental arrangement used in the impulse-response method (*19*).

line and on each side of the questionable one can be used for the reaction. Such a favorable situation is thought to be rare.

A procedure that has been developed involves the performance of a dynamic load test (*12*). A testing arrangement is made that allows a mass of sufficient magnitude to be dropped onto the top of the drilled shaft. Measurement of the applied dynamic load and movement of the top of the shaft allows the performance of the foundation to be deduced by the wave-equation method (*22*). While the method has been used to a limited extent in the United States and abroad, it has promise as a tool to be used in special cases and even routinely on important projects.

OTHER METHODS OF INTEGRITY TESTING

There are several other methods for investigating the integrity of piles or drilled shafts. Methods that involve the use of access tubes and down-the-hole instruments, such as sonic or nuclear logging tools, have been used successfully. The use of drilling and coring has also been done. These methods are, however, not discussed herein because of space limitations.

CONCLUSIONS

- The performance of static-load tests of instrumented piles, or drilled shafts, is feasible and can yield valuable results.
- The selection of instruments and their placement along a pile should take into account the analytical model of the pile-soil system.
- A variety of instruments is available for yielding data giving internal load or displacement in a pile as a function of depth.
- The Mustran cell and the telltale have proven to perform well in the testing of drilled shafts under axial load.
- With the collection of a sufficient body of data concerning the distribution of axial load with depth, it is probable that load-transfer functions can be developed that will allow designers to predict by numerical techniques the load versus settlement for an axially loaded pile.
- Investigation of the integrity of a concrete pile by the use of dynamic methods (stress wave measurements) is feasible. In addition, such measurements can also be used to evaluate the small-strain modulus of the member if embedded measurement points are used.
- Off-the-shelf transducers and digital recording equipment are available that can be used to perform embedded wave velocity measurements in a pile.
- Steady-state and impulse-response tests (dynamic tests) can also be used to evaluate the integrity of piles and drilled shafts. In addition, the deformation behavior of these members at small strains to obtain a sense of the initial load-settlement curve of the pile can be determined with these tests.
- Only on rare occasions are static or dynamic load tests used specifically to evaluate pile integrity.

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