CAPACITY EVALUATION METHODS OF DEEP FOUNDATIONS
A CRITICAL REVIEW

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ABSTRACT

Determination of bearing capacity and behavior of deep foundations under applied load is one of the most important problems in foundation engineering. Several methods based on concepts ranging from purely theoretical to field testing are used to evaluate the load bearing capacity of deep foundation elements. This paper presents a critical review of a number of conventional methods and recently developed concepts for establishing pile load bearing capacity using field tests. For each method, theoretical principles, application considerations, and limitations will be discussed.

INTRODUCTION

The choice of foundation type is generally based on considerations of structural requirements, subsurface conditions, site characteristics and economics. Deep foundations are utilized when shallow type foundations do not provide adequate support. They are of two major categories: cast-in-place, or prefabricated and installed with a pile driving hammer. In some cases, a deep foundation element may incorporate both prefabricated and cast-in-place features. Driven elements usually having diameters less than about three feet are commonly referred to as piles while cast-in-place elements are known by a variety of names such as drilled shafts, bored piles, or caissons. The term "pile" will be used here to refer to a deep foundation element of any size or method of installation; distinction will, however, be made where necessary.

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Performance under applied load is a function of the pile strength and integrity as a structural element, supporting soil strength and deformation properties, pile-soil interaction characteristics, and the nature and magnitude of the applied load. In the case of pile foundations, it is possible and common to actually test single piles to determine their capacity. This paper presents a discussion of field testing methods for evaluation of axial compression load carrying capacity of single piles. Specifically, the following techniques are critically reviewed: conventional static loading tests, Osterberg Method, dynamic pile testing, and Statnamic.

There are many other considerations, in addition to strength, that place limitations on pile design. These considerations are handled using a variety of site assessment methods including subsurface investigation with borings, in-situ and laboratory tests for evaluation of soil and/or rock properties and ground water conditions. It is also necessary to evaluate the long term effects such as the potential for pile deterioration due to the chemical reaction between the soil and the pile, scour, downdrag, long term settlement, etc. For driven type piles, Wave Equation analysis is an integral part of the pile design, the selection of the installation equipment and the determination of driving criteria and procedures. Knowledge of the static load bearing capacity of single piles, the topic considered here, is essential for a proper evaluation of the foundation system but it is only one of several considerations.

STATIC LOADING TESTS

Traditionally, pile testing has meant a static loading test. The purpose of the test is to examine the response of a pile under load applied at the pile head. Several different procedures have been proposed for conducting this type of test. The main differences are in load application, instrumentation, and interpretation of results. Standards and procedures detailing arrangement, performance, and evaluation of results are available in the literature (ASTM D-1143; FHWA-SA-91-042, 1992; ISSMFE 1985; Canadian Foundation Engineering Manual, 1992). Pile testing may be performed during the design or construction phase of a project depending on whether foundation design parameters are desired or the pile adequacy is to be verified. For small projects, testing cost may be significant compared to the overall foundation cost. On projects involving a large number of piles, only a small percentage (typically one percent or less) of the piles are tested. In cases such as offshore construction and land construction in waterways or congested areas, static pile testing may be impractical or even impossible.

The number and location of the test piles is usually determined by the engineer after considerations of variability in subsurface conditions across the site, pile type and installation method, and loading type and magnitude. The physical setup for conducting the test is generally installed by the contractor. Testing is normally performed by the contractor under the supervision of the engineer.

Figure 1 presents "typical" arrangement for applying load and measuring movement at the pile head. A hydraulic jack acting against a reaction beam which is held by a system employing weights, piles, ground anchors, or a combination thereof is used for load application. Loads are measured with a load cell placed between the jack and the pile, by measuring the jack pressure, or by both methods. Pile head movement under

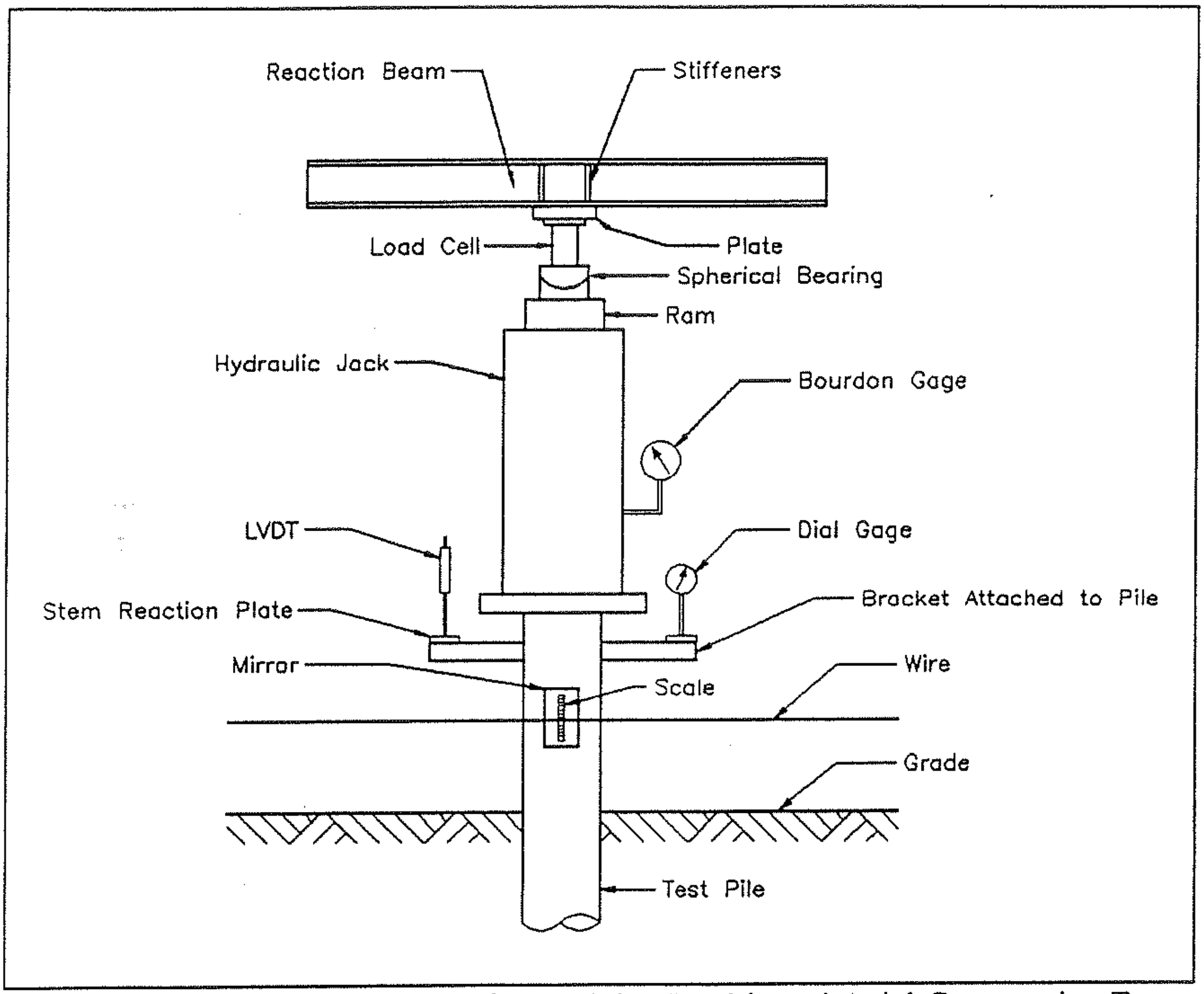

Figure 1: Typical Arrangement for Applying Load in and Axial Compression Test

applied load is measured with mechanical dial gages or electro-mechanical devices. Care must be taken to prevent apparent pile motion due to temperature effects on the dial gage supports. For redundancy, movement measurements are also taken with a wire-and-mirror system or with a surveyors level. Load and head movement measurements constitute the minimum measurements that are made during a static test. Measurements of movement along the pile shaft are sometimes obtained with telltales, rods that are supported at various levels along the pile and extended to the top where the measurements are made. Strain gages are occasionally used to measure internal forces at selected places along the pile length. For safety and proper evaluation of test results, movement of the reaction system should also monitored during the test.

The two most commonly used loading procedures are: the Maintained Load (ML) and the Constant Rate of Penetration (CRP) methods. According to the ML method, load is applied in increments that are large fractions of maximum anticipated load. Each increment is maintained until pile movement is less than a prescribed value (typically 0.01 inch per hour, or for two hours whichever occurs first). The final load is maintained for 24 hours. The procedure is made into a "Quick Test" by applying fairly small load increments (25 to 40 increments of the maximum anticipated load) and holding each increment for a constant time interval (5 to 15 minutes). Pile movements are recorded before and after the application of each load increment. The CRP test method consists of continuously loading the pile such that its rate of pile head motion is constant (typically between 0.01 and 0.10 inches per minute). Readings of pile head movement are taken at least every 30 seconds. In some practices, the ML test is changed to the CRP procedure when the rate exceeds 0.8 inch per hour. Figure 2 presents plots of pile head load-movement relationships for the three loading procedures.

Commonly, test results are presented as a pile head load-movement plot. Other types of data may be obtained from the test, particularly with fully instrumented piles loaded to failure. Shapes of load-movement graphs vary considerably and so do the procedures used for evaluating the test result. Controversy arises in the interpretation of data due to the lack of a universally recognized definition of "failure". Practically, failure occurs when pile movement continues under sustained or slightly increased load. Studies have shown that it is possible to obtain a wide range of results from a single test depending on the method of interpretation (Fellenius 1980). The definition of failure is best based on rules that produce repeatable results independent of the engineers judgement.

The potential benefit of a static loading test should be carefully weighed against the cost and time required in performing a test. Although static load testing is an excellent procedure for evaluating pile load bearing capacity and insight into pile behavior under load, improperly performed or poorly executed load tests can produce results that do not reflect the conditions at the site.

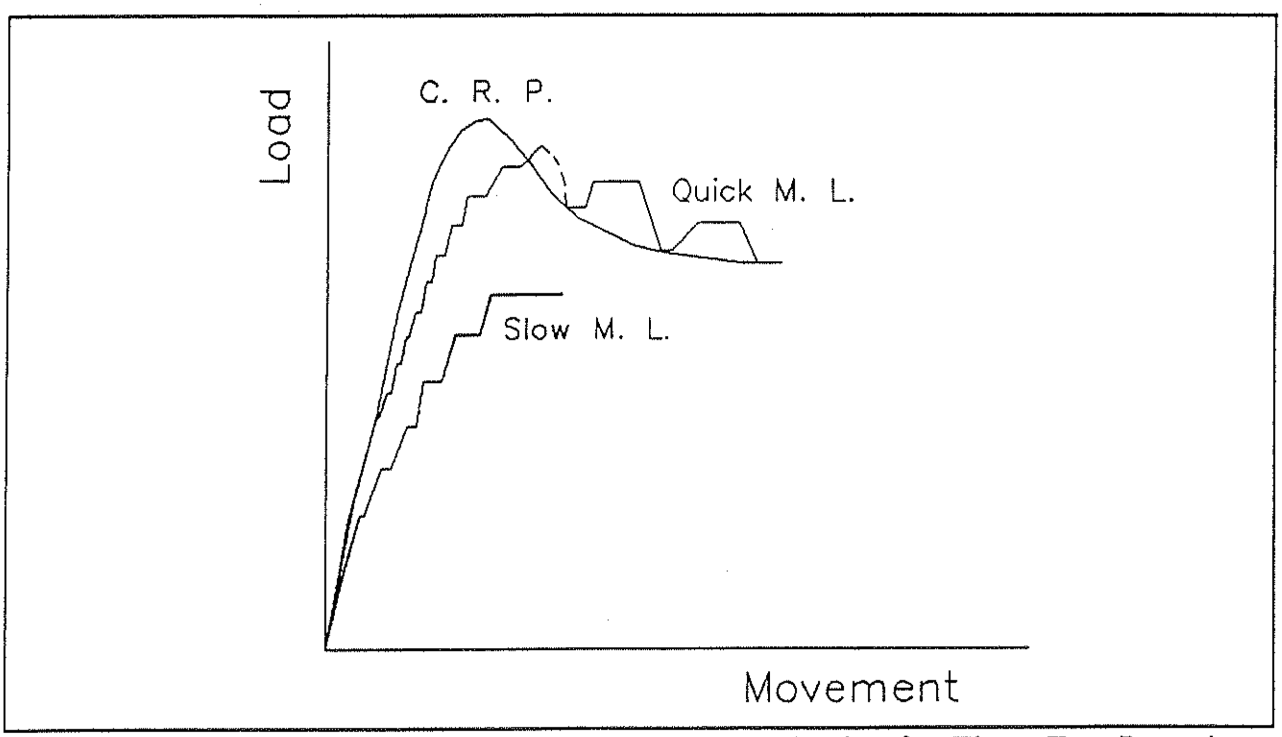

Figure 2: Comparison of Typical Load-Movement Behavior for Three Test Procedures

COMMENTS ON STATIC LOAD TEST ACCURACY AND RELIABILITY

The problems and limitations of the static load test fall into two categories; difficulties arising from incorrectly performed tests, and problems inherent in the static test itself. In the first category, static tests are limited by the cost and time required to perform the test. Furthermore, the cost will increase rapidly with the increased magnitude of the test load. Probably of all of the limitations this is the most serious.

Safety considerations present serious limitations. The large loads involved in a static test store large amounts of elastic energy. If something fails, serious injury of the testing personnel is possible. One hears frequently of failures in static load tests that cause injury and death of the testing staff.

Problems arise in the measurement of load and movement. Particularly load measurement can yield substantial error. The most common means of load measurement is to read the jack pressure. This can produce substantial error due to jack friction or simply a poor jack gage calibration. Fellenius (1980) has shown that an error of 15% may be typical due to jack friction. A poor calibration can lead to more serious errors. These problems become more serious when more than one jack is used in testing a high capacity pile. It is essential that an electronic load cell be used for measuring the applied load. In addition, the introduction of a spherical bearing in the load column will reduce the possibility of error in load measurement.

Probably the most serious problem with the performance of a successful static load test is the fact that most of the personnel that perform the test are inadequately trained. It seems that the test is looked upon as a relatively simple and routine task and ,therefore, special training is unnecessary. In fact, since the test must be performed correctly and carefully it is essential that the testing crew be well-trained.

Many, if not most, static tests are not carried to failure. They may not be carried to failure in order to limit expense and effort required to set up a suitable reaction system, or due to lack of a jack of sufficient size. In these cases the test result only represents a lower bound on the pile capacity. As such tests are normally performed they only represent proof tests and increased pile capacity cannot be justified. As the standard ML test is performed it often generates a failure load at the end of the load application. Since the load is rapidly applied failure only appears to occur when the load is held. In some cases if the load increments were smaller a lower failure load would occur.

Studies of data bases containing thousands of test results indicate that in most cases (certainly more than half) testing and test documentation were not done in a proper professional manner (i.e., in some cases pile type and dimensions, soil information, information on driving equipment, blow counts, etc.) (Dennis and Olson 1983) and (Wysockey and Long 1994).

In the second category, several basic problems inherent in the static test itself can be enumerated. The static test does not yield any information on pile driving stresses or hammer performance so a proper criteria cannot be set for production driving considering pile tension stresses and the possible need to vary the stroke during the driving of concrete piles. If a change is made in the hammer selection, then the absence of driving information severely reduces the reliability of the quality control for the production piles.

Most static load tests are impractical or impossible to perform offshore, in deep and strong river waters, or congested areas. In deep water, there is a danger that the test pile will buckle under load. Anchorage of the reaction system is also a difficult problem.

The static load test will not indicate pile structural damage in some cases. For cast-in-place piles where the concrete is totally lacking and all the load is taken by the steel reinforcement cage, if the steel can carry the test load this may mean trouble later if the steel corrodes. In general, the static test will not provide clear information on structural damage or integrity problems.

Even though the test is "static" it does not account for long term pile behavior (i.e., setup or relaxation, group effect, or long term settlement due to consolidation). There are even differences in results between ML and CRP results due to creep and loading rate effects (Walker 1972) and the lack of a uniform failure criteria is a further limitation.

In spite of the above limitations, the static test is still, appropriately, the standard by which pile capacity is evaluated. It is important that the test user understand that care must be used in performing the test. If the test is carefully executed and electronic load cells are used, it can be expected that the results will be good within the limitations listed in group two above. In the experience of the authors it is desirable that a rapid loading procedure be used so that over-night testing is not necessary. The long, maintained load test places larger demands on the testing crew and often lead to problems of test execution.

THE OSTERBERG LOAD CELL

The Osterberg test is a truly static load test that uses the shaft friction to react the toe force during the application of the toe load by hydraulic means (Osterberg 1984, Osterberg 1994). Using this method the cost of the static test must be reduced by eliminating the need for a reaction system. The test setup is shown in Figure 3. The Osterberg Test is performed using an Osterberg Load Cell (named for its inventor, Jorj Osterberg). Savings are achieved by utilizing the shaft soil resistance forces as the reaction load. The load cell (also known as the O-cell) is a calibrated high capacity hydraulic testing device of the flat jack type capable of exerting very large loads at high internal pressure. It is typically installed at the pile toe, but can also be located along the pile shaft. It is possible to utilize more than one O-cell in testing a single pile and, thus, determine more details of the resistance distribution. This testing method was originally developed for testing drilled shafts, but has been also applied to driven piles.

For typical applications, the O-cell is lowered to the bottom of the drilled shaft hole before concrete placement. A pipe, welded to the top of the device, extends to ground surface and serves as a conduit for applying fluid pressure to the cell. Inside this pipe is another smaller diameter pipe connected to the bottom of the device and extending to the top of the shaft for measurement of the downward movement of the bottom of the cell during the load application. Generally, the fluid used to apply pressure is water with a small percentage of water-miscible oil. When the test is completed the fluid can be replaced by grout.

Loading is achieved by internally pressurizing the cell, creating equal but opposite upward and downward forces. As the pressure in the cell increases, the inner pipe moves downward and toe resistance increases. The pile moves upward with load application and mobilizes the skin friction. The downward movement is measured with Dial Gage 2 (Figure 3) and pile top upward movement is measured with Dial Gage 1. Typically, three dial gages are used to measure the movement of the pile top in order to eliminate (by averaging) the effects of any pile bending. Tests are usually performed according to the ASTM D-1143 Quick Load Procedure. Load-downward movement for the bottom of the load cell in end bearing and load-upward movement plots are obtained from the test data. An example of the measured results is given in Figure 4. In this example the Minimum Capacity Curve will not really develop as the sum of the two curves since the pile toe will carry increasing load. With increased load, some failure condition will occur, either in end bearing or in shaft friction. At failure, no further increase in cell pressure can be obtained. The cell failure force can be considered to be a working load at the top of the shaft having a factor of safety of at least two against failure. Loads as high as 12,000 kips (6,000 kips each up and down) have been applied to shafts three feet or larger in diameter.

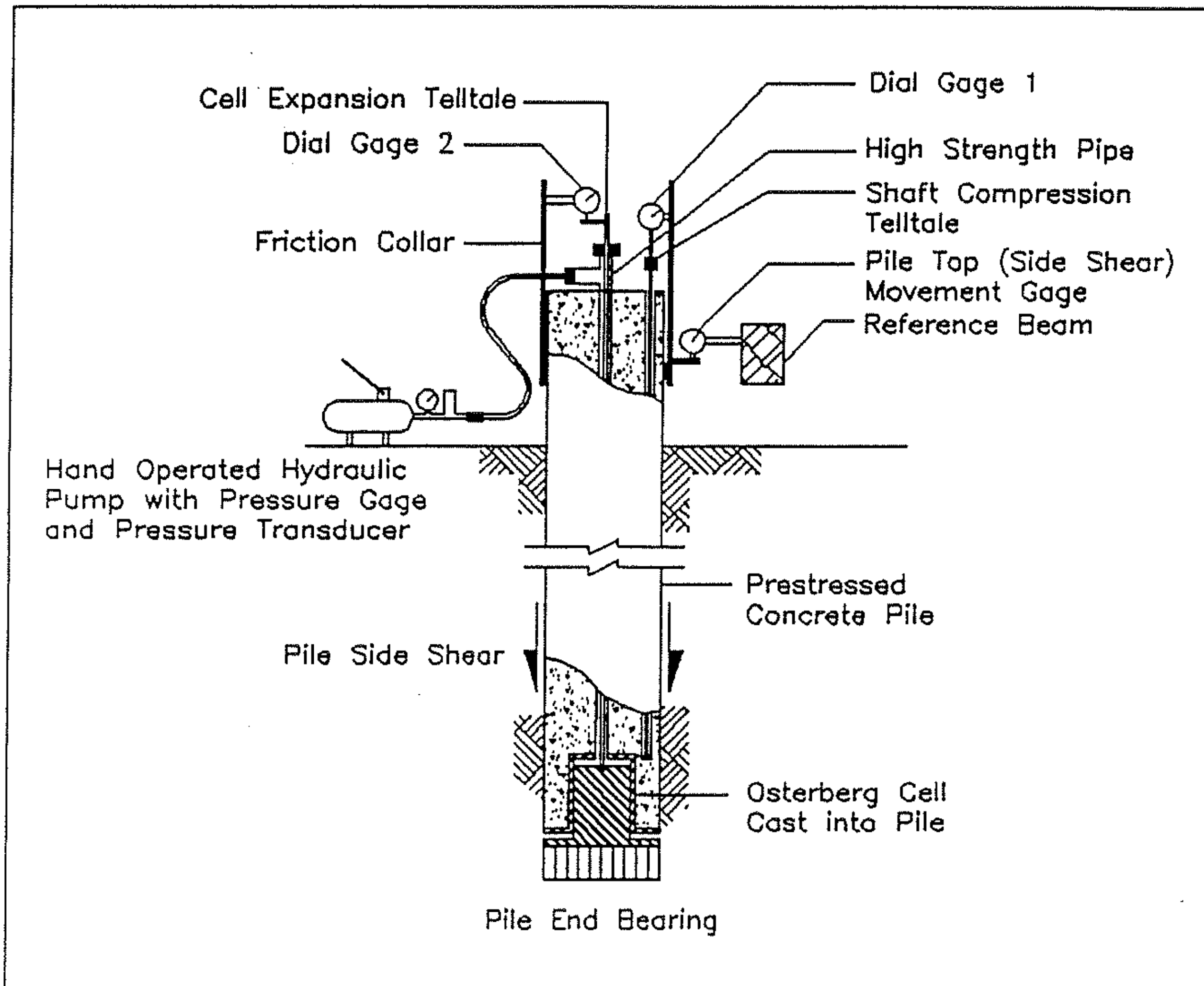

Figure 3: Osterberg Cell and Related Equipment

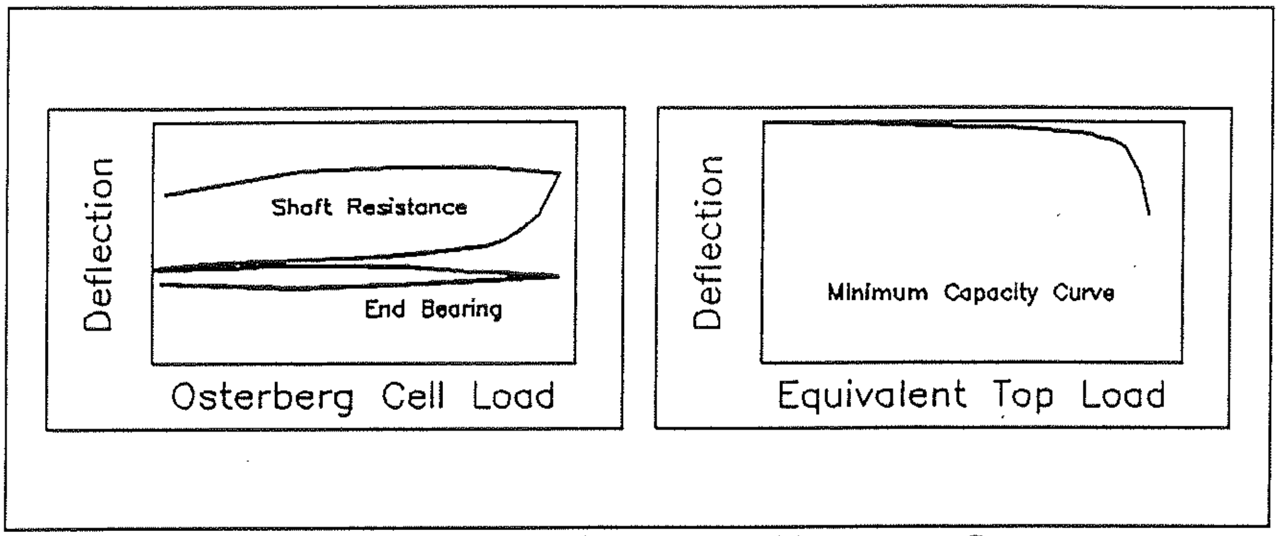

Figure 4: Equivalent Pile Head Load-Movement Curve

COMMENTS ON THE OSTERBERG LOAD TEST

The main advantage of the Osterberg test method over the conventional static test is the savings of time and cost in the test performance. In addition, the end bearing and skin friction are measured separately. Testing can be performed on piles over water, in congested areas, or on piles installed on a batter. Loading rates can be varied and it is possible to run several cycles of loading. Grouting the cell after the test takes advantage of the increased compression induced during the test and stiffens the end bearing resistance of the pile. The safety problems associated with the usual static load test are also greatly reduced.

Disadvantages of the Osterberg test method include most of the disadvantages of the second type listed above. In addition, the load cell must be installed prior to pile installation which eliminates the possibility of selecting the test pile on a random basis after the piles are installed. The load cell is expendable and cannot be retrieved. Total pile capacity in both friction and end bearing cannot be obtained since only one of the two fails. It may be more expensive than other testing methods for lightly loaded piles (perhaps up to about 400 kips). In addition, the test requires specialists for setup and performance and its applicability may be dependent on the soil conditions at the site.

DYNAMIC PILE TESTING

Modern dynamic pile testing methods are based on research initiated in 1964 at Case Institute of Technology (now Case Western Reserve University) with funding from the FHWA and the Ohio Department of Transportation. Additional funding was received from a number of state Highway Departments and private companies (Goble et al 1975, Goble et al 1980). Initially, the goal of the dynamic pile testing research was to develop methods for the evaluation of static pile capacity from measurements of pile force and acceleration under hammer impacts. The methods were later expanded to evaluate other aspects of the hammer-pile-soil system. Today, these procedures are collectively called the Case Method and are routinely applied in the field using a dedicated computer based system called the Pile Driving Analyzer (PDA) (Rausche et al 1985). The Case Pile Wave Analysis Program (CAPWAP) was developed by the same investigators as an extension of the original research (Rausche 1970). Many organizations around the world have established standards and guidelines for dynamic pile testing (ASTM, FHWA, etc.). During the past fifteen years, the applicability of the method was expanded to test the various types of cast-in-place piles (Goble et al 1993).

The main objectives of dynamic pile testing now include: evaluation of pile driving resistance and static capacity, determination of pile driving stresses, assessment of pile structural integrity, and investigation of hammer and driving system performance.

Dynamic pile testing is performed by making measurements of pile force and motion under the hammer impact with reusable strain transducers and accelerometers attached near the pile top. The PDA is a field computer that acquires the data from the strain and acceleration transducers, provides signal conditioning, calibration and processing of those measured signals, integrates the acceleration to velocity, and displays the measurements for PDA operator evaluation. An example of a set of measured data is given in Figure 5. Using the measurements of force and velocity, the PDA applies the Case Method equations, derived from one dimensional wave mechanics, to compute, in real time, some 30 variables which fully describe the hammer-pile-soil system behavior. The Case Method capacity is calculated and displayed for each hammer blow.

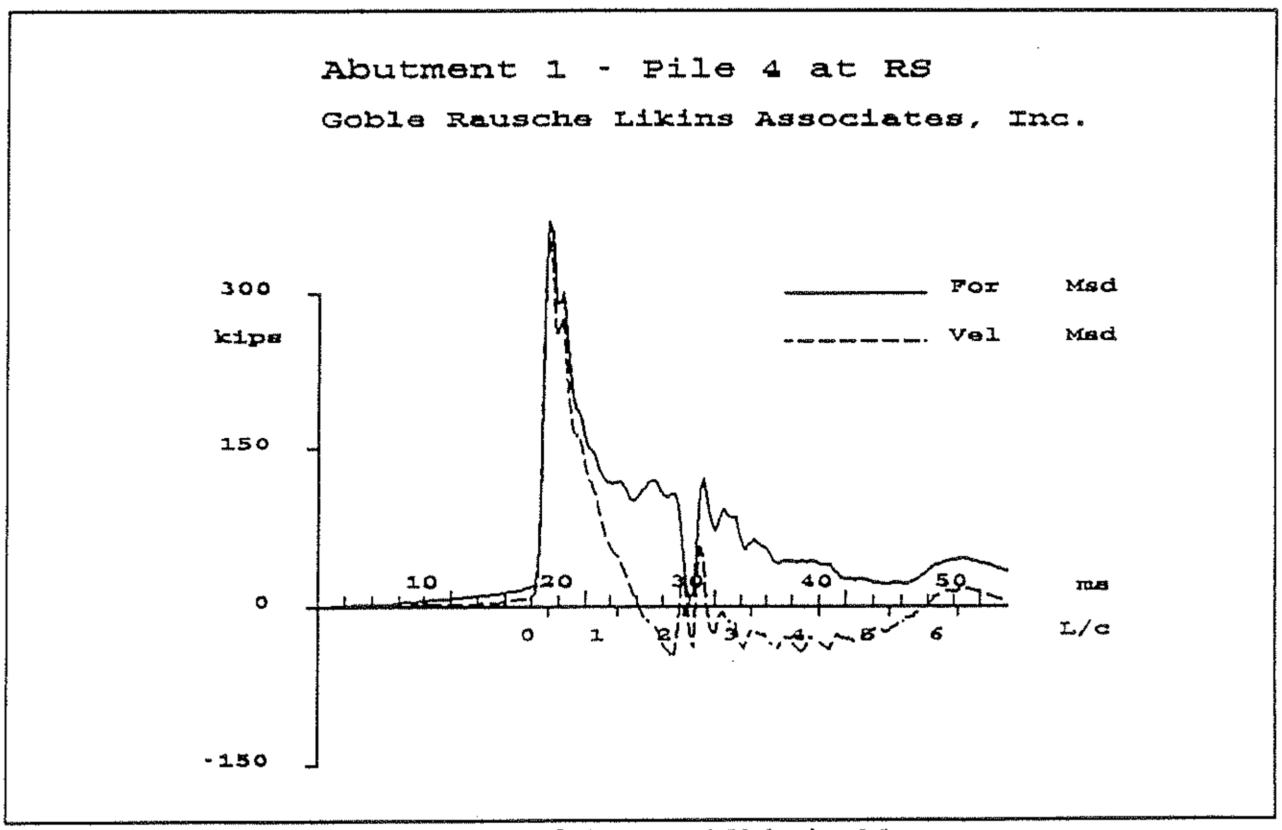

Figure 5: Example of Force and Velocity Measurement

The CAPWAP procedure is an analytical method that combines field measurements and a discrete wave equation type analysis to predict static pile capacity, soil resistance distribution, soil damping and stiffness values, pile load-movement and pile-soil interaction characteristics. The process is based on signal matching techniques utilizing system identification methods. Figure 6 shows a schematic description of the CAPWAP method. The result of the analysis gives not only the static capacity prediction but also the distribution of the static resistance forces and several other soil modeling parameters that give a more complete description of the soil.

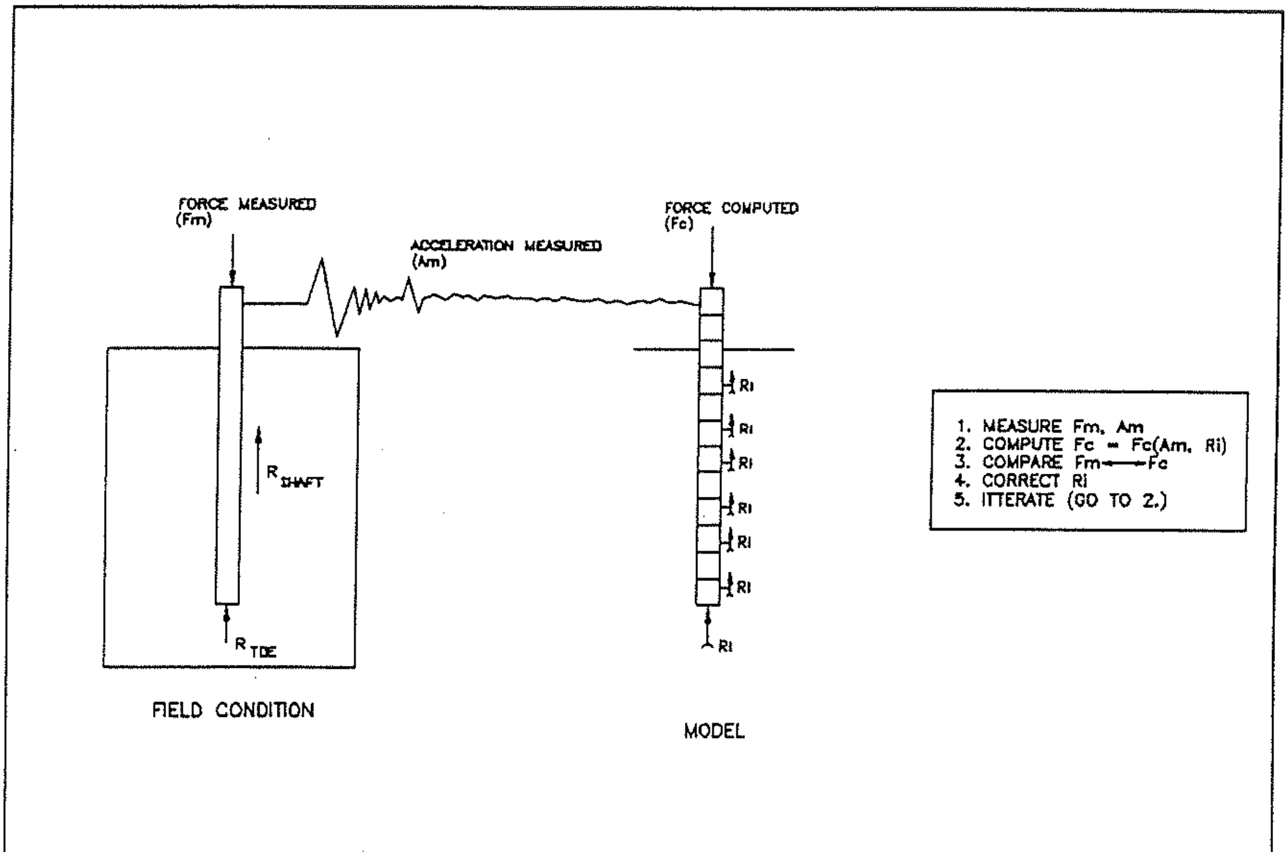

Figure 4: CAPWAP Method

An example of the results of the CAPWAP analysis is presented in Figure 7. Presented here are results of the analysis of a dynamic pile test. It includes plots of the force and velocity measurements, the match between measured and calculated impact force, soil resistance distribution at ultimate load, and pile top and toe load-movement relationships under a simulated static load test. The capacity obtained is the value existing at the time the test was conducted.

A dynamic pile test can be performed in a few minutes at a fraction of the cost of any other type of test. The technical literature contains numerous Class A prediction cases, assembled over the past 25 years, that compare results of dynamic testing and full scale load tests on the same pile. Also, pile damage predictions have been verified by inspection of extracted piles. Dynamic testing has been used routinely since 1972. In

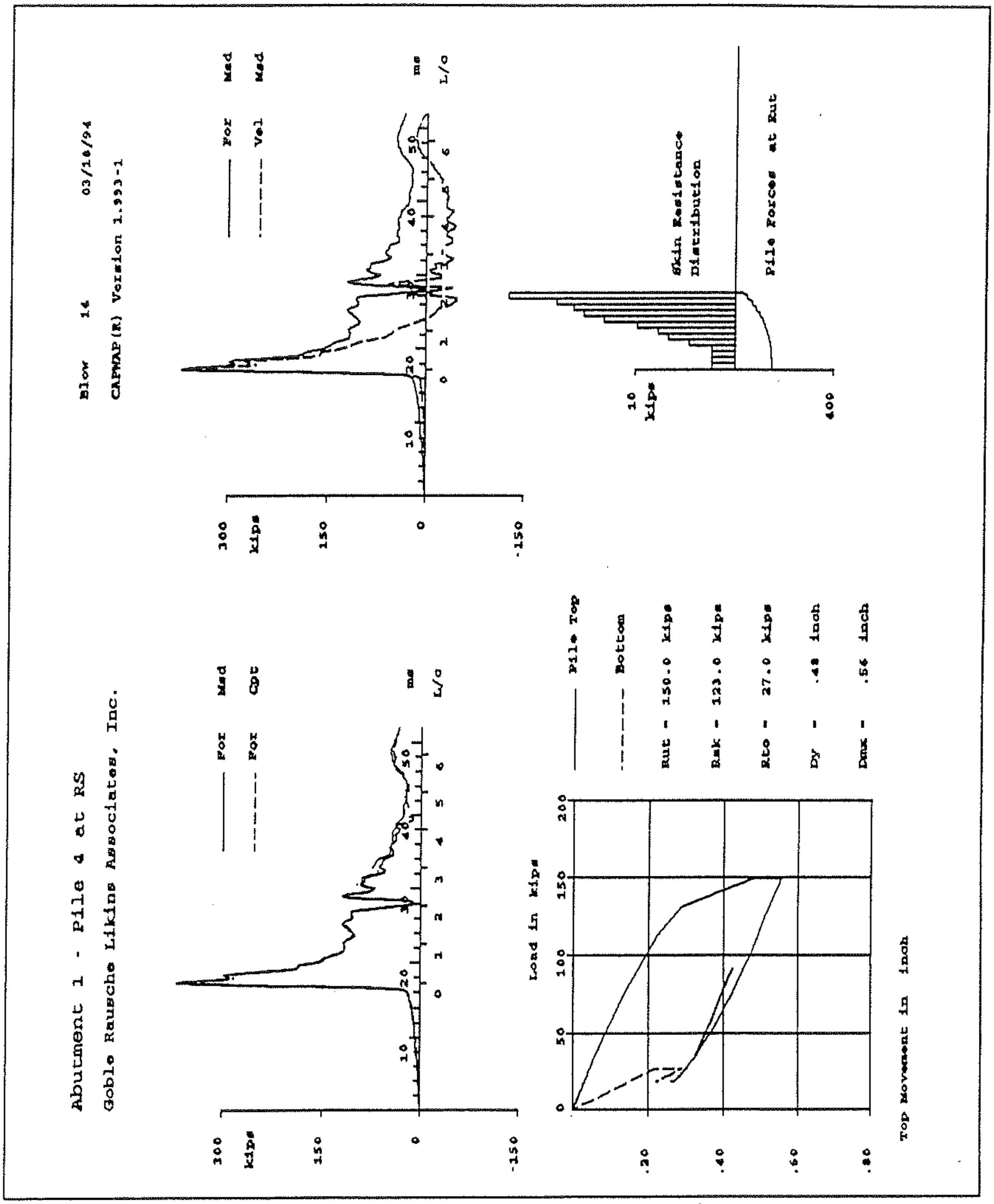

Figure 5: Sample of CAPWAP Result

locations where the method has been verified by static load tests it is often used to completely avoid the requirement of static testing. In other or areas, high foundation reliability can be achieved with dynamic testing combined with a calibrating static load test.

COMMENTS ON DYNAMIC TEST ACCURACY AND RELIABILITY

Like static tests dynamic tests do not consider group effect and long term settlement. Dynamically determined static capacity has been proven by correlation with static load tests conducted on the same piles. In fact, since the dynamic results were compared with a statically defined load it is natural that the capacities would be similar. A dynamic test can be used to assess setup and relaxation effects by performing the dynamic test at a variety of different wait periods.

The dynamic test can be performed using the pile driving hammer for driven piles, but requires a drop weight for drilled shafts. This drop weight must be about one percent of the capacity that must be predicted. The size of the ram for the dynamic test can be checked by Wave Equation analysis. Any pile that can be hit with a hammer can be dynamically tested.

The full pile capacity is not mobilized if displacement during the hammer impact is not sufficient. Depending on the soil type limiting blow counts will be in the range of 10 to 20 blows per inch. However, a capacity is determined and that value will be a lower bound on the total capacity. If it is sufficient, further testing is unnecessary. It is also possible to improve the capacity if dynamic measurements are available from the end of driving in addition to the restrike. Then the restrike shaft resistance can be added to the end of driving toe capacity to estimate the capacity gain from setup on the shaft.

Dynamic testing requires the use of specially trained personnel to perform the test and analyze the data. The training requirements are quite substantial and tests must be performed by an engineer.

STATNAMIC LOAD TESTING

The Statnamic test is a recently proposed testing procedure for determining static pile capacity. In this procedure, an explosive charge is set off on the top of the pile directly under a large mass. The force of the explosion is contained between the mass and the pile top. The inertia force of the mass, which is accelerated upward by the explosion, provides the reaction for the downward acting pile force. The system is shown in Figure 8. The rate of increase of the explosive force is controlled and is supposed to increase in an approximately linear fashion. The loading process is slow compared with an impact force. The time required to load the test pile will be on the order of 40 milliseconds compared with one or two milliseconds in a dynamic test. The total time of loading in a Statnamic test is about 0.1 seconds compared with about 0.02 seconds for a dynamic test.

When the test was initially suggested by the Bermingham Company, it was presented as being a static test. Subsequent work has caused researchers to conclude that

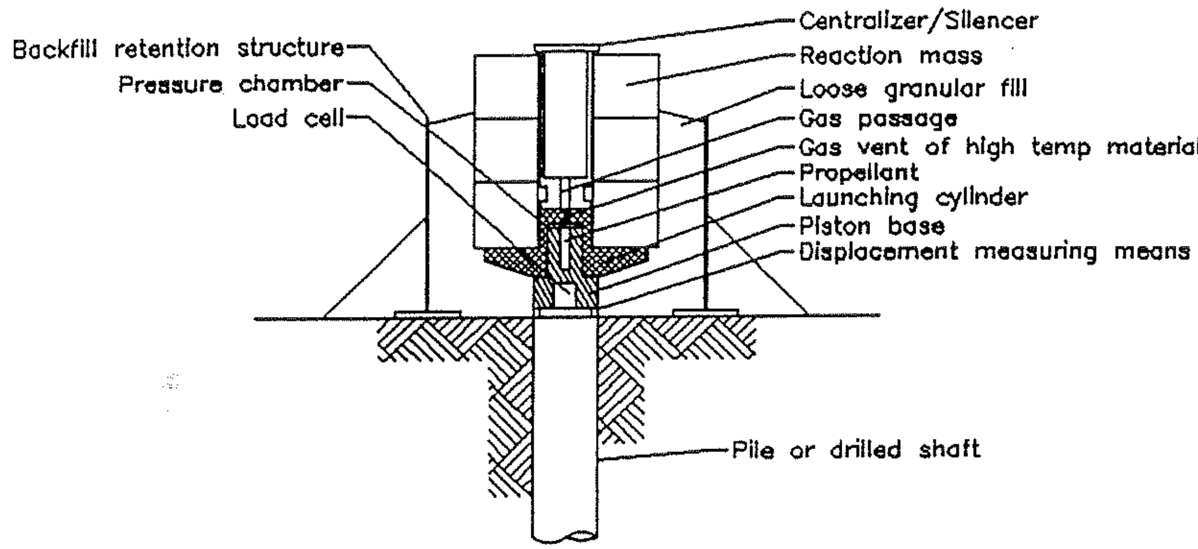

Figure 8: Statnamic System

the test is, in fact, "dynamic" (Middendorp et al 1992, Brown 1994). An analysis has been proposed by Middendorp (1992) that deals with the dynamic effects. During the application of the explosive force the pile moves into the ground, generating both static and dynamic resistance. Eventually, the pile downward movement stops and it rebounds upward to a final position. At the point of zero velocity the assumption is made that the dynamic resistance is zero and that all of the resistance is, therefore, static. This concept is based on the assumption that the pile is rigid.

The method is best described with an illustration. Consider the case shown in Figure 9. This shows the force-time record measured at the top of the pile during the explosion together with the pile top displacement. In Figure 9, the displacement is also plotted as a function of the force. The point of maximum displacement, point A, on these curves corresponds with the zero velocity condition and the load associated with this point is the predicted static capacity. The difference between the load at Point A and the maximum load is the dynamic component of the resistance. It is possible from this information to obtain a predicted load-displacement curve. The procedure was described in detail by Brown (1994).

The Statnamic test is a patented method and is promoted by the Bermingham Company of Hamilton, Ontario, Canada. Therefore, they are the only ones to perform the test. Until recently it was difficult to evaluate the results since the test evaluation

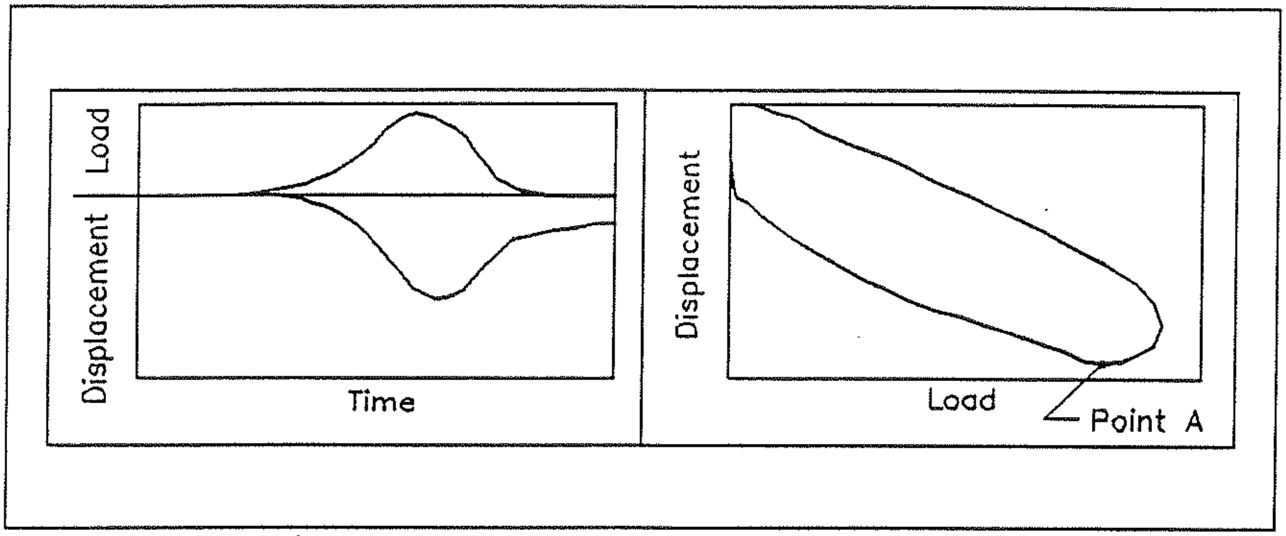

Figure 9: Force Time Measured at the Top of the Pile during the Explosion Together with the Pile Top Displacement

procedure was frequently changed. Thus, only very limited results of Class A predictions are available.

COMMENTS ON THE STATNAMIC TEST

The Statnamic test must be viewed as a dynamic test. Thus, some computational procedure must be used to evaluate the results. The currently used procedure assumes that the pile is rigid and that the soil resistance contains a portion that is a linear function of the pile velocity. The test has the advantage that it is less expensive than a static test. Costs on the order of half the cost of a static test have been mentioned. It does not require a load frame and it can be set up fairly quickly, probably in something less than one day. The test can be performed on batter piles as easily as on plumb piles.

The disadvantages include the fact that even though the test is dynamic the analysis procedure assumes that the pile is rigid and, therefore, the pile resistance distribution cannot be determined as in the case of the dynamic test or the Osterberg Test. The test is fundamentally different from other static tests in that it is performed by applying a force rather than a displacement.

SUMMARY COMMENTS

Over the past 30 years, the frequency of use of static pile tests has increased substantially with the reduced dependence on dynamic formula for pile capacity determination. Standards are available that govern the performance and evaluation of the test. However, the most commonly used standard, ASTM, does not describe a single method but, rather, multiple. This problem has inhibited the development of a set of orderly procedures. In addition, the test is often not performed as carefully as would be desirable. Unless the engineer has specific reasons for doing otherwise, he should specify the Quick ML test with the load carried to failure or at least three times the design load, whichever is lower. Load measurement should be with an electronic load cell and evaluation should be by the Davisson Method.

As stated above the static load test remains the standard by which capacity is evaluated.

The Osterberg test offers the advantage that it is a static test. It can be performed on large diameter piles to very high capacity. It does load the soil surrounding the shaft in the opposite direction from the normal static test. However, the stress state at the toe of the pile is similar to the normal static test in that the toe is in compression and the influence of the toe compression on the lateral stresses on the shaft near the toe will be similar. This test will probably increase in popularity, particularly, for the very high capacity cast-in-piles. Since the test uses a patented system its general use will be somewhat limited.

The dynamic test has been in general use for about 20 years. A huge volume of experience has been generated, greatly expanding the usefulness of the test. Since the test is quite inexpensive it can be very effective in expanding the results of limited static testing. In many soils there is sufficient experience to make a static test unnecessary. The test does require that well-trained engineers perform the test and the measurement evaluation.

The Statnamic test has only recently appeared. During the early stages of its development it was presented as a static test. Now that it is treated as a dynamic method and procedures have been proposed for the test evaluation some time will elapse before sufficient Class A capacity predictions have been collected to evaluate the accuracy and reliability of the test. Due to its cost it must be proven to be an equivalent to the static test. It seems that it costs about the same as the Osterberg test. Like the Osterberg test it is limited by the fact that it uses a patented system.

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