DEEP FOUNDATION CAPACITY – WHAT IS IT?

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Abstract: As foundation design becomes more structured by codes the question of axial strength definition becomes more important. Most deep foundation elements, when tested to soil failure, do not exhibit a clearly defined failure load. But the design procedure requires that a specific ultimate capacity be taken from the load test results. The load test result is also affected by the procedure used in load testing and particularly by the loading rate. Loading procedures are discussed and suggestions are made for standardization of these procedures. Failure load definition is also discussed and some commonly used methods are reviewed. It is suggested that more consideration should be given to the requirements of the structural engineer and that load testing and load test result evaluation methods should be standardized.

INTRODUCTION

Capacity is usually the basic consideration in the design of deep foundations. But, what exactly do we mean by capacity? The basic function that is usually assigned to a deep foundation is to transfer a load to deeper, stronger soil layers or in a few cases to limit and control settlements in soft soils. We presume that if the foundation has inadequate strength it will displace, probably slowly, into the ground. However, to make design decisions we must have a precise definition of inadequate strength and thus we imply that the foundation will be adequate until some load level is exceeded at which point it will fail. The nature of structural design is such that this approach is necessary. However, the determination of strength is not so simple and clear cut.

Structural design was converted to Load and Resistance Factor Design (LRFD) in several design codes beginning in the early 1960's. This approach to design has developed into a procedure where failure modes are considered separately from

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serviceability limits and in some countries it has become known as Limit States Design. However, until recently LRFD was not used for the design of any geotechnical facilities in the United States. Today, LRFD is used in foundation design in the design codes of AASHTO, ACI, AISC, and PDCA in the United States. Design codes based on LRFD are also available in Canada, Australia, and the European Community.

When LRFD is used it is implied that well-defined methods are available to determine strength. In the case of deep foundations, there are two failure modes due to axial loads, structural failure and soil failure. Structural failure can be reliably predicted with currently available methods for strength prediction from structural design methods. This paper is primarily concerned with the definition of failure as limited by soil failure.

Of course, axial strength is not the only design limitation. Other considerations include lateral behavior, settlement, downdrag, etc. These considerations may be considered to be strength limitations or they may be performance limitations that do not include failure but only some type of unsatisfactory performance. The latter type of limitation is referred to as a serviceability limit state. In this paper, limit states other than the axial strength due to the soil failure condition will not be considered.

Deep foundation design, installation, and quality control is unusual in that it is possible to statically test to failure and if the failure is a soil failure, certainly the most common case, the pile can still be used in service. The load is applied to induce some substantial displacement and when removed a portion of the displacement is recovered. If a still greater load is applied the load-displacement curve will approximately follow the previous unloading curve and then may continue to higher loads and displacements. An example of this type of load test curve with multiple load cycles is shown in Figure 1. In other cases, the load displacement curve may be nearly plastic as illustrated in Figure 2.

TESTING PROCEDURE

Given the conditions of Figure 1, how should the load test be performed? Thirty years ago the most common load test procedure was to impose an increment of axial load and hold it for an extended period of time after displacement stopped (or became less than a specified level). The load increments applied were a fairly large fraction of the design load. Due to the long hold periods the time required to perform the test was measured in days. This required 24 hour monitoring of the test operations and, thus, the cost of the test was increased as was the possibility of an error in the test performance. When field tests must be monitored 24 hours a day it can become difficult to staff the test and it may be necessary to use less well-qualified test personnel. The performance of a good quality load test requires engineers and technicians that are well trained in the performance of the test.

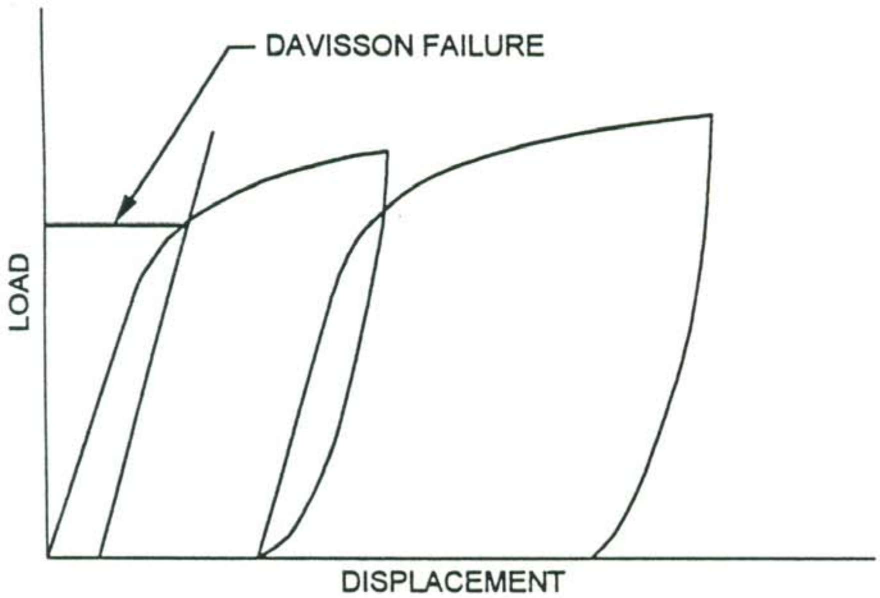

Figure 1 Load Test on Primarily End Bearing Pile in Sand with Two Loading Cycles.

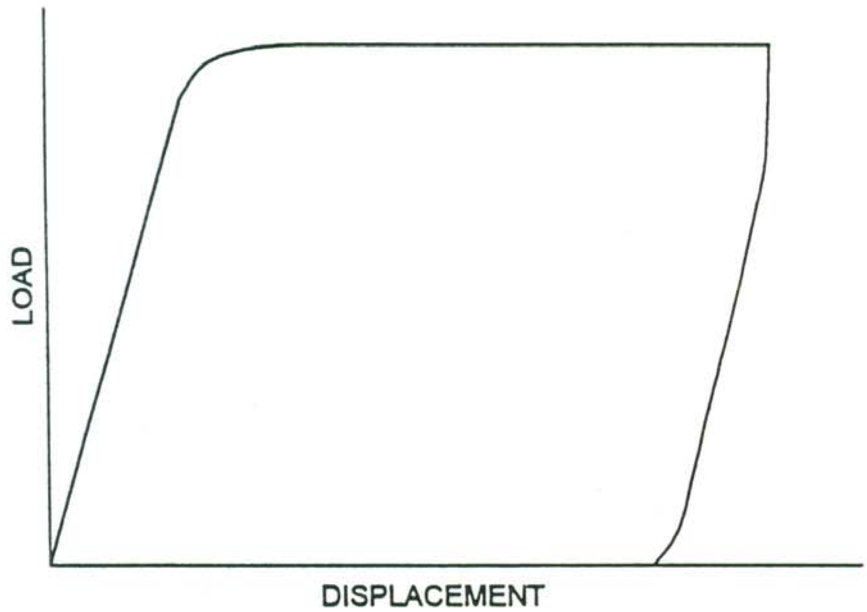

Figure 2 Load Test on Friction Pile.

If a large increment of load is applied at widely spaced time intervals there is a tendency for failure to occur at the level of load application. A particular load level is carried. The next level is applied rapidly and the load level is reached followed immediately by gradual pile failure. This behavior may bias the test result.

During the early days of the research project at Case Western Reserve University (Goble et al 1975) Constant Rate of Penetration Tests (CRP) were used extensively. In this test procedure, a particular, continuous rate of displacement is selected and imposed at the pile top. Such an approach is attractive, particularly to the structural engineer since it is similar to procedures used for testing structural elements in the laboratory. Rate of displacement for pile testing is not easily selected and if the rate is fairly fast the capacity can depend on the rate with increased capacities at higher loading rates. A CRP test has the additional disadvantage that it is difficult to explain to typical field personnel that must execute it. Then test specifications appear in which unnecessary complexity in testing procedures are specified. For example, specifications have been used in which a non-pulsating pump is required. During the Case Project it was found that such refinements were unimportant. This should not be surprising since if this type of loading were critical deep foundations would be sensitive to vibration and such considerations would have to be considered in design.

Modern practice in the United States has moved to a test procedure where the load is applied in smaller, closely spaced intervals. ASTM D1143 includes the specification of a Quick Load Test Method in which the load is applied in increments of 10 to 15% of the proposed design load and held for a 2-1/2 minute time interval. With this approach a test is usually completed in one to two hours. Such a test procedure is easily defined for the field personnel and it will probably be applied correctly.

In the recent past, it has become more common in Western Europe to perform static load tests where the loading rate is controlled, frequently with feedback controlled systems. It is argued that such a system type is required to obtain meaningful results. This topic has become of great interest among European foundation engineers. Because of the difference in pile stiffness the selection of a loading rate is complex. If soil failure is limiting it would be desirable to use a reasonably constant rate of loading of the soil. A very flexible pile will load the soil more slowly than a very stiff pile for a given rate of pile top displacement.

The selection of loading rate is important because time dependent effects can influence the definition of pile capacity if widely varying loading rates are used. An example of this problem is shown in Figure 3. First, a maintained load test was performed on this driven pile located in West Palm Beach, Florida (Goble and Likins 1973). The 18-inch prestressed concrete pile was driven through silica sand to a blow count of 40 blows per foot at a depth of 35 feet. After completion of the maintain load test a CRP test was performed with a rate of 0.02 inches per minute. This rate was taken from experience testing steel piles that was considered to be successful. Figure 3 shows the large difference in the failure load between the two tests. This problem seems to be more serious accentuated in this case where the pile is lightly loaded and, therefore, relatively stiff compared to the soil. In addition, it is quite short and this accentuates the problem.

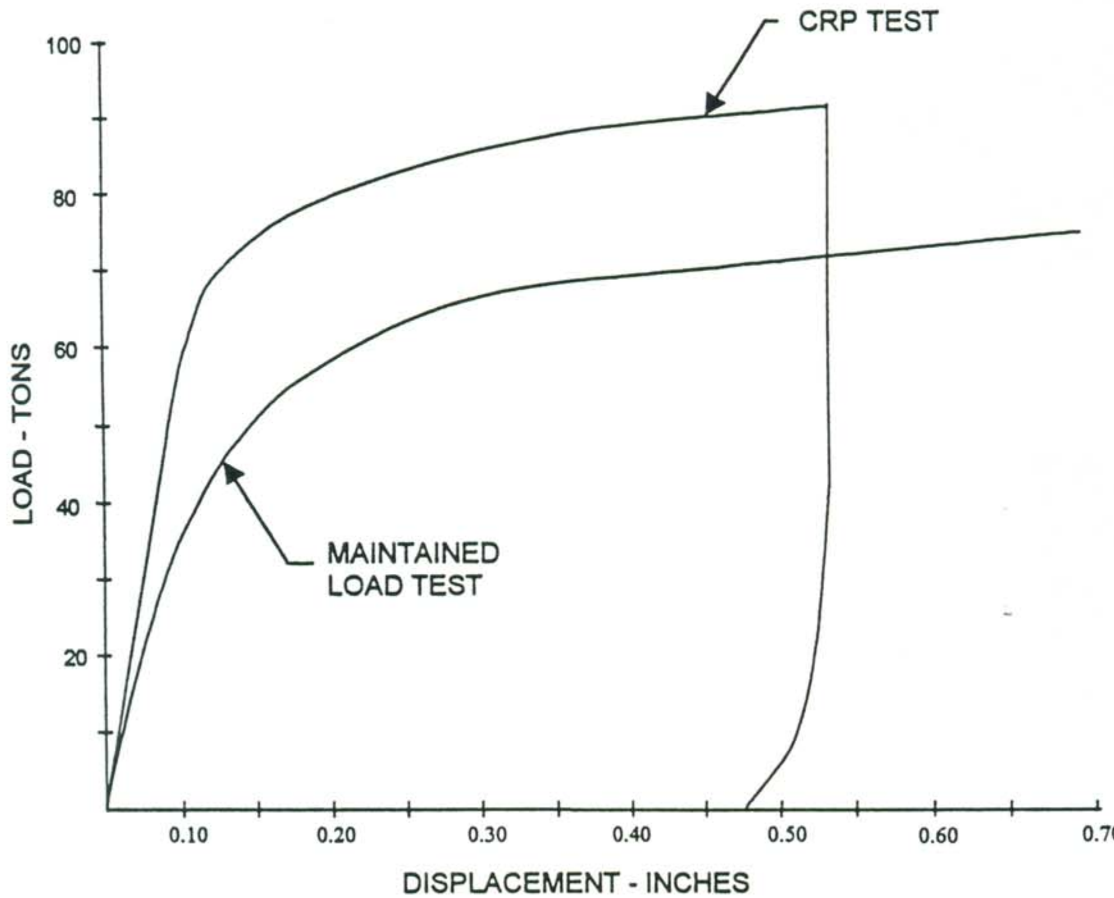

Figure 3 Static Load Test Results for 18 Inch Square Concrete Pile by Two Test Methods.

The failure load was reached in about five minutes in the CRP test with this loading rate. The use of the ASTM Quick Test procedure can provide a simple approximate control of loading rate. Since load increments are selected as fractions of the design load the time to failure will be approximately constant for a given factor of safety. In the example of Figure 3, the time to failure would have been on the order of 45 minutes or more. Had the test have been performed at that rate the load test curve would have probably more nearly followed the path of the maintained load test.

It would be useful to perform some load tests on a single pile at a variety of rates to try to quantify the loading rate where the strength is no longer strongly sensitive to rate. If such tests were performed for a variety of soils it would give an idea of the sensitivity of the test result to loading rate.

Longer holding times for the loads have been popular. The goal of such test methods has been to obtain a measure of long term behavior. However, a test of two or three days will not measure settlement behavior since a much longer loading period is required. It is important and advantageous to use the same loading procedure for all tests to make the comparison of results easier.

What can cause problems in pile load testing? The load must be accurately measured. This implies that a load cell should be used. The load cell must be treated as a sensitive measuring instrument and it must be re-calibrated frequently. Today the use of load cells has become quite common. These load cells are usually of good quality and can be expected to give good results. The use of jack pressure has been shown to under-measure capacity due to jack friction (Fellenius et al, 1983).

Displacement must be carefully and accurately measured with the gages supported on unyielding supports that are unaffected by the motion of the test pile. Displacement measurements are sometimes quite inaccurate due to non-rigid supports for the displacement measurement transducer, slack in the displacement system and other problems. Inaccurate displacements can produce large changes in the defined failure load for most of the evaluation procedures. Errors in either load or displacement measurements can seriously effect the defined capacity. A static load test requires care in its performance if it is to produce accurate results.

Perhaps the most serious problem in all of static load testing is the failure to continue the loading to failure. A distressing percentage of all pile load tests are performed to only twice the design load. If failure does not occur the test is deemed a success and production pile installation begins. It is entirely possible that the pile failure load may be several times the required ultimate load. Less stringent installation criteria could be used in such cases. All load tests should be carried to the highest load possible.

LOAD TEST EVALUATION

Some load test curves will have a sharply defined failure such as illustrated in Figure 2 and the failure load is easily defined. The example load test curve of Figure 1 does not have a well-defined failure load and this is the more common case. However, it is necessary that a defined failure load be obtained from the test data. A large number of different failure criteria have been proposed for determining the "ultimate" capacity of a deep foundation element. In fact, in most cases, a true ultimate capacity does not exist. Particularly for deep foundations where there is substantial toe capacity, the load test will exhibit considerable strain hardening.

As a graphic example, the Michigan State Highway Commission (1965) reported that one static load test was carried to a displacement of about two feet. At the end of this large displacement the load had approximately doubled beyond the point on the curve where the stiffness showed a large decrease. This characteristic becomes more pronounced as the deep foundation element increases in diameter. In some large drilled shafts with tips in sand the test load displacement will be strongly rounded with a very large displacement required to even approach something like ultimate load. It is important that a larger view be taken in the evaluation of the load test result and maybe one that is more in agreement with the evaluation of other construction materials such as steel or concrete.

It is important that the requirements of the structural engineer be considered since the performance of the foundation is often limited by the requirements of the structure. In past and current practice there is usually limited communication between the structural and geotechnical engineer and often the one has little understanding of the requirements of the other. Consider two examples, pile support in the design of a commercial building and a freight-handling wharf. In the case of the commercial building, the ratio of dead to live load on the foundation will be large. On the other hand, the wharf dead load will be very small, so the forces designing the piles will consist mostly of live load. Thus, the commercial building load can be determined quite accurately and a smaller factor of safety is justified. (Remember that part of the factor of safety belongs to the structural engineer.) For the wharf, the design load will be almost entirely live load and it can be highly variable. A larger factor of safety is appropriate. In the case of the commercial building, the tolerable settlement may be quite small while the dead load on the wharf will be small producing little settlement and, in addition, the structure may be quite settlement tolerant.

Test Evaluation Methods

The Offset Method (also referred to as the Davisson Method) defines failure as the intersection of the elastic stiffness of the pile (PL/AE) drawn through an offset on the abscissa that depends on the pile diameter. The method is mostly, but not completely, independent of judgement since the elastic modulus of the pile material, particularly for drilled shafts may not be easily established. Since the offset is defined by the pile diameter the capacity is dependent on the pile diameter.

The Diameter Ratio Method is particularly popular in Europe. The failure load is defined as the load associated with a pile top set of 10% of pile diameter. This method yields relatively high failure loads particularly for large diameter piles. It does not make much sense for the structure that larger displacements are tolerated when the foundation pile diameter is increased. Obviously, this method favors large pile diameters.

The Chin Method assumes that – at least near the failure load – pile top deflection and the quantity pile top deflection divided by pile load fall on a straight line and that therefore the load-set curve is a hyperbola. The inverse of the straight line defines the failure load. In many cases failure is extrapolated using this method. Probably, among the most commonly used methods in the world, the Chin method produces the highest capacity value of any method for a given load set curve. It is frequently used in the Far East.

Kulhawy, (1997) has suggested that the load test curve be defined by two linear portions at the beginning and at the end with a curved portion between. The portion between the two straight lines is defined by the points and the slopes at the junctions between the straight and curved portions. This recommendation was developed for use with drilled shafts and Kulhawy reports that available drilled shaft data fits this description very well. Rather predictable relationships between the transition points are reported based on available data.

The Fixed Total Set Method is proposed as a means of being more responsive to the requirements of the structural engineer. The pile capacity is defined by three points on the load test curve. With this data, the structural engineer could specify an appropriate displacement where the capacity is defined. For example, failure may be defined at a pile top set of 25 mm. This method is quite simple and reasonable. The absolute value at which capacity is to be taken may be variable or several values may be picked from the load test curve as an indication of elasticity and plasticity of the load set curve. (For example, loads may be picked at pile top sets of 20, 40 and 80 mm. A plunging pile would then be characterized as 900/1000/1020 kN while a displacement pile in granular soil could have a test load result of 800/1100/1250 kN.) This method would form a basis for a rational way in which the interaction of structure and foundation can be calculated. To the authors knowledge, this method of characterizing pile capacity with several values has not been utilized to date.

CONCLUSIONS

Pile design is continually being refined and improved and pile design capacities are increasing. As the process is refined it is appropriate that methods for performing and evaluating the results of static load tests should become more standardized. Some load testing and evaluation methods have been summarized and discussed critically. As a minimum, some limits should be placed on loading rates to limit the effect of time dependent deformations. Selected methods of load testing must also be selected with consideration of the practical problems that arise in the field.

The method that is used for evaluating the load test result must also be standardized. A major consideration in selecting the evaluation method is the requirements of the structural engineer.

APPENDIX-1

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