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Test Loading of Piles and New Proof Testing Procedure

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Introduction

Piles are test loaded for three main purposes:

1. As part of a research investigation. The results of the test are to be used for improvement of the general knowledge of pile behavior, and furnish data to be compiled with data from other investigations.
2. As a part of a field investigation at a particular site prior to the driving of the contract piles. The results of the test are compiled with a soil investigation and are the basis for the recommendations for the contracting work.
3. As a check on contract piles during or after the installation of these piles (proof testing) and as a part of the pile inspection. Normally, the test piles are chosen at random. The aim of the test is mainly to ascertain a minimum bearing capacity of the tested piles.

This paper deals exclusively with test loading performed by reasons 2 or 3. Many different test methods are used in the current practice. The most commonly used test method in North America is the one recommended by the American Society for Testing and Materials (ASTM) (12), which is a slow Maintained-Load test (Slow ML test). Another well-known test is the Constant-Rate-of-Penetration test (CRP test) but this test is not used in North America to any large degree. A third test method is the cyclic procedure. These three methods can be said to represent basic test types. However, there are almost an indefinite number of methods, which lie in between and combine some features of the aforementioned procedures to various degrees. The most important of these is the Quick ML test.

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Current Test Methods

Slow ML Test.—The ASTM Designation D 1143-69 (12) recommends a slow ML test, where the pile is loaded in eight equal increments to 200% of the anticipated working load of the pile. Then, the load is removed in four equal decrements. Each load is to be maintained until the rate of settlement has decreased to 0.001 ft/hr (0.3 mm/hr), i.e., 0.002 in./10 min (0.05 mm/10 min) or for 2 hr, whichever occurs first. The 200% load is to be maintained for 24 hr. The test will take about 70 hr or more to perform, depending on conditions.

There are many currently used modifications to the ASTM prodecure. For instance, the method of equilibrium according to Mohan, et al. (13), where the jack piston is locked once the load increment is reached and the load (jack pressure) is allowed to drop to an equilibrium value. This is a highly recommendable modification, as it reduces testing time without impairing the results of the test.

The settlement criterion of 0.002 in./10 min (0.05 mm/10 min) is often referred to as the "zero settlement." It may be pointed out that this "zero" is misleading, as the settlement rate is still equal to about 7 in./month (180 mm/month) or 6 ft/yr (1.8 m/yr).

CRP Test.—The constant-rate-of-penetration method (CRP) is the reverse to the ML method. The CRP test is presented by Whitaker (20,21) and Whitaker and Cooke (22). In the CRP test, the pile head is forced to settle at a predetermined rate, normally 0.02 in./min (0.5 mm/min) and the force that is required to achieve the penetration is recorded. The test is carried out to a total penetration of 2 in.-3 in. (50 mm-75 mm) or to the maximum capacity of the reaction arrangement, which means that the test is completed within about 2 hr-3 hr. The Swedish Pile Commission (15) has published a detailed standard for the performance of routine CRP tests. The New York State Department of Transportation (16) recently published a manual containing, among others, a standard for the CRP test.

The CRP test will provide some important information, when carried to failure, i.e., from the shape of the load-movement curve, the behavior of the pile as an end-bearing pile, a friction-pile in sand with more or less end-bearing resistance, or a friction-pile in clay can be evaluated (see Fig. 1). To perform a CRP test, a pump that can provide a constant and nonpulsing flow of oil is imperative. Ordinary pumps with a pressure holding device, manual or mechanical, are not suitable. Garneau and Samson (8) have described a simple pump arrangement for the performance of CRP tests.

Swedish Cyclic Test.—Many tests can be described as cyclic. A simple cyclic procedure is to unload the pile at a few or at all load levels in the Slow ML test. However, a loading is not truly cyclic unless the pile is unloaded and reloaded repeatedly. Weele (19) has presented a method based on the Slow ML procedure, but combined with repeated loading and unloading cycles at each load. The aim of this test is to separate shaft-resistance from end-resistance. The test duration is considerably longer than that of the ordinary Slow ML test.

In Sweden, a different cyclic method has been used, which takes 40 hr-60 hr to perform. Broms (2) has presented several results obtained from such cyclic loadings on piles. In the Swedish cyclic test, the pile is first loaded

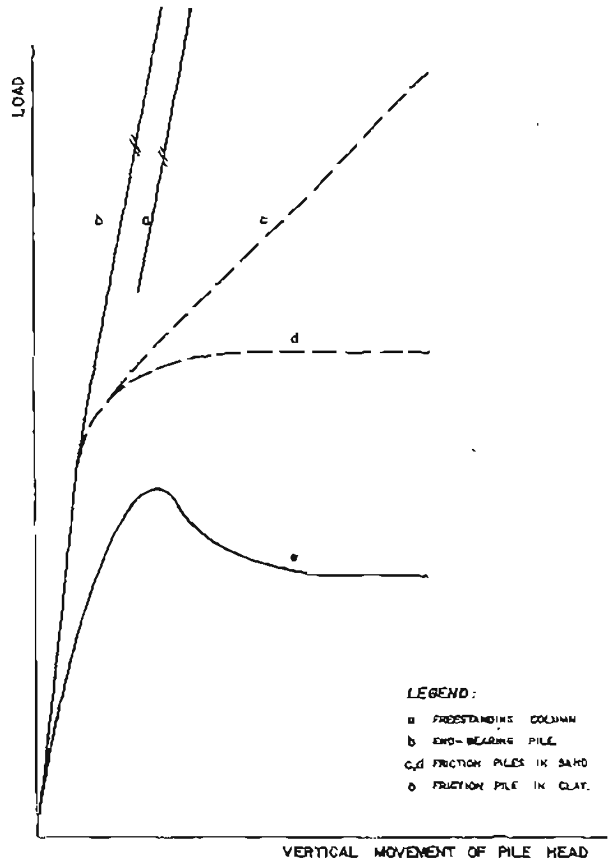

FIG. 1.—Typical Load-Deformation Curves Obtained in CRP Test (15)

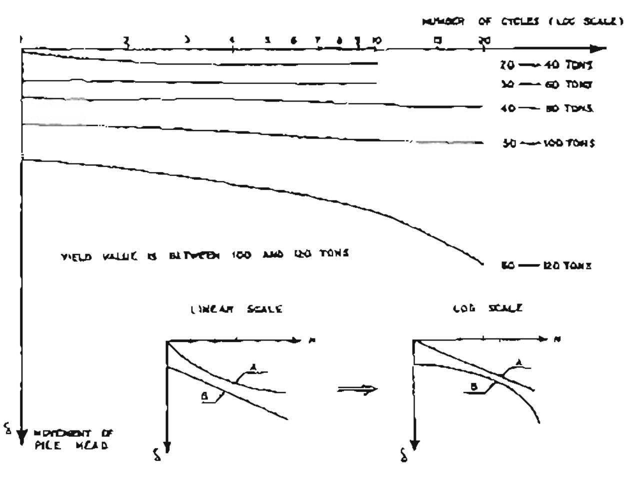

FIG. 2.—Semi-Log Plot of Results from Swedish Cyclic Pile Test

to a certain small load, equal to about one-third of the anticipated allowable load of the pile, e.g., 40 tons (360 kN). It is then unloaded to one-half of this value, i.e., 20 tons (180 kN). This is repeated 20 times (10 times for the first few load levels) and as each individual cycle takes 20 min, the loads will be 50% higher than in the first, i.e., in the example, a high load of 60 tons (540 kN) and a low load of 30 tons (270 kN). This goes on in cycles 20 tons–40 tons, 30 tons-60 tons, 40 tons-80 tons, 50 tons-100 tons, 60 tons-120 tons, 70 tons-140 tons, 80 tons-160 tons, etc., with 20 cycles for each load combination until "failure" is reached (1 ton = 8.9 kN). During the first cycle phases, the additional movement for one cycle is lower than that of the preceding cycle. As the cycle loads are increased, the additional movements become larger, and at large loads, finally, the movements will increase at an accelerating rate. There is one cycle phase in the test, when the additional movement is approximately equal to the preceding movement. The high load in this particular cycle phase is called the "yield value." When plotting in a diagram, the movements for each cycle phase versus number of cycles, the yield value can be determined by interpolation. However, as the actual value can be difficult to determine, the Swedish Pile Commission recommends to plot the movements versus logarithm of number of cycles as shown in Fig. 2. The yield value, when interpreted according to this plotting method, has the advantage of being less dependent on the judgment of the interpreter, as opposed to plotting the number of cycles on a linear scale. As shown in the two scale illustrations in Fig. 2, the yield value obtained from a semi-log-plot is also somewhat smaller than the one obtained from a linear plot. More important, the yield value is normally smaller than the ultimate capacity, as the shaft resistance of the pile is reduced by the cycling.

Quick ML Test.—The Quick ML test is comparable to the CRP test in the sense that it also eliminates the influence of time-dependent movements of the pile, which are measured in the Slow ML test. The pile is usually loaded to 300% of the anticipated allowable load in 20 small increments, each equal to 15% of the allowable load. Each load is maintained for a period of 15 min with readings taken every 3 min and the total duration of the test is 3 hr-5 hr.

Field experience has shown that the initial parts of the load-settlement curves of the CRP test and the Quick ML test agree closely. Often the two methods are combined. Then, one starts with the Quick ML test and shifts over to the CRP test, when the rate of movement of the pile head is approaching 0.02 in./min (0.5 mm/min), i.e., when failure is imminent. However, a special pump is needed for this combination, which can maintain a constant pressure alternating with a constant flow without changes in oil pressure.

Comparison of Test Methods.—The aforementioned test methods are compared in Fig. 3 for a time duration point of view. One immediate conclusion drawn from the set of curves is that when time is imperative, the more time-consuming tests, i.e., the Slow ML and the Cyclic tests, should be clearly justified before choosing them instead of one of the quick tests, i.e., the CRP and the Quick ML tests. The direct cost of an extra day testing is about $400–$700, not counting additional cost due to the delay of work and the delayed answer to the question of allowable bearing capacity of the piles.

Fig. 4 presents a comparison of typical load-movement curves on a friction pile in clay. The shape of the CRP curve is well defined and relatively easy to study. The shape of the Quick ML curve agrees well with the CRP curve before reaching the peak value. the Quick ML test curve shown illustrates how, as generally happens when testing shaft bearing piles to soil failure in clay, the pile head suddenly moves when the last load increment is applied and thus partially releases the load applied to the pile head. The following dotted line portion of the curve indicates approximately the subsequent part of the curve, which cannot be measured due to the rapid development. The subsequently reduced load on the pile is practically stable, i.e., an equilibrium is reached. The continued curve shows how the load is increased up to a certain

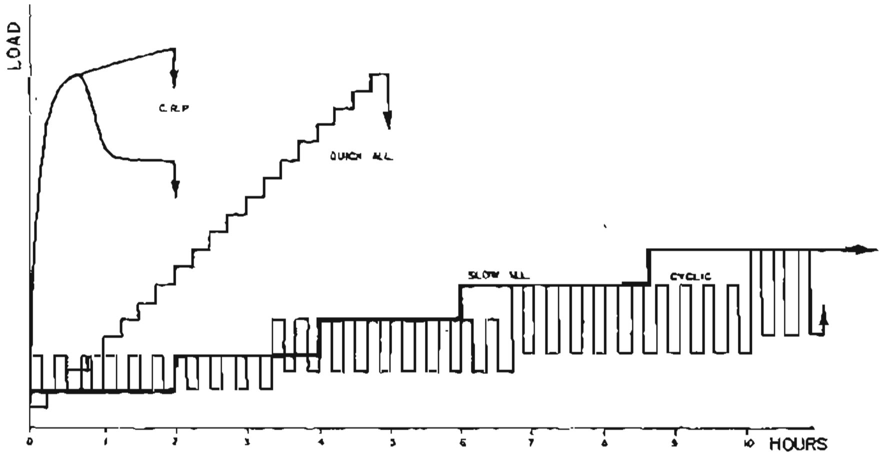

FIG. 3.—Comparison of Required Time for Four Test Procedures

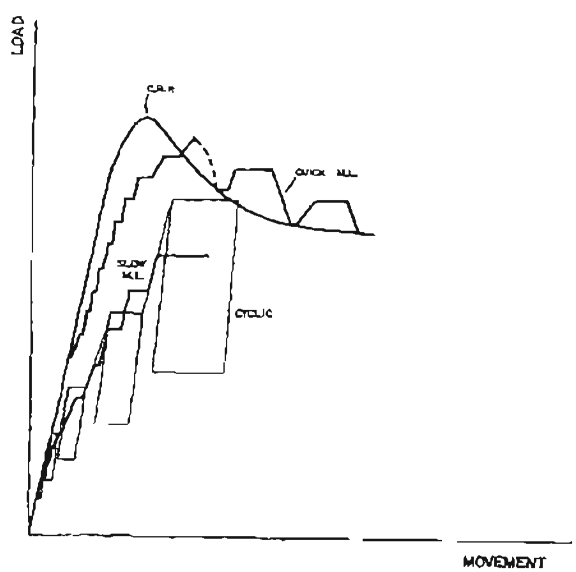

FIG. 4.—Comparison of Typical Load-Movement Behavior for Four Test Procedures

value, which is held constant by continuous pumping. Upon discontinuing the pumping, the load again drops to an equilibrium value. By repeating this procedure, a couple of equilibrium values are obtained, which lie approximately on the CRP curve. Thus, also the Quick ML test can be used to provide indication of the behavior of the pile as shown for the CRP test in Fig. 1. However, the peak value is lost. If the testing equipment allows, it is better to shift from the Quick ML test to the CRP test, when approaching the peak load.

A third curve in Fig. 4 shows the typical results of a Slow ML test. This test is normally only inadvertedly carried to failure and consequently, it shows nothing more than that failure has not occurred. Also, the shown plot of the cyclic test gives very little information. The results of the cyclic test are to be interpreted from a plot as shown in Fig. 2.

Pile tests carried out as a part of a field investigation prior to the installation of the actual contract piles should, on most occasions, be carried out to the ultimate failure—soil or pile failure, or to at least three times the possible maximum allowable load. Also, the test should provide information on the

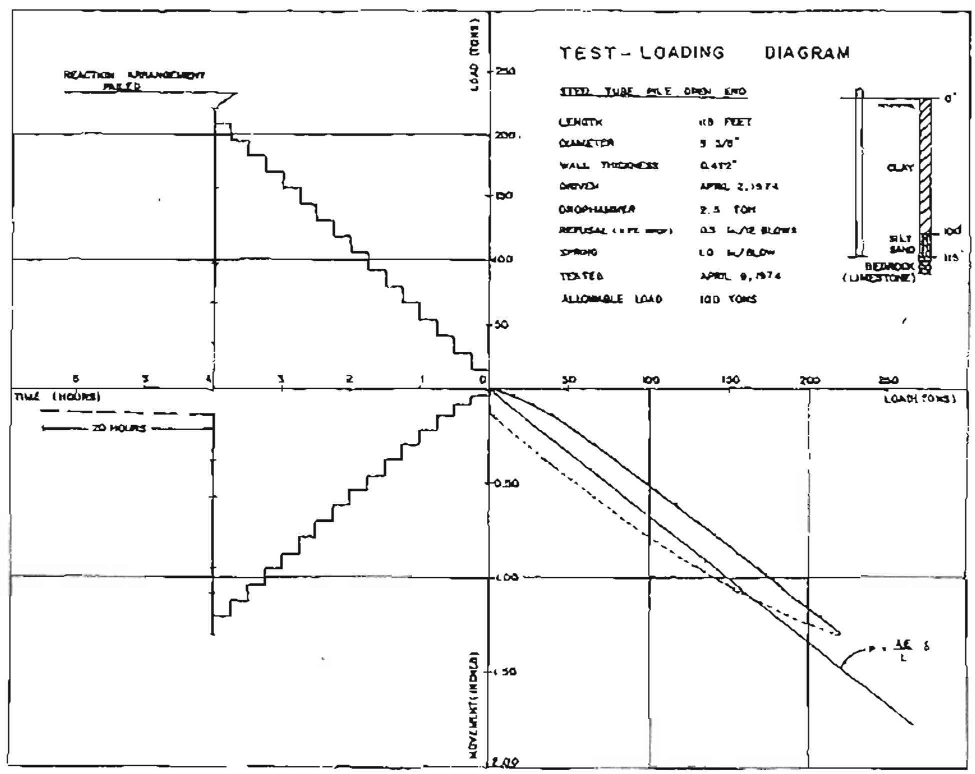

FIG. 5.—Presentation of Results from Proof Testing Pile According to Quick ML Method

behavior of the pile. In comparing the test methods, it is obvious that the ultimate failure load and information on the behavior of the pile are most readily obtained by the CRP test.

Next in practical value comes the Quick ML test, though the true value of the ultimate failure load for friction piles in clay, where the peak of the load-settlement curve is lost, could be difficult to decide. However, this test is easier to perform than the CRP test due to less rigid requirements for simultaneous readings, which are particularly difficult to perform if the pile is instrumented. Fig. 5 presents an example of a Quick ML test performed for proof testing reasons. The given diagrams are the load-movement, the load-time, and the time-settlement diagrams. Also the basic pile and soil data are given in order to summarize the test results. The pile has an obvious larger capacity than the maximum test load of 200 tons (1,800 kN) and therefore it was accepted for the intended design load of 100 tons (900 kN) despite the failure of the reaction arrangement before reaching the 250-ton (2,200-kN) test load. The Slow ML test would have taken an additional testing time of 70 hr without providing any additional value to the question of the acceptance of the pile.

Cyclic tests are only recommended on very special circumstances as the cycling changes the pile behavior so that it is different than the original pile. Also, such tests are expensive and time consuming and rarely provide useful data, as compared to a test without unloading cycles. The Swedish cyclic method can be justified when the available reaction load is insufficient to reach the ultimate capacity and when the end-bearing capacity is the important factor in combination with an allowable load consisting of mainly transient loads.

There are three justifications for the Slow ML method: (1) The method is familiar to most engineers; (2) the interpretation after the measured gross and net settlements as, e.g., in the National Building Code of Canada (14) is simple; and (3) the method does not require any special equipment and skill to perform. Often it is said to furnish information on expected settlements; but this is highly questionable, as settlements obtained from a short-term test (24 hr or 48 hr is short) on a single pile do not say anything about settlements for a pile group nor even about neighboring single piles.

INTERPRETATION OF TEST RESULTS

The interpretation of failure value from a test loading is subject to some confusion, which is understandable because "Load tests do not provide answers—only data to interpret" (4). The peak obtained in the CRP test can be defined as representing the ultimate failure value, but such a peak is normally only clearly obtained for friction piles in soft or loose soils. Generally, certain simple approaches have to be used in order to find a value for the "failure" load.

The Swedish Pile Commission (15) suggests a so-called 90% criterion, presented by Brinch Hansen (1), which defines failure as the load that gives twice the movement of the pile head as obtained for 90% of the load. The criterion is proposed for CRP tests irrespective of the soil and is shown in Fig. 6(*a*). The criterion, which is based on the assumption that the test curve is hyperbolic at failure, has the advantage of giving reasonable results and, more importantly, providing reproducible values independent of the judgment of the interpreter.

For the interpretation of a Slow ML test, De Beer (5) plots the load movement values in a double logarithmic diagram, where the values can be shown empirically to fall on two straight lines as shown in Fig. 6(*b*). The intersection of the lines corresponds to the failure value. As pointed out by De Beer, the interpreted failure value is conservative, and should not be called ultimate failure. In a paper by De Beer and Walays (6) several examples of this interpretation method can be studied.

Housel (10) suggests use of a Slow ML method with a succession of equal load increments applied every 1.0 hr, and plots the movements of the pile head, obtained during the last 30 min of each load, versus the applied load.

As shown in Fig. 6(*c*), the 30-min head movements falls on two approximately straight lines, intersection of which is the failure value, termed yield value. Stoll (17) has presented examples of this interpretation method.

The failure loads according to the three previous methods are interpolated from the loads applied on the pile. Mazurkiewicz (11) proposes a method that allows the failure load to be extrapolated, even if the maximum test load is smaller than the failure load. Fig. 6(*d*) shows how a set of equal pile head movement lines are arbitrarily chosen and the corresponding load lines are constructed from the intersections of the movement lines with the load-movement

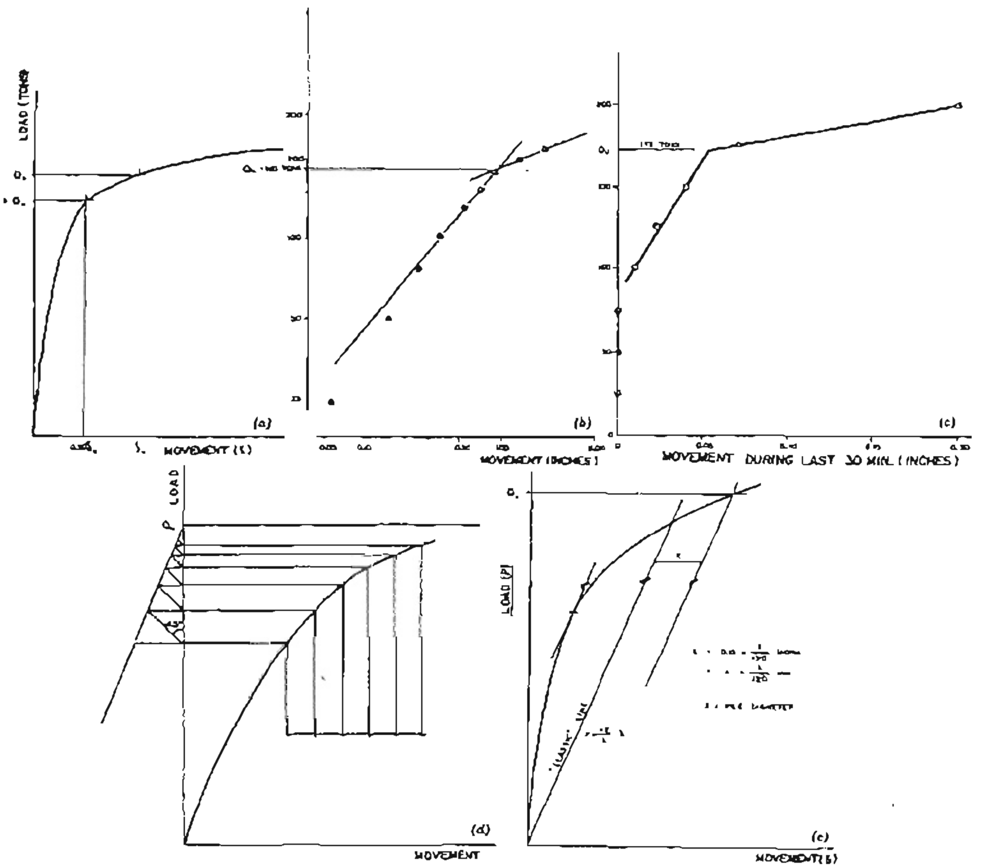

FIG. 6.—Interpretation of Failure Load According to: (*a*) 90% Criterion (15); (*b*) De Beer (5); (*c*) Housel (10); (*d*) Mazurkiewicz (11); (*e*) Davisson (4)

curve. From the intersection of each load line with the load axis, a 45° line is drawn to intersect with the next load line. These intersections fall approximately on a straight line, the intersection with the load axis defining the failure load. This method is based on the assumption that the load-movement curve is parabolic at failure.

Often, a load-movement diagram shows, more or less distinctly, an initial straight line followed by a curved transition to a steeper straight line. The intersection of the two straight lines can be defined as the failure load, better named the critical load. Fig. 7 shows actual test results from a 130-ft (40-m) long 12-in. (300-mm) concrete pile driven through loose silt and sand into dense

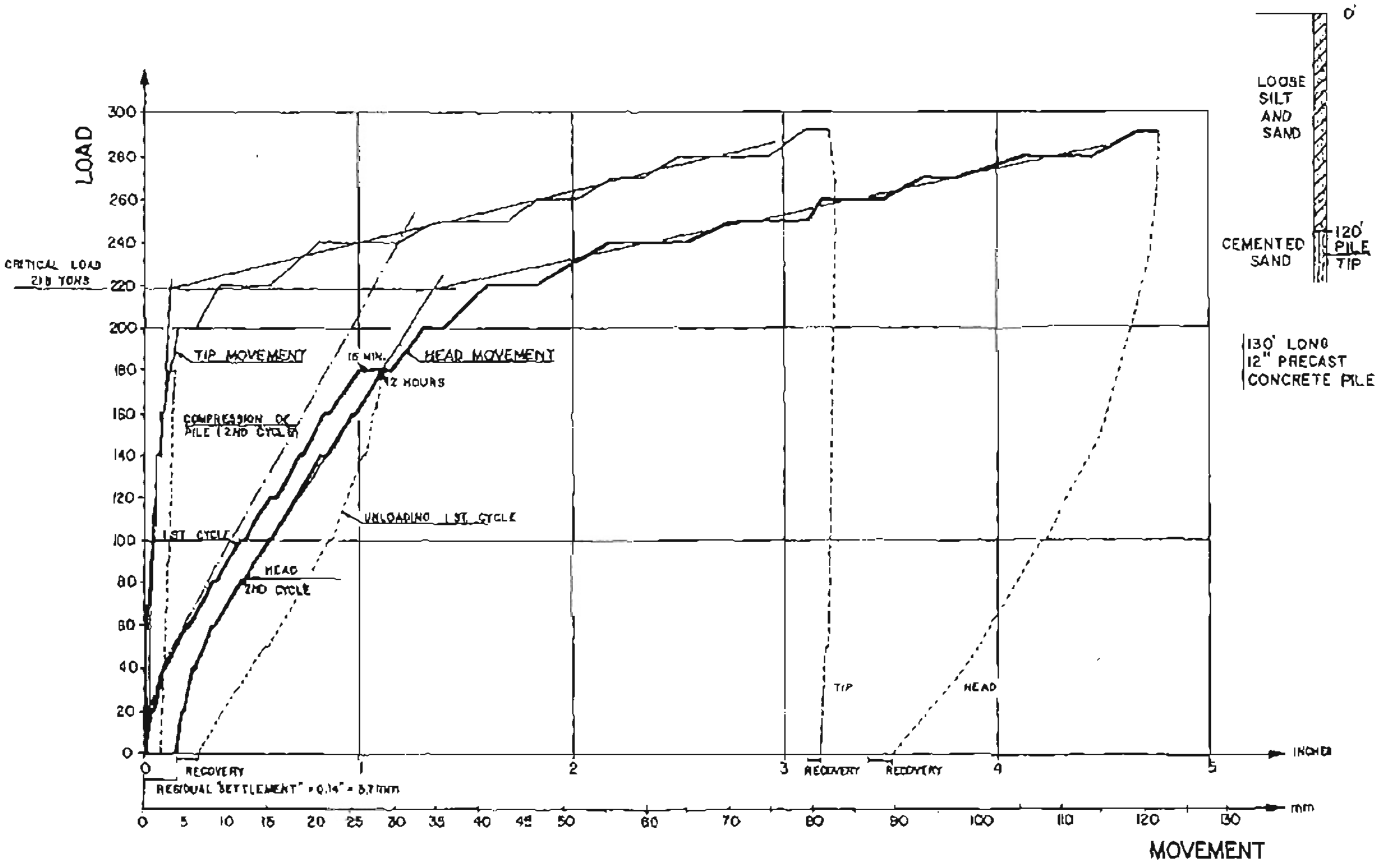

FIG. 7.—Illustration of Critical Load Concept and Measurement of Tip Movement

slightly organic cemented sand. The testing method, which was used for this pile test, is a combination of the Slow and Quick ML test. The pile was first loaded up to 180 tons (1,600 kN), which was kept on the pile for 12 hr, whereupon the pile was unloaded and then reloaded to plunging failure.

This test was made more elaborate than is usually the case by also measuring the tip movement of the pile. This addition provides very useful data for the study of the behavior of the pile.

The difference between the tip movement and the movement of the pile head gives the compression of the piles. After about a 60-ton (530-kN) load, the compression follows a straight line, indicating that after this load the additional applied load is unrestricted by shaft friction and goes straight to the pile end. The line of pile compression is, from this point on the curve, parallel to the elastic line. Trow (18) has shown mathematically that when the load-movement curve becomes steeper than the elastic line, the additionally applied load goes unrestricted to the pile end. This is verified in this test.

The tip movement curve in Fig. 7 shows that the critical load corresponds to the point where the pile-end starts moving appreciably. The plunging failure of close to 300 tons (2,700 kN) is obtained at a too large movement to be an acceptable basis for any judgment of the pile capacity.

Fig. 7 shows further that the residual movement of the pile head after unloading from a 180-ton (1,600-kN) load is 0.14 in. (3.7 mm), while the residual movement of the tip is negligible (0.1 mm). The difference between the residual movements consists of remaining compression of the pile, due to the soil resisting the full rebound of the pile. This example illustrates the inadequacy of the concept of net or residual settlement for judging the acceptance of proof-tested long piles.

There are other methods for determining the failure load from the shape of the load-movement curve. For example, Chellis (3) and Fuller and Hoy (7) cite that the failure point is where the slope of the curve is parallel to a line sloping 0.05 in./1.0 ton of load (0.14 mm/kN) increase. However, this and the aforementioned methods of defining the failure value do not consider the length of the pile.

Davisson (4) suggests a method that includes the length of the pile, as shown in Fig. 6(*e*). The failure load is defined as corresponding to the movement, which exceeds the elastic compression of the pile, when considered as a free column, by a value of 0.15 in. (4 mm) plus a factor depending on the diameter of the pile. According to this definition, a 12-in. (300-mm) diam pile reaches failure at a pile head movement exceeding the elastic compression by 0.25 in. (6 mm). The method is suggested for application on results from Quick ML tests.

It is of interest to see how the quoted methods of determining pile failure compare. In Fig. 8, six applicable methods have been applied on the pile test, which was presented in Fig. 7. As shown, there is a considerable spread between the different failure values from Davission's 210 tons (1,900 kN)–280 tons (2,500 kN) for the 0.05-in./1 ton (0.14-mm/kN) method. However, it must be kept in mind that the test is a Quick ML test, and only the critical load and Davisson's methods are directly proposed for application on this test method. Fig. 9 gives an additional example, showing the load-movement curve of a 73-ft (22-m) long, 12.75-in. (324-mm) diam closed-end steel tube pile tested in a Slow ML test procedure. At a 215-ton (1,900-kN) load plunging failure occurred and the test was stopped. The actual evaluations of the test results, according to De Beer and Housel, were used in Figs. 6(*b*) and 6(*c*) and give failure loads of 185 tons (16,500 kN) and 172 tons (1,530 kN), respectively. The results of the interpretation according to the other cited methods are shown in the diagram. Thus, also in this test, a large scatter of failure values is obtained. Generally,

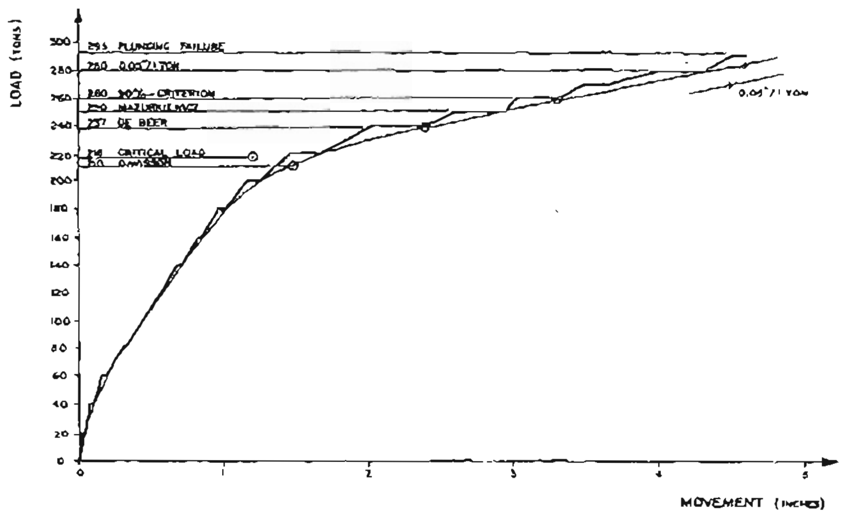

FIG. 8.—Comparison of Method of Determining Failure Load Applied on Test Results Obtained in Quick ML Test Presented in Fig. 7

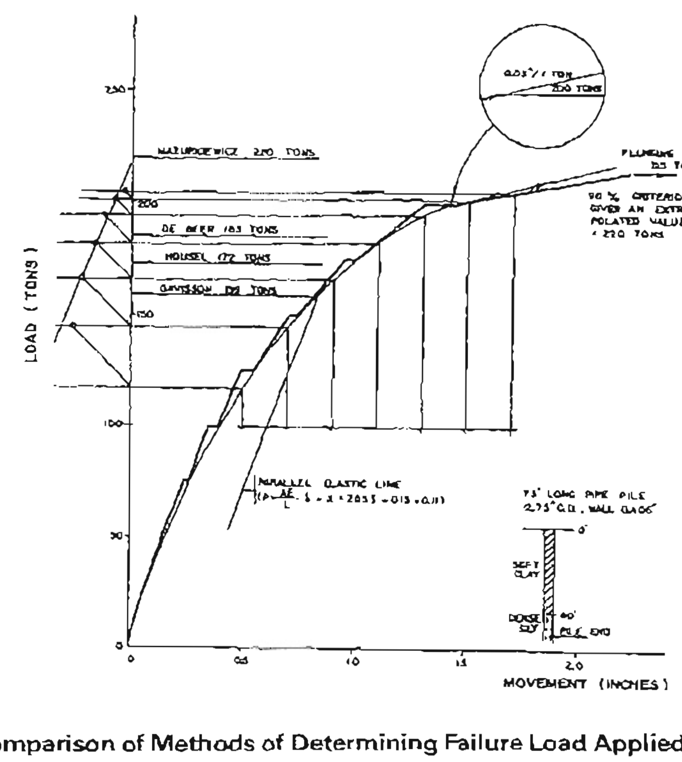

FIG. 9.—Comparison of Methods of Determining Failure Load Applied on Test Results Obtained from Slow ML test

when referring to test results, one is therefore well advised to state clearly how the failure in each case has been interpreted from the test data.

PROOF TESTING

When the aim of the test is limited to ascertain a minimum capacity, e.g., a check on contract piles, i.e., proof testing, almost any test method can be used. The Slow ML test is, as mentioned, the most commonly used procedure. However, the current acceptance criteria for pile tests do not consider the length of the pile. For instance, a long pile can show gross elastic movements exceeding those stated in the National Building Code (14), and, in unloading, the soil can prevent the full rebound and thus the net or residual movement could exceed the allowable. The bearing capacity of the pile can yet be sufficient.

A short pile may exceed failure at 200% allowable load, but may have settlements within the acceptance limits. Can we really accept a safety factor less than two against ultimate capacity on all such occasions?

An important reason, however, for the prevailing of the Slow ML test for proof testing of piles is that it is limited to twice the design load and thus the cost for reaction support, etc., is limited.

PROPOSED QUICK PROOF TESTING METHOD AND NEW ACCEPTANCE CRITERION

The writer proposes that the Slow ML test, currently used for proof testing of piles, be replaced by a Quick ML test. The proposed test procedure consists of loading the pile in 16 equal load increments to 250% of the allowable load with each load kept constant for 15 min. Thus, the duration of the test loading

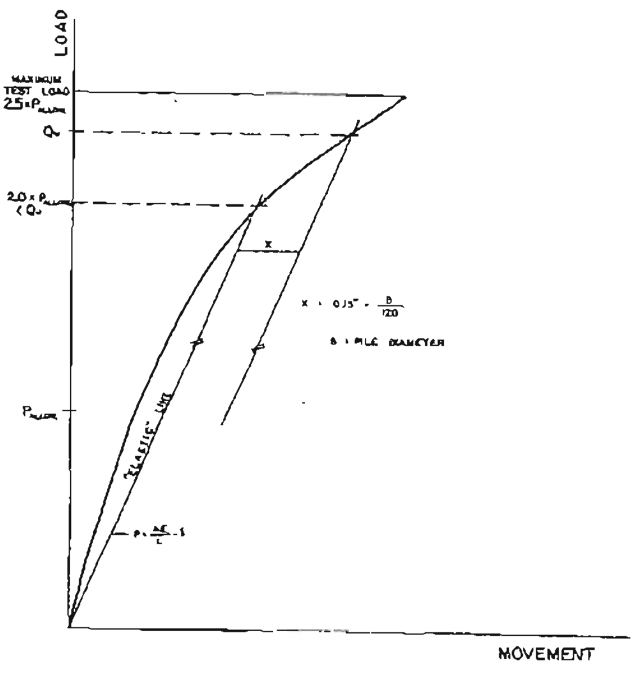

FIG. 10.—Proposed Acceptance Criterion for Contract Piles Proof-Tested According to Quick ML Procedure

is 4 hr. When the 250% load has been kept on the pile for 15 min, the pile is unloaded rapidly, stopping only momentarily to take readings of load and movement at approx 200%, 150%, 100%, and 50% load to obtain data to complete the load-movement curve with the rebound portion.

The proposed new acceptance criterion for the test is shown in Fig. 10. If the load corresponding to twice the allowable load is smaller than the failure load, as defined by Davisson's criterion, the pile is accepted.

The proposed test method is carried out to 25% higher maximum load than the current Slow ML test to give a better basis for the judgment than does a test stopping at 2.0 times the allowable load. This load increase does not involve any substantial extra cost. On the other hand, the Quick ML test provides considerable savings of time and cost, as it can be performed during an 8-hr working day.

The acceptance criterion permits the results of the test to be used for possible increase of the allowable load, and, should the pile not have the desired capacity, it also allows a determination of the new lower allowable load, which is not possible to judge from the Slow ML test.

Furthermore, the recommended new acceptance criterion accounts for the influence of the pile length, which the current criteria do not. It must be pointed out that the Davisson's failure value is conservative, as is shown in the comparisons given in Figs. 8 and 9. Naturally, when interpreting the results of a pile test experienced engineering judgment has to be exercised and the judgment not just based on the mathematically established failure value.

It is not necessary to reach the failure load in the proof testing, nor is the engineer restricted to apply the acceptance factor of 2.0 times the allowable load, as both higher and lower values can be incorporated.

SAFETY FACTOR

Assume that as a part of a field investigation, a test-loading has been performed showing an ultimate bearing capacity of 250 tons (2,250 kN). For this particular case, assume that a safety factor of 2.5 is called for and thus the allowable design load is 100 tons (900 kN). Naturally, all piles will not have the same failure load and thus the same safety factor. Therefore, we must accept that a few piles will not meet the demand for a safety factor of 2.5. The question is, "What is the limit"? If we state that only one pile out of a thousand may be allowed to have a smaller bearing capacity, for statistical reasons, we must aim for a very impractical ultimate capacity of the tested pile on the order of 700 tons-1,000 tons (6,000 kN-9,000 kN). If we accept one in a hundred, the aim can be set much lower. In fact, by stating a safety factor of 2.5 based on the results of a very limited number of test piles, we actually accept that a certain number of the foundation piles will have a smaller safety factor, about 1.5 or 1.8.

If all, or at least a much greater number, of the piles could be tested, the concept of necessary safety factor on the ultimate bearing capacity would have to be revised completely. And the true safety factor will most definitely be lowered to somewhere near the mentioned values of 1.5 or 1.8. Or to rephrase, the safety can be increased with, at the same time, a lowering of the safety factor. Such methods, based on the wave equation, are currently being investigated

(9), and will in due time become valuable tools for the engineer who is responsible for the design of a safe and economical pile foundation.

Summary and Conclusions

A presentation and analysis is given of four methods of test loading of piles: (1) The Slow Maintained-Load; (2) the Constant Rate of Penetration; (3) the Swedish Cycling; and (4) Quick Maintained-Load test methods, representing current methods of test loading of piles. It is claimed that on most occasions, where the test is a part of a field investigation or a proof testing, any one of the methods presented could be used equally well. Eight methods of defining pile failure are given and examined with examples from full-scale field tests, showing a difference of failure value on the order of 40% between the interpreted smallest and highest values.

The commonly used proof testing method and acceptance criteria are reviewed and proposed to be replaced by a Quick ML method to a load of 250% of the intended allowable load. The new acceptance criterion consists of the requirement that the gross pile head movement at a certain load, normally the 200% load, shall be less than the calculated elastic pile compression for this load and an additional value of 0.15 in. (4 mm) plus 1/120 of the pile diameter (see Fig. 10).

By use of the Quick ML method considerable saving of cost and time can be achieved, as the test can be completed during one working day. The proposed new acceptance criterion has the advantage of considering the length of the tested pile. It also enables the engineer to evaluate better the allowable load on the pile, and, if warranted, increase or decrease this load, and does not restrict the engineer to a fixed safety factor, should reasons for changes of the safety factor be justified after completion of the test.

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