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Determining the Resistance Distribution in Piles

Part 1. Notes on Shift of No-Load Reading and Residual Load

Bengt H. Fellenius

Introduction

A pile loading test carried out just to confirm that the pile has a certain at-least capacity, that is, a proof-test, needs no special instrumentation. However, when the purpose of the test is to provide data for design of a piled foundation, for example where the test results will be applied to piles that can be longer or shorter or have different size, for resolving a downdrag problem, or for determining the distribution of the soil resistance, then, the pile must be instrumented so that the load transfer (resistance distribution) can be determined.

With few exceptions, pile instrumentation consists of strain gages, i.e. the measurement is strain, not load. The load in the pile at a gage location is determined from the change of strain (induced when load is applied to the pile head in the test) by multiplying the strain value with the modulus of the pile material and cross sectional area. The change of strain is the strain reading minus the "zero reading", or the "initial reading" of the gage, assuming – somewhat optimistically or naively – that the reading represents the "no-load" condition (i.e., when no external load acts at the gage location). However, calling a reading "the zero reading" does not mean that its value is null – that it would represent the no-load reading. One must recognize that, at the time of the start of the loading test, loads exist in the pile and they can be large. Such loads are due to locked-in strain, i.e., strains that are present in the pile at the start of the test. Locked-in strains are the cause of loads called "residual loads". And, if residual loads are not considered in the evaluation of the measurements, the conclusions drawn from the test will be suspect. It might seem that the problem would be eliminated by relying on the gage calibration that determines the "no-load" reading of the gage. The gage reading during the test would then indicate the true load in the pile at the gage location. However, the gage may be influenced by a shift in the no-load reading resulting in a false indication of load in the pile for a no-load condition. The conditions for shift of no-load reading and the residual load will be addressed in this article. A second article will present a method for analysis and determination of residual load and true resistance in an instrumented pile.

The Reading for No-Load

A strain gage can be subjected to direct damage, such as overstressing when extracting or pushing down a rebar cage, which can cause a gage attached to the cage to be pushed or pulled beyond its safe limit. Overstressing will not only shift the gage reading for the no-load condition, it can also disturb the calibration for a change of strain, severely impairing the gage and making the data unusable for analysis. It is important to ensure that such damage be avoided, and if it yet occurs, that it be discovered, e.g., by that the gage response conflicts with values from other gages (obviously, a redundancy is necessary when planning what number of gages to place in the pile). Damage due to overstressing is usually fatal for a gage, and data from such a gage must be discarded.

Other potential occurrences are more subtle as they can occur without gage damage and only result in a change of the no-load reading of the gage, leaving the linear response calibration intact. Such occurrences are slippage of the fixed end of a vibrating wire, bending of a pile (resulting in increase of strain on one side and release of strain on the other), strain transfer between materials in the pile, and temperature change.

The influence of bending is offset by having a gage level in the pile consist of a pair of gages placed diametrically opposed at equal distance from the pile center. Of course, should one gage become damaged, the surviving gage of the pair will be affected by bending and become less "truthful". Therefore, where information from a certain gage level is important, good practice is to place four gages – two pairs – at that level to achieve redundancy. Placing three levels in a triangular orientation is not a good idea. The loss of one gage will impair the other two.

A transfer of strain within the pile material without a corresponding change of load in the pile can, for example, be caused by a change of net prestress in a prestressed pile, changes during the curing of the concrete in a bored pile, and relaxation of strain induced by unequal cooling during the manufacture of a steel pile. Moreover, for gages attached to the pile before it is installed, even if the gages are insensitive to temperature change, the pile material is not, and the cooler environment in the ground will have some effect on the strain in the pile across the gage length. There is not much information available on the magnitude of the shift of the no-load reading due to such strain transfer. Although the common thought is that the effect is insignificant, it is desirable that the magnitude of such shifts be investigated (by manufacturers or other interested parties) so that the potential influence can be quantified. (For example, no-load condition strain transfer between materials due to temperature change, shrinkage, and aging can be studied by placing a sister bar in a steel pipe and attaching resistance gages to the side of the pipe, taking frequent readings before, during, and some time after filling the pipe with concrete).

To find the gage reading that represents no load in the pile, the gages need to be read several times before the start of the test. All of these readings need to be considered (and included in the report of the factual test results) to enable the engineer charged with the analysis of the test data to find the true no-load value of the gages. For example, in case of a sister bar gage used in a driven prestressed concrete pile, the first reading is always the "factory zero reading", the reading for no-load established in the gage calibration. A second reading is the reading taken immediately before placing the gages in the casting forms. Third is the reading after the release of the strands and removal of the piles from the forms. Fourth is the reading before placing the pile in the leads to start driving. Fifth is the reading immediately after completion of driving. Sixth is the reading immediately before starting the test. Similarly, in case of a sister bar in a bored pile, the second reading is taken immediately before placing the gages (attached to the rebar cage) in the shaft hole, third is when the gages have adjusted to the temperature in the ground, fourth is immediately after placing the concrete, fifth the readings (***note, plural***) taken during the curing of the concrete. Sixth, again, is the reading immediately before starting the test. The principle is that readings should be taken immediately before (and after) every event of the piling work and not just during the actual loading test. A similar sequence of readings applies to other types of piles and gages. These readings will tell what happened to the gage before the start of the test and will be helpful in assessing the possibility of a shift in the reading value representing the no-load condition.

Instrumentation cases do exist, where readings one through six are more or less identical (but for the influence of the weight of the pile, of course). However, for the majority of tests, this is not the case. The reason is that between the pile installation and the start of the test, residual load will build up in the pile. For a driven pile, this is obvious. However, residual load will also develop in a bored pile.

Residual Load

The residual load in a pile is, for example, caused by recovery of the soil after the disturbance of the installation ("set-up"), such as dissipation of induced excess pore water pressures (called "reconsolidation") be the pile driven or bored. Residual load (as well as capacity) may continue to increase after the excess pore water pressures have dissipated as the soil continues to recover from the construction disturbance. In driven piles, residual load also results from shear stress developed between the pile and the soil during the driving ("locked-in load"). Residual load is characterized by negative skin friction in the upper part of the pile, which is resisted by positive shaft resistance in the lower part of the pile and some toe resistance. (The mechanism is analogous to the build-up of dragload in a pile. The difference between residual load and dragload is merely one of preference of terms for the specific situation: "Residual load" is used when analyzing the results of a loading test and "dragload" is used when considering long-term response of a pile supporting a structure).

Residual load is associated with movement of the soil relative to the pile and the difference in stiffness between the pile and the soil. Such differences are not unique in civil engineering composite materials. For example, a reinforcing bar placed in concrete will experience noticeable compressive strain, as the concrete cures, ages, and shrinks. The stiffness ratio for steel and concrete is about 10. The stiffness ratio for pile and soil is a hundred to thousand times larger than that for steel and concrete and its effect is correspondingly more important.

The main error resulting from not recognizing the residual load in the evaluation of results from a pile loading test is that the shaft resistance appears larger than the true value, while the toe resistance appears correspondingly smaller than the true resistance. If the residual load is not considered, then, in a homogeneous soil, the results will typically show a load-transfer distribution that gets progressively steeper below approximately a third to half of the pile length. That is, the load-transfer curve denotes a unit shaft resistance that gets smaller with depth, as opposed to the resistance represented by a more realistic curve, one that becomes less steep with depth in keeping with a progressively increasing unit shaft resistance. Therefore, where residual load is present in a pile at the start of a loading test, if ignored, the measured load distribution is a false distribution of the soil resistance.

The existence of residual load in piles has been known for a long time. Nordlund (1963) is probably the first to point out its importance for evaluating load distribution from the results of an instrumented static pile loading test. However, it is not easy to demonstrate that test data are influenced by residual load. To quantify their effect is even more difficult. Regrettably, common practice is to consider the residual load to be small and not significant to the analysis and to proceed with an evaluation based on "zeroing" all gages immediately before the start of the test – solving a problem by declaring it not to exist, as it were. This is why the soil mechanics literature includes fallacies such as "critical depth" and the erroneous conclusions that unit shaft resistance would be essentially constant with depth in a homogeneous soil.

That residual load does exist and is significant is demonstrated in numerous tests on driven and bored piles (Hunter and Davisson 1969; Hanna and Tan 1973; Holloway et al. 1978; Fellenius 2002). However, most conventional static loading tests on instrumented piles do not provide the distribution of residual load in the pile immediately before the start of a test, only the load introduced in the pile during the test. An exception is presented by Gregersen et al. (1973) who reported tests on instrumented, 16 m long, 280 mm diameter, precast concrete piles driven into a very loose sand. The pile experienced plunging failure in the test and Fig. 1 presents the distributions of residual load (diamond symbols) and the load in the pile at the maximum test load (plus symbols). Fig. 1 shows also a curve determined by subtracting the residual values from the values measured for the maximum load. Had this test been performed without measuring the residual loads and with "zeroing" of the gages before the start of the test, the latter curve would have shown a "false" resistance that might have been taken as representative of the actual resistance distribution along the pile.

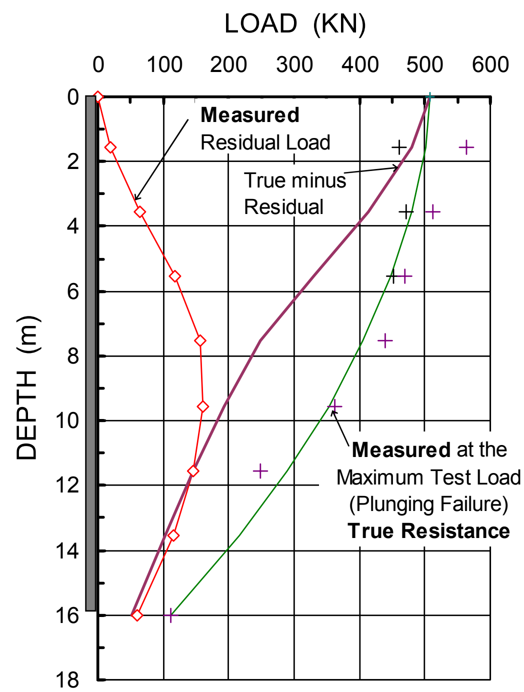

Fig. 1 Measured Distributions of Residual Load and True Resistance with Difference between the Two (from Fellenius, 2002; data from Gregersen at al., 1973)

Most of the time, a test on an instrumented pile includes no measurements of the distribution of load in the pile at the start of the test. That is, whether or not and to what extent the pile is subjected to residual load is not directly known. However, on the condition that the soil profile is reasonably uniform, the measured load in the pile during the test – the "false" distribution – can still be used to determine the distributions of true load and residual load in the pile. To illustrate, Fig. 2 presents the results of a static loading test to plunging failure on a 0.9 m diameter, 9.5 m long bored pile in clay. The pile was instrumented with two levels of strain gages placed at depths of 3.8 m and 8.3 m. The strain gage values represent the load increase due to the load applied to the pile head. A series of load distribution curves are obtained by connecting the load at the pile head with the load measured at the strain gage levels.

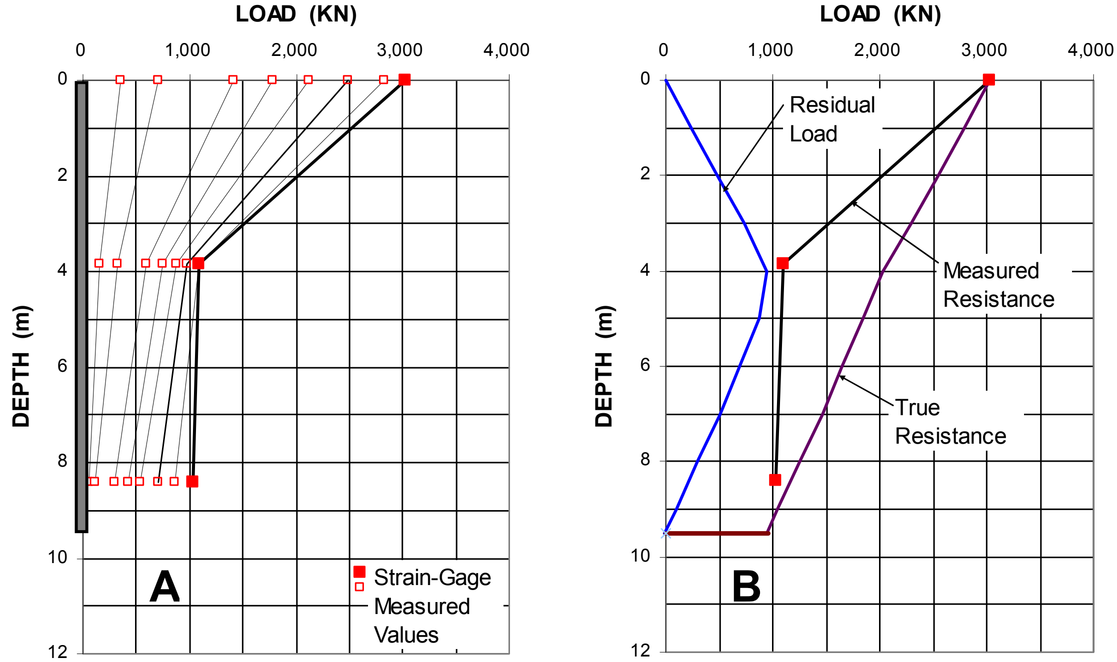

Fig. 2 Load Distribution in a 0.9 m diameter, 9.5 m long bored pile
(from Fellenius, 2002; Data from Baker et al., 1990)

A. Measured Load Distributions

B. Distributions of Measured Load, Residual Load, and True Resistance
(Loads Corrected for Residual Load)

As shown in Fig. 2A, the loads measured at the two strain-gage levels are about equal, implying that no shaft resistance exists below the depth of 3.8 m. It would appear that either one or both gages are malfunctioning. But this they are not. The distribution shown is typical of a pile affected by residual load and both gages are working well. Fig. 2B compares the measured distribution at the maximum load to the results of an analysis of the distributions of residual load and true resistance.

Fig. 3 presents results from results from a static loading test on a driven pile, a 21 m long Monotube pile in a loose to dense sand. (The Monotube pile is a 450-mm diameter steel pipe with a 7.6-m bottom section that tapers down to a 200-mm diameter at the pile toe). The measured distribution is shown together with the distribution of residual load and the resulting true resistance distribution. Notice that a residual load is indicated at the pile toe.

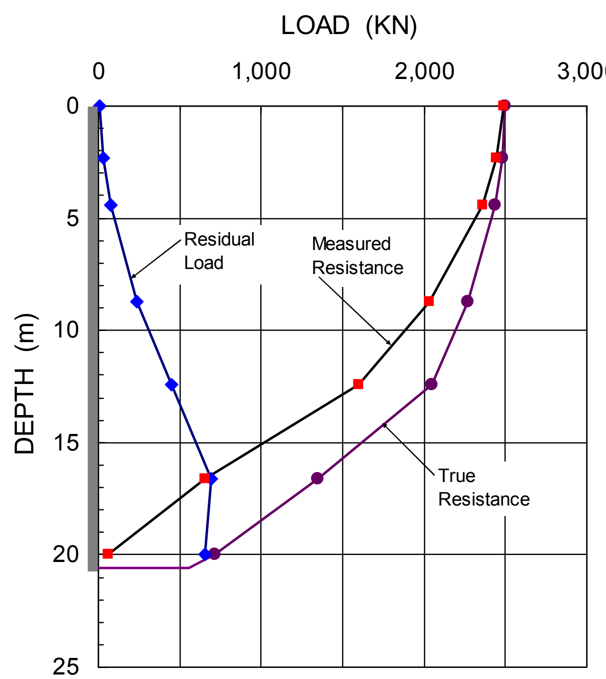

Fig. 3 Distributions of Measured Load, Residual Load, and True Resistance (from Fellenius et al., 2000)

It is obvious from the results of the analysis that ignoring the residual load would have resulted in very different conclusions. For the tests shown in Figs. 2 and 3, the distributions of residual load and true resistance were not measured directly, but determined from the measured increase of strain in the gages due to the load applied to the pile head. The method of analysis presupposes that one understands and accepts that significant shear forces and corresponding strain in the pile will have developed before the start of the test, that the shear forces along the pile have different directions, and that the magnitude and distribution of these forces follow certain rules. The analysis process establishes the soil response to the loading of the pile and the soil parameters to use when subsequently applying the results of the test to the design of the piled foundation.

The method of analysis used for the two example cases will be presented in a second article scheduled for the next episode of GIN. It applies to loading tests where instrumentation or other methods have been used to determine the resistance distribution in the pile The method is independent of strain-gage shift of no-load reading, and, indeed, for where the gages were installed after all or some of the residual load already had developed in the pile.

Closing Words

When analyzing data from a loading test on an instrumented pile, one must ascertain whether or not all gages have operated correctly and whether or not residual loads were present in the pile before the start of the test. It is easy to jump to conclusions, as the appearance of residual load can be deceiving and might be due to erroneous gage readings (e.g., gage damage and calibration changes caused by mishaps during the construction of the pile). However, unless residual load is accounted for in the analysis of the test data, instrumentation adds very little of value to a pile test. On a positive note, when the residual load is accounted for, the procedure increases the understanding of the pile-soil interaction for the specific project beyond the correct separation of shaft and toe resistances for the tested pile.

Acknowledgment

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Determining the Resistance Distribution in Piles

Part 2. Method for Determining the Residual Load

Bengt H. Fellenius

Introduction

The first part of this article stated, convincingly it is hoped, that unless residual load is accounted for in the analysis of data from a loading test, instrumentation adds very little of value to a pile test. On the other hand, when the residual load is accounted for, the procedure increases the understanding of the pile-soil interaction and adds significant value to the design of the specific project and — as a spin-off benefit — to the general understanding of pile behavior. The article left the reader with the cliffhanger of not indicating how residual load can be determined when all that is known is the increase of load in the pile due to the load applied to the pile head in the test. The second part of the article will present the "how to".

Case I. Analysis of a static loading test on an instrumented precast concrete pile

Altaee et al. (1992) present data and analysis of static loading tests on two instrumented 285 mm diameter square precast concrete piles driven to depths of 11.0 m and 15.0 m in a loose to compact sand. The instrumentation in the pile consisted of strain gages placed in the pile before casting. Fig. 4A presents the cone stress (q_c) of a cone penetration sounding and the SPT N-indices at the site. The CPT and SPT diagrams indicate that the soil is of uniform density. Fig. 4B shows the loads measured at the strain gage levels at plunging failure for the static loading tests. For both piles, the measured load distribution curves show a slight S-shape, that is, the slope of the curve goes from steep to less steep to steep again.

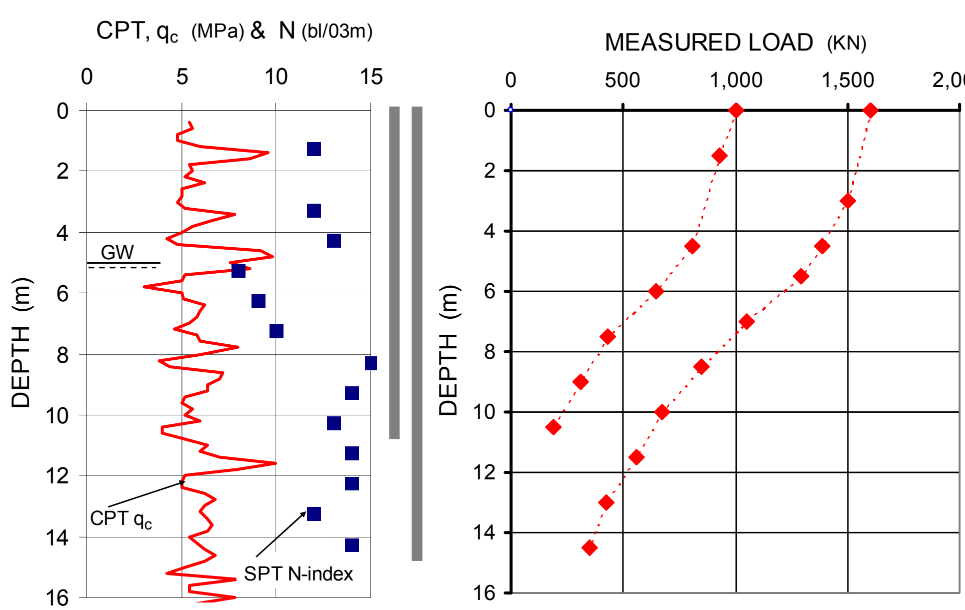

Fig. 4 Soil Test Results and Measured Load Distribution at Failure of Two Instrumented Precast Concrete Pile Driven 11 m and 15 m into a Uniform Loose to Compact Sand. (Data from Altaee et al. 1992)

Because the slope of the load-transfer curve is an indication of the unit shaft resistance in the soil, (the shaft resistance is equal to the reduction of load with depth) the S-shape suggests that the shaft resistance along the middle third of the pile is larger than along the lower third. However, the soil profile does not support that the unit shaft resistance would be smaller with depth. In fact, the S-shape is typical for results of a test on a pile affected by residual load and the measured distributions do not show the true distribution of resistance of the pile.

Residual load develops from negative skin friction along the upper part of the pile. In the loading test, therefore, before the positive shaft resistance is mobilized, the residual load must first be unloaded. This means that the slope of the measured curve overestimates the mobilized shaft resistance by as much as a factor of two. (For all practical purposes, the shear resistance is independent of the direction of shear). Therefore, where the residual load is built up of fully mobilized negative skin friction, the reduction of load along the pile is twice the true shaft resistance. This fact can be used to determine the distribution of true shaft resistance. The method for the analysis is illustrated using the results of the test on the longer of the two piles.

The analysis begins by plotting half of the measured reduction of load, that is, the true shaft resistance, versus depth in a diagram, as shown by the solid diamond symbols in Fig. 5. (The solid square symbols indicate the load values measured in the pile). Thereafter, the so-determined "half curve" is matched to a theoretical distribution in an effective stress analysis. As indicated in the figure, a match is possible down to a depth of about 8.5 m. Below this depth, the rate of increase of the measured shaft curve (the "half curve") reduces, whereas the rate of the theoretical curve continues to increase. The depth where the two deviate from each other is where the transition from negative skin friction to positive shaft resistance begins, i.e., the transition from increasing to decreasing residual load. The true resistance distribution curve over the "matched length" is the difference between the load applied to the pile head and the calculated shaft resistance values.

Considering the soil profile, it is very likely that the soil response below depth 8.5 m is similar to that above this depth. This means that it is reasonable to assume that the soil parameters below 8.5 m are equal to those above. The dashed extension ("extrapolation") of the true resistance distribution is the result of an effective stress calculation applying the parameters that governed the fitting of the analysis to the data for the ground surface down to 8.5 m depth. The pile toe resistance indicated by the value at the depth of the pile toe is the load applied to the pile head minus the total shaft resistance (as calculated). Of course, had the soil profile indicated a different soil below 8.5 m, the extrapolation of the true resistance would have been less assured.

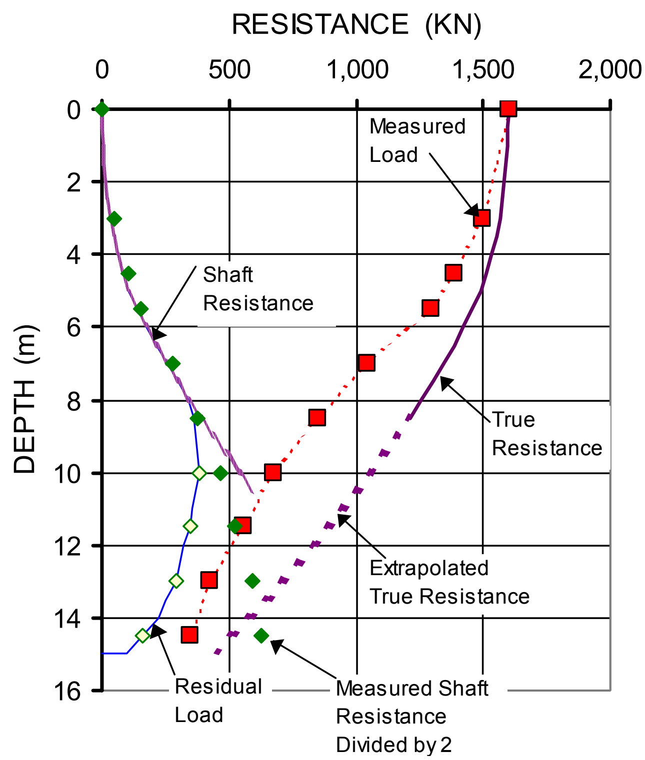

Fig. 5 Soil Test Results and Measured Distribution of Load at Failure of a 15 m Long Instrumented Precast Concrete Pile Driven into a Uniform Loose to Compact Sand.
(Data from Altaee et al. 1992)

Finally, the distribution of residual load for the length below 8.5 m to the pile toe is now determined by subtracting the measured loads from the calculated true resistance distribution along the pile.

Two conditions serve as a check on the construction of the extension of the true distribution curve: (1) if the residual load in the lower portion of the pile (positive direction forces) is fully mobilized, the true distribution and the residual distribution are parallel, and, (2) if it is not fully mobilized, as in the example case, the slope of the true distribution can never be steeper than the slope of the distribution of residual load along this length of the pile. These conditions will assist in determining the length of the transition zone from negative skin friction to positive shaft resistance. For simple soil profiles, the conditions and the curve fitting can be handled by spread sheet calculations. Cases involving non-uniform soil profiles, non-hydrostatic distribution of pore water pressure, effect of adjacent piles and/or excavations require special software or the calculations will be very time-consuming.

The results of the testing of the 11.0 m long pile were also analyzed. The results of both analyses are presented in Fig. 6.

Fig. 6A combines the distributions of measured load, true resistance, and residual load. Fig. 6B shows the distributions of measured shaft and corrected shaft resistance (for reference, the distribution of residual load is also shown). The calculations establish the parameters to use in the design at the site. Without the correction for residual load, the data could have been mistaken to show the presence of the so-called critical depth at about 25 and 30 pile diameters depths for the short and the long piles, respectively. Use of such mistaken interpretation for the design of piled foundations at the site involving piles of different length and/or diameters would then have been confusing, as calculations of a new pile based on the results from the 11-m pile would have been distinctly different from those based on the 15-m pile. A design based on the results corrected for residual load has no such difficulty.

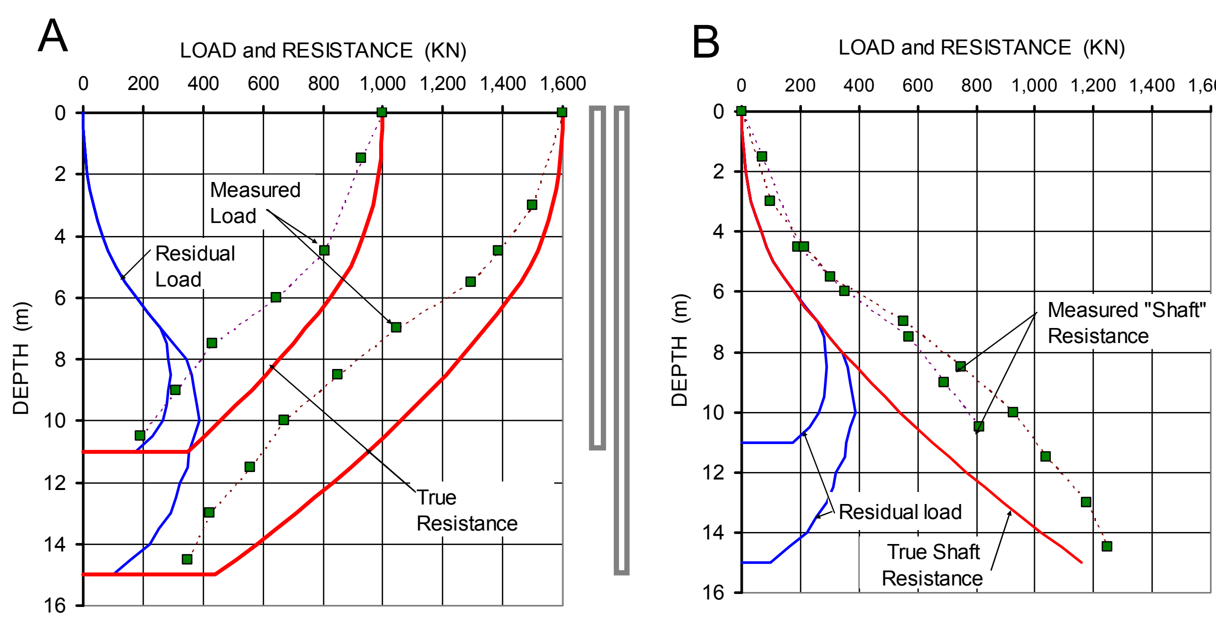

Fig. 6 Results of the Analysis of Both Piles (Data from Altaee et al. 1992)

Case II. Analysis of results from dynamic testing of a precast concrete pile

A residual load analysis on results from a static loading test requires that the pile is instrumented. Such tests are quite rare. However, regardless of type of test, any test that produces a load distribution as a change of load due to the applied load (initial values taken as “zero” at the start of the test) is suitable for analysis of residual load distribution. For example, a dynamic test using the Pile Driving Analyzer (PDA) with a CAPWAP analysis, a test that is common for driven piles and occasionally also for bored piles. The CAPWAP analysis provides the distribution of static resistance along the pile in a manner similar to that of resistance distribution measured by strain gages in static loading test on an instrumented pile. Therefore, although this is not generally realized, CAPWAP[1] results are similarly influenced by residual load and may need similar adjustment before the true resistance distribution is found.

Where the strain-gage values obtained in a static loading test on an instrumented piles are independent of each other, the CAPWAP determined load values in the various elements simulating the pile in the analysis do exhibit a mutual dependence. It is not within the scope of this article to explain why and how, however. The fact is that a resistance indicated for a particular element should be considered as less definite than a value from a strain-gage reading in a static test and one should proceed with caution and carefully corroborate the results with static analysis based on good information on the soil profile. (This does not mean to say that pile capacity determined in a CAPWAP analysis is in any way less reliable that that determined in a static loading test).

Case History II is used to demonstrate the method of analysis for residual load on the results of a CAPWAP analysis on a pile subjected to residual load. The case is a test on a 250 mm diameter square precast concrete pile driven 19 m into a loose to compact sand deposit (the test data are from Axelsson, 1998). The soil profile at the test site is presented in Fig. 7A in the form of a CPT q_t-diagram from a sounding close to the test pile, showing a consistent cone resistance within the pile embedment depth. A dynamic test was carried out at restrike 143 days after the initial driving. The first blow of restrike was used in a CAPWAP analysis.

Fig. 7B shows the CAPWAP determined resistance distribution in a manner similar the strain-gage measured distribution obtained in a static loading test. The ultimate total resistance is 1,440 KN and the shaft and toe resistances are 1,110 KN and 330 KN, respectively. Again, the "measured" load distribution curve is "S"-shaped, which is typical for a "false distribution", i.e., a distribution influenced by residual load. That residual load exists in the pile is no surprise. Some load developed as a result of the driving of the pile and the rest developed during a series of earlier restrikes performed at different times after the end of the initial driving. Indeed, the question to resolve is not "if" but "how much" and "with what distribution".

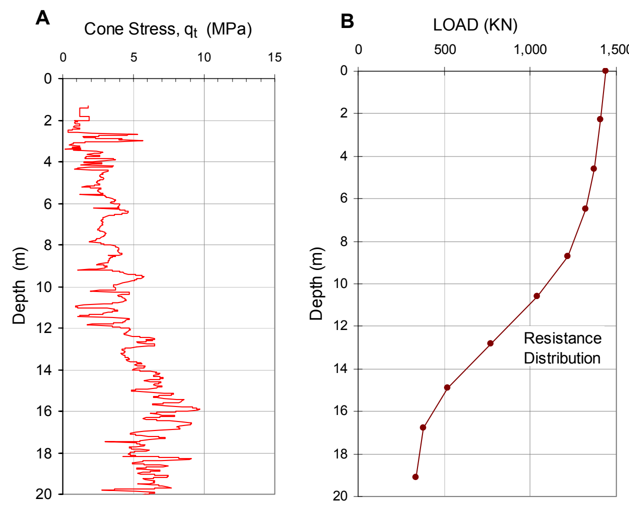

Fig. 7 Case 2 CAPWAP Analysis at Restrike of a 285 mm Diameter, 10 m Long Precast Concrete Pile Driven into Loose Sand

A CPT Profile B CAPWAP Determined Resistance Distribution

(Data from Axelsson 1998)

The "measured" resistance distribution indicates that the unit shaft resistance increases to a depth of about 13 m. Progressively below this depth, it becomes smaller, and over the last 4 m length (below about 15 m), the unit shaft resistance is very small. This is inconsistent with evenness of the soil profile established by the CPT sounding.

Fig. 8 demonstrates the results of the procedure for determining the true resistance distribution in the test. A calculated shaft resistance distribution was matched to the "half curve" and a good fit was obtained down to 13 m depth. Thereafter, the assumption was made that the effective stress parameter (beta-coefficient) found in calculations applied also to the soil below 13 m depth and the distribution of the true resistance was calculated.

[1] The CAPWAP analysis makes use of strain and acceleration measured for an impact with a pile driving hammer. The analysis delivers amongst other results the static resistance mobilized by the impact. In the calculation, the pile is simulated as a series of many short elements and the results are presented element per element, as if load measurements had been made at each element location along the pile. That is, each element can be considered having the role of a strain gage. Although the CAPWAP program allows an adjustment of the results for locked-in load due to the immediately preceding impact, the analysis cannot provide full recognition of the residual load in the pile.

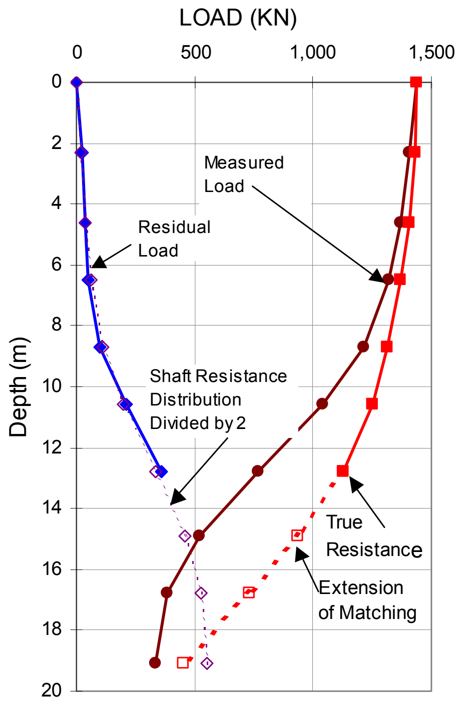

Fig. 8 Case II. Matching the Distributions of Measured and Calculated True Shaft Resistances

The CAPWAP determined loads (the "measured" loads) were then subtracted from the true resistance values to arrive at the distribution of the residual load. The full results are presented in Fig. 9.

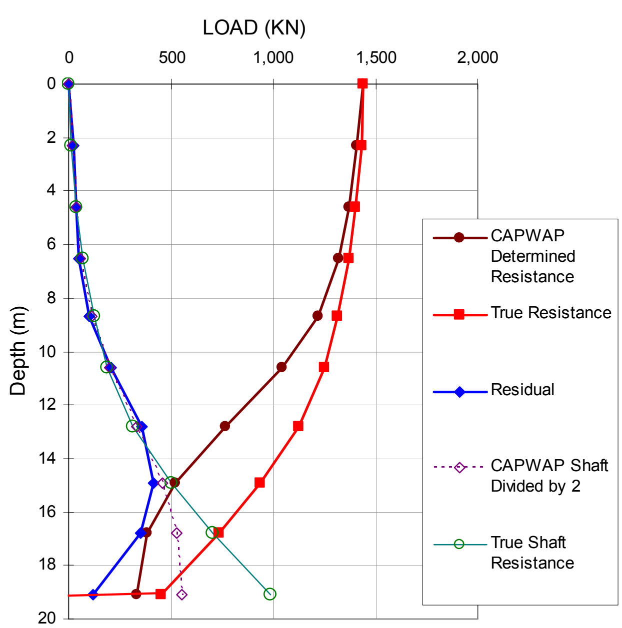

Fig. 9 Final Results: Measured Load, Residual Load, and True Resistance

For the example case, the assumption that the same beta-coefficient applies above and below 13 m results in a distribution of residual load that indicates that the positive shaft resistance was not fully mobilized in the lower portion of the pile, but for the about 2 m length immediately above the pile toe.

The analysis could be polished by applying a slightly larger beta-coefficient near the pile toe. (Repeating the conditions, an upper boundary of the beta-coefficient is governed by that the resulting residual load distribution and the true resistance distribution can be parallel, but the slope of the true resistance distribution must not become steeper than the slope of the residual load distribution). However, the fact that the CAPWAP determined distribution (the "measured" resistance) is not quite vertical for the last element (below 17 m) does support that the positive shaft resistance immediately above the pile toe is not fully mobilized by residual load. At the same time, the CPT-profile supports the conclusion that the unit shaft resistance below 13 m depth is not smaller than above 13 m depth, that is, the choice of using the same value beta-coefficients above and below 13 m depth is supported. In other words, a good portion of engineering judgment and reasoning is necessary in the process and often the results of the analysis can only be obtained within upper and lower boundaries.

For the example case, the corrected shaft and toe resistances are 985 KN and 455 KN as opposed the uncorrected values of 1,110 KN and 330 KN. Hardly an insignificant correction. The objective of the analysis procedure is to obtain a true distribution of resistance for the test pile, and then to use this in analysis of the basic soil parameters, such as beta and toe bearing coefficients. False values will result in false conclusions and unreliable design recommendations.

Direct Measurement of Residual Load

In contrast to conventional "head-down" tests, tests using the Osterberg Cell (Osterberg 1998; Fellenius 2001) provide data that allow an analysis of the residual load in the pile. The O-Cell loading test consists of expanding a special hydraulic jack normally placed at the toe of a pile, pushing the shaft upward and the toe downward. The maximum test load is when either the ultimate shaft resistance is reached or a maximum toe movement is obtained. When the test starts, the load at the toe of the pile is the weight of the pile plus the residual load. This load is gradually transferred from a physical contact between the O-Cell top and bottom plates to being carried by the pressure in the cell. During this transfer, no or only insignificant separation movement occurs of the O-Cell plates. Once the load transfer is completed, continued increase of load in the O-Cell results in a much larger separation movement of the O-Cell plates, signifying increasing compression of the pile and corresponding increase of load in the pile. Thus, analysis of the early behavior of the O-Cell measurements load will establish the magnitude of the residual load in the pile at the location of the O-Cell. For other locations in the pile, the O-Cell test is routinely combined with strain gages placed at several levels in the pile. The analysis of the true distribution of resistance of these strain gages applies the same method as used for the conventional head-down test. Of course, the analysis must recognize that the O-Cell test engages the pile in negative skin friction for the entire length above the O-Cell. The advantage of the O-Cell test is that the analysis of the strain gage data is assisted by the actual knowledge of the residual load at the O-Cell.

Closing Words

The method has the advantage of making the analysis independent of strain-gage zero shift due to strain transfer within the pile material, temperature change, or slippage. This is because the method works only with the loads introduced (as measured at the gage levels) during the static loading test.

As mentioned in Part I, the mechanism behind the build-up of residual load is analogous to the build-up of dragload in a pile. Therefore, if a long-term test on an instrumented pile for the purpose of studying the development of negative skin friction and dragload is "finished" with a static loading test , the method can be applied to determine the dragload distribution and eliminate the potential influence of zero shifts (i.e., changes in the no-load reading) of the strain gages.

Before applying the analysis method, however, one must be certain that residual load indeed is present in the pile. It is easy to jump to conclusions, as the appearance of residual load can be deceiving and due to erroneous gage readings (e.g., gage damage and calibration changes due to mishaps during the construction of the pile). The procedure presented in this article applies to test data which can be accepted without reservations about accuracy and validity. Then, one must remember that the procedure is one of curve-fitting and shrewd curve-fitting will always produce good agreement between calculations and measurements. In other words, the accuracy of the final numbers is construed. Therefore, considerable judgment must be exercised in thenalysis and use of the results and the results must be related to a static analysis of the soil response based on basic principles of soil mechanics. Don't attempt the analysis method without having the soil profile well established from a CPTU sounding and independent soil sampling. A borehole log with SPT data and its intermittent soil information is rarely sufficient.

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