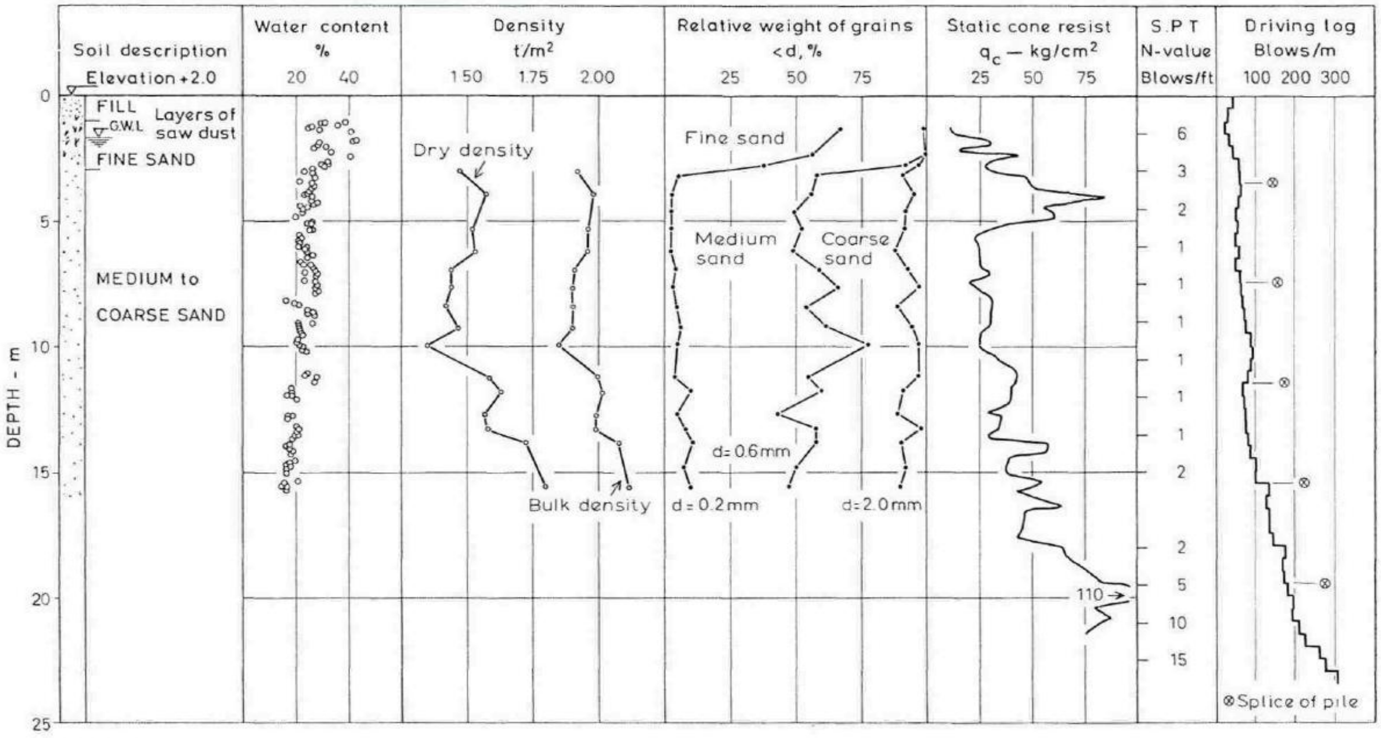

Gregersen et al. (1973)

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Case Study

Revisiting Hunter and Davisson (1969) and Gregersen *et al.* (1973): Establishing residual force

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Abstract: Hunter and Davisson (1969) wrote a pioneering paper that brought the presence of residual force and its consequence for pile load-transfer to the attention of the profession. The paper presented observations at the 1963 Lock and Dam 4 project of the Corps of Engineers, where, for one of the first times in the US, strain-gage instrumentation was used in static-loading tests. The tests combined results from compression (push) tests with those of subsequent tension (pull) tests and presented an innovative analysis linking the results of compression and tension test on the test piles to determine the true load-transfer of the pile. The analysis established that driven piles are left with locked-in force-distribution—residual force—and that this force affected the evaluation of records from an instrumented static loading test. While the conclusion that static loading tests should combine push and pull tests and the piles should be instrumented in order for the true load-transfer mechanism be determined was not that often followed by the profession, the paper certainly established the importance of the residual force. The findings were soon afterward confirmed by Gregersen *et al*. (1973) who determined the presence of residual force by actually referencing all records to a calibrated distribution of axial force before the pile was driven. This paper re-visits the original test records and results and adds additional insight by re-analyzing the original test records in terms of effective stress, as opposed to stress-independent method of the old times, and of pile movement as opposed to “capacity”.

Keywords: precast concrete pile, H-pile, telltales, static loading tests, back-analysis, load-movement

Introduction

The first mention of presence of residual force in piles as affecting the interpretation of pile loading tests was in a couple of papers published in the 1950s and 1960s, e.g., Mansur and Kauffman (1956), Smith (1950), and Nordlund (1963). However, the main reference is Hunter and Davisson (1969), who quantitatively addressed the subject, employing force-distributions measurements from head-down and tension static loading tests performed in 1963 for the Corps of Engineers, Lock-and-Dam 4. Hunter and Davisson (1969) concluded: *Residual force remaining in the pile after driving, and after compression loading, must be accounted for if a true representation of load transfer is to be obtained*. The analysis results presented by Hunter and Davisson (1969) warrant re-visiting and evaluation in terms of effective stress, as opposed to old time stress-independent method, and in terms of full pile movement as opposed to a single-point “capacity”. In a paper to the Moscow ICSMFE, Gregersen *et al*. (1973) presented full-scale tests where the distribution of axial force in the piles was measured after pile installation and before the static loading test, confirming the findings and conclusions of the Lock and Dam 4 tests.

Soil Profile and Test Piles

The Lock-and-Dam 4 tests were performed in a compact to dense poorly graded alluvial sand. Figure 1 shows the upper and lower grain-size boundaries of the sand established from borehole samples recovered from down to 17 m depth. Before drilling, the site was excavated to 6 m depth, close to the highest river level, which varied seasonally. Mansur (1964) indicated that the groundwater level was 3.5 m below the excavated surface at the time of performing the tests. The excavated soil was placed around the excavated area to form a protection levee.

The excavated test area was rectangular about 40 m by 50 m. A total of sixteen, 15.9 to 16.1 m long piles were driven and tested. Six of these tests were addressed by Hunter and Davisson (1969): five were closed-toe pipe piles and one was an H-pile 12BP73. The pipe piles were TP1–12-inch, TP2–16-inch, TP3–20-inch, TP10–16-inch, and TP16–16-inch. All but Piles TP10 and TP16 were installed by impact driving. Pile TP10 was installed by vibratory driving using a Bodine high frequency vibrator. Pile TP16 was installed by jetting to 12 m depth before it was driven to full depth. Figure 2 shows the location of all test piles in the excavated area. The figure also shows a diagram of the SPT N-indices (BH-203, and BH-204) at the test site, indicating

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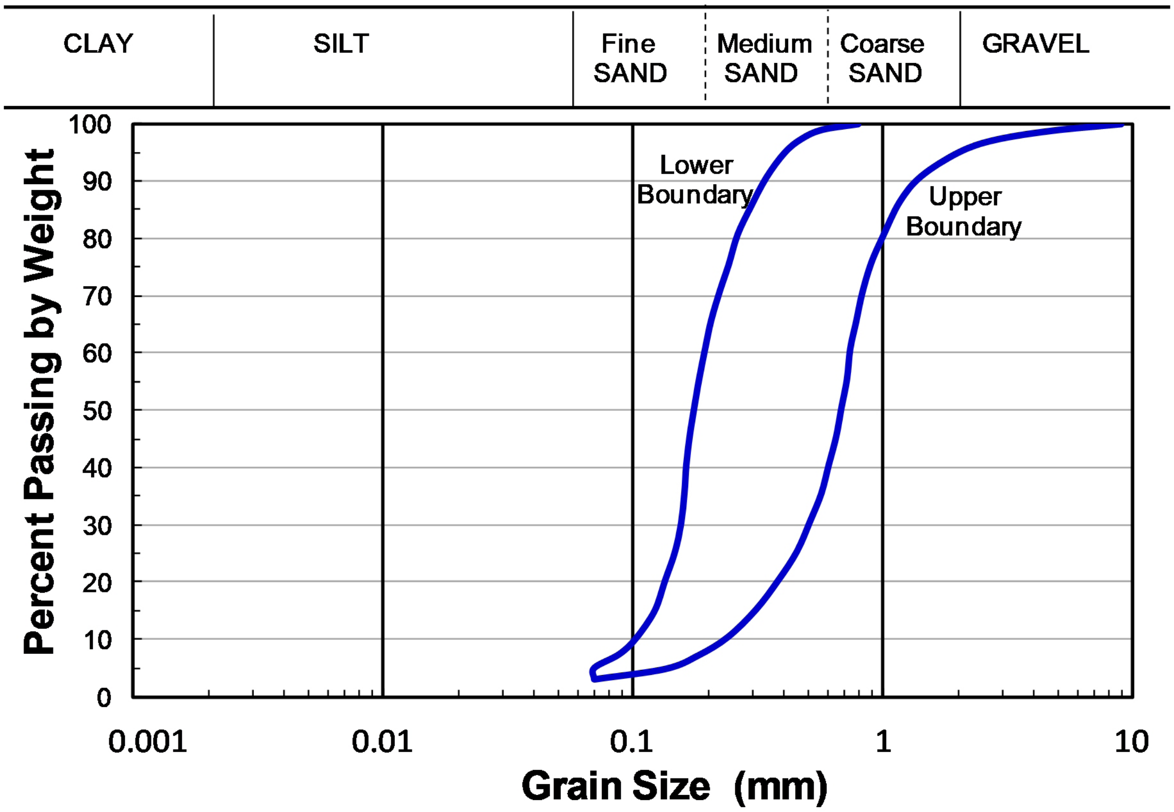

Figure 1. Sieve analysis results (data from Mansur 1964)

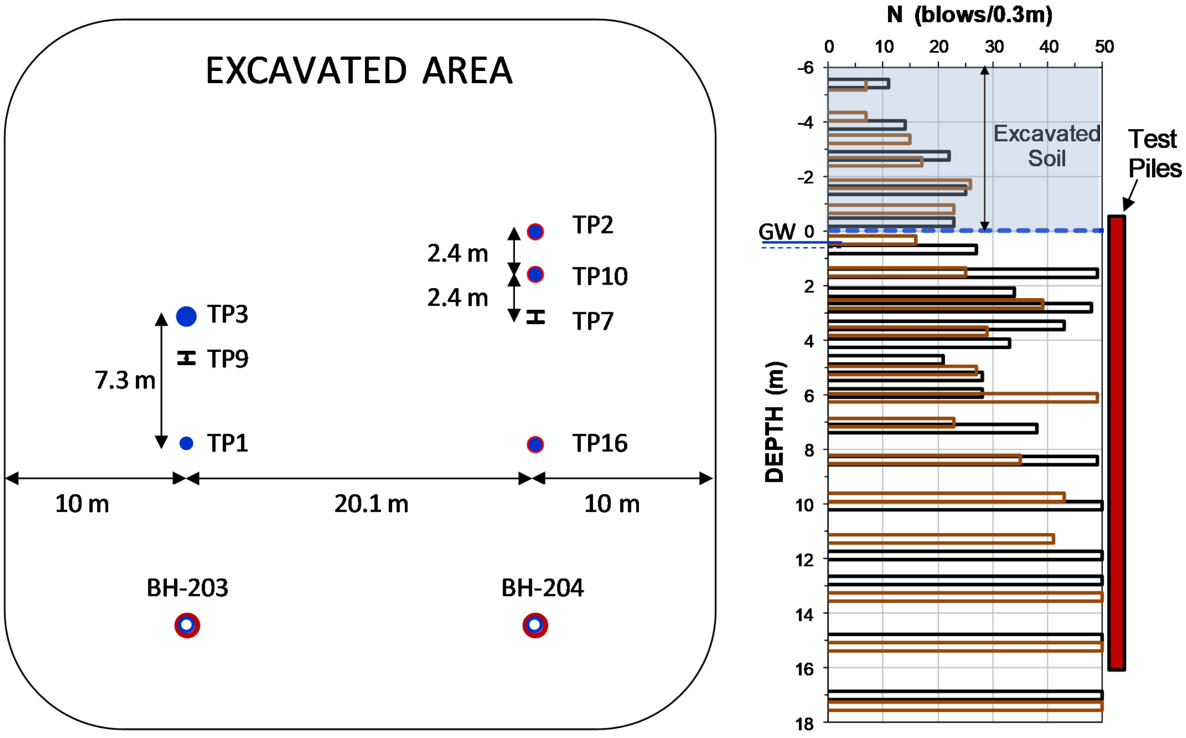

Figure 2. Test area and pile layout with N-indices diagram (data from Mansur 1964)

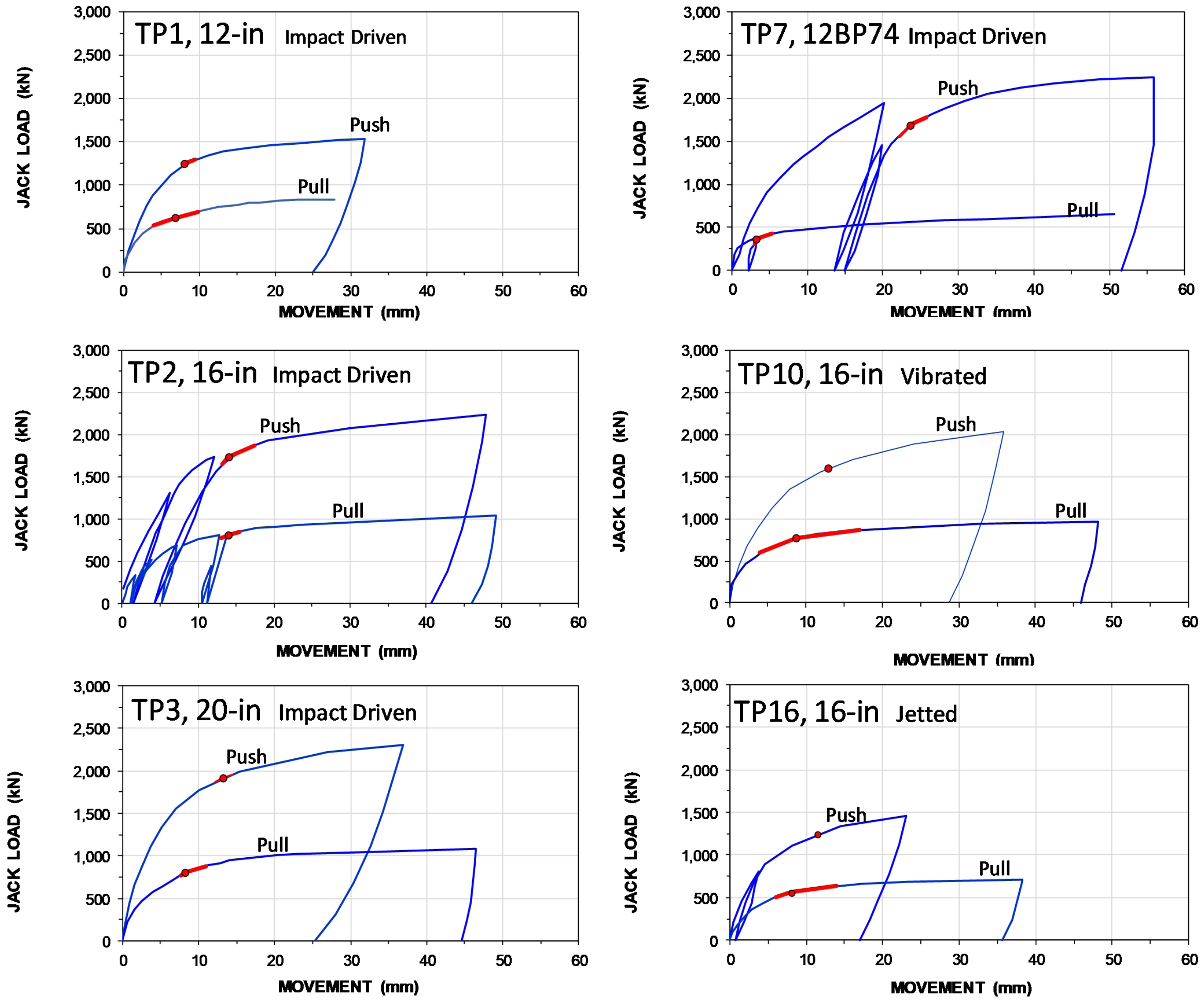

Figure 3. Pile-head load-movements and capacities (data from Mansur 1964)

that the sand (from about 1 m depth) was mainly dense to very dense with a compact zone between the depths of about 4 through 7 m.

All piles were tell-tale instrumented with telltale anchors at 3 depths (pipe piles) and 4 depths (H-piles) and 1 at the pile toe. Piles TP2, TP7, TP10, and TP16 were also instrumented with electrical resistance strain gages placed at 15 depths! The telltale-measured pile compressions were transferred to average strain over the telltale length. The strains—from telltales and strain-gages—were converted to axial force in the piles.

The static loading tests comprised a head-down test (push) followed by a tension test (pull). Both push and pull tests included a few unloading and reloading events. Hunter and Davisson (1969) included force distribution graphs of the six tests—of push- as well as of the pull-tests, but no load-movement records. However, Mansur (1964) presented load-movement curves of all the six piles addressed by Hunter and Davisson (1969). Figure 3 shows the curves—obtained by scanning and digitizing the graphs contained in Mansur (1964), although he did not include any actual load-movement points. The test loads were applied in approximately 10 equal increments selected on the basis of the pile capacity estimated from driving information and static calculations. Loads were determined from pressure in the jack. All loads were applied and released at a rate of 2 tons/min (20 kN/min). Each load increment was maintained for a minimum period of one hour; holding off increasing to the next load until the pile head movement was less than 0.01 in/h (0.25 mm/h), determined from or 0.002 in/10 minutes (0.05 mm/10 minutes. For nine of the twelve tests, Mansur (1964) listed applied loads that ostensibly represented pile capacities obtained by four different definitions and their average value, stated to be the pile "failure load". The definitions were based on a specific movement value or a specific value of or distinct change of slope of the load-movement curve. The "Davisson offset limit" (Davisson 1972) was not included—it was still in the future.

The capacity range and the average capacities are indicated by the fat red portion of the curves and the red dots, respectively. For four of the tests, the load-movement schedule included unloading-reloading events.

All piles were loaded to "plunging failure" defined as a gross pile head deflection exceeding 0.01 in/ton (0.02 mm/kN). It can be assumed that, at "plunging", no stable load, movement, or strain values were obtained.

Load and Force Distribution Graphs in Hunter and Davisson (1969)

Hunter and Davisson (1969) presented the back-calculated force distribution in the six test piles, again without showing any data points. The curves are smooth showing no scatter. Yet, forces determined from telltale and strain measurements always have uncertainty and will show scatter—then and now. Moreover, the applied load was determined from the jack pressure, which for at least some of the tests will have indicated a larger load than that actually delivered to the pile. Therefore, the accuracy of the force records determined from the force diagrams might be somewhat low.

Figure 4 shows facsimiles of TP1 and TP16 force-distribution; two of the six graphs presented by Hunter and Davisson (1969). The force distributions are for push and pull tests (compression and tension) and were stated to be those determined at an applied load equal to the "capacity" of the pile. However, the paper does not state which of the four methods that was considered to be the "capacity" or if the average value was used.

The solid curves, (1) and (3), show the force distribution fitted to the force values converted from measured strains induced from assuming that the pile was unstressed at the start of each test. Curve (2) shows the distributions determined after unloading the pile from the push test. Curve (4), shown only for TP1, is the distribution measured after unloading the pile from the pull test. Curve (5) is the force distribution adjusted by subtracting Curve (4) from Curve (3). Although Curve (4) was not plotted for TP16, it can be indicated by the difference between Curves (3) and (5) and appears to have been very similar to that shown for TP1. Curve (6) is Curve (1) to which is added the absolute value of Curve (4) subtracted by Curve (2).

Hunter and Davisson (1969) concluded that Curves (5) and (6) represented the true pull and push test force distributions in the test piles and suggested that the true force distribution of an instrumented static loading test could be established by performing a pull test after a push test and adjusting the measured pull-test distribution by adding the post-test remaining distribution, Curve (4), to Curve (5)—taking it to be the residual force distribution before the pull test—and, for the push-test, adjusting the distribution by adding the post-test force distributions from both tests to Curve (6).

Note that the force distribution for both the push and pull tests are drawn connecting data points (not shown) and extrapolating the trend of the curve from the uppermost values to intersect with the pile head level. This means that Hunter and Davisson (1069) and Hunter (1964) assumed that the unit shaft shear near the pile head was equal to that somewhat deeper down the pile, i.e., they assumed the shaft shear to be stress-independent. If, instead, the force distribution would be stress-dependent, as in an effective stress analysis, along the nearest length below the pile head, the slope of the curve would bend upward and end being essentially vertical.

Figure 5 shows the back-calculated force distributions for the six piles with Curves (1) through (6) as evaluated by Hunter and Davisson (1969). Again, the figures were obtained by scanning and digitizing the original figures. The type of curves and numbering of Curves (1) through (5) is the same as that used by Hunter and Davisson (1969). Curves (2), the distributions after unloading the pile from the push test, were only reported for Pile TP1, and these distribution indicate that the residual force created by the driving and that remaining after the push test were same. However, finding that the end-of-test strains were the same as those at the start of test is somewhat unusual.

Two curves have been added: Nos. (7) and (8) to represent "true" distributions (distributions corrected for residual force) simulated by effective stress calculation and, for

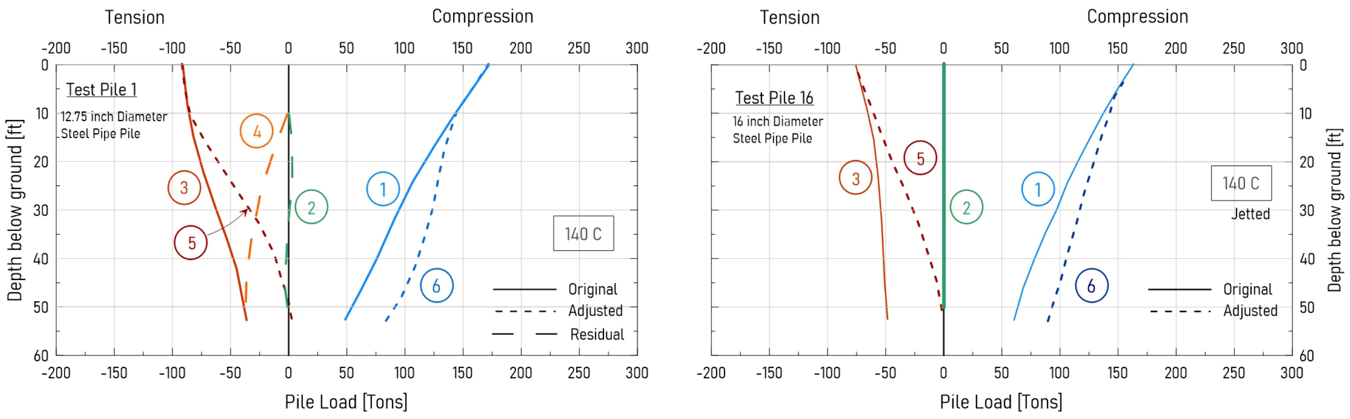

Figure 4. Force distribution in TP1 and TP16 from Hunter and Davisson (1969) (redrawn after Hunter and Davisson (1969))

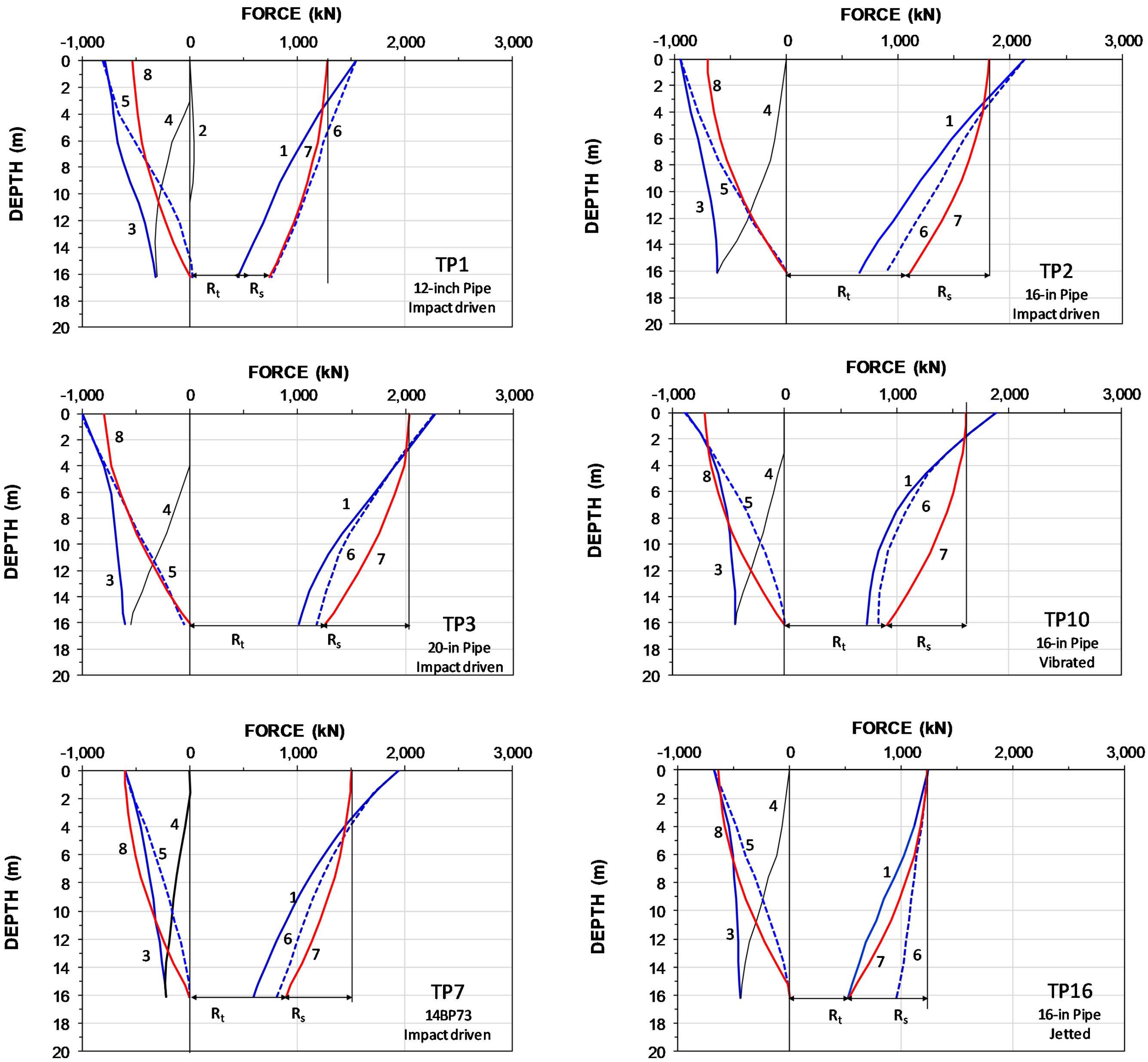

Figure 5. Force distributions

each test assuming a soil density, ρ_t, of 2,000 kg/m^3 and a plastic beta-coefficient, ß, of 0.30—the same values were applied to all analyses. The movement of the pile elements for the back-analyzed distributions ranged between 8 through 12 mm. For the H-pile, TP7, the pile circumference was set equal to that of a square around of the pile cross section. The stress from the excavated soil placed as levees around excavation is included, but it had minor effect only, a Boussinesq stress distribution of the calculated total results in an about 2 % increase of shaft resistance as opposed to a calculation without levees. The toe force (push test) was set to a value that made the reported and simulated curves agree to the stated average "capacity" for each test. The toe force stress that, together with ß = 0.30, gave a pile head load equal to the assigned "capacity" were 9.0, 8.5, and 6.2 MPa for the impact driven pipe piles, TP1, TP2, TP3, and TP7, respectively, and 7.0, 7.0, and 4.0 MPa, for TP7, TP10, and TP16, respectively, the H-pile, vibratory driven, and jetted piles.

Applying a shaft distribution determined using constant density and same beta-coefficient through the pile length is reasonable considering the uniformity of the soil within the pile length. First to note is that Curves 7 and 8 show an almost vertical distribution nearest the ground surface in contrast to Curves 1 and 5 (which slopes were from extrapolating the uppermost force values—stress-independent shear). Second is that the indicated "true" tension distribution, Curve (5), agrees well with the simulated force distribution, Curve (8), for TP2 and TP3, but not for the others.

The true toe-force in a pull tests is zero, of course, and the "true" force distribution must start from zero at the pile toe level. The fact that the force distributions for the pull tests indicate a toe-force is due to presence of residual force in the pile. The conclusion of residual force in the pile is reinforced by the fact that the force (3) along the lower length of pile is almost vertical. This means that the residual force distributions are the results of fully mobilized residual negative skin friction from the pile toe upward.

Hunter and Davisson (1969) were certainly correct in stating that determining the magnitude and distribution of residual force and "true" force distribution requires results of static loading test on instrumented piles in both push and pull. However, they were wrong in suggesting that the force distribution remaining in the pile after unloading a pull test would be equal to the residual force before the test. The shaft and toe responses are affected by the hysteresis condition of the interaction between the pile and the soil. The residual shaft force has engaged the soil in a combination of negative and positive directions and the shear force vs. movement is different in increasing as opposed to decreasing conditions. The push test reverses the negative direction, which reduces the interpreted force and increases it for the positive direction, whereas the pull test does the opposite. The before and after cannot be equal. For a graphic illustration of t-z and q-z curves with and without development of residual force, see Fellenius (2021).

Principles of Interaction Between the Force Distributions When Back-Analyzing Test Results

Figures 6A to 6C show principles of interaction between the distributions of residual force, measured force, and "true" force. As in the subject static tests, the residual force distribution before and after the push test are assumed equal and the shaft shear response is assumed hyperbolic with an almost plastic shape after an initial about 5 mm movement. The soil is assumed to be homogeneous and similar to that for the subject test site. The curves marked "FALSE" would be the distribution determined from the measurements, if the presence of residual force would be disregarded. The curves marked "TRUE" would be the distributions had there not been any residual force and if assuming that the test has fully mobilized the shaft resistance. The transition zone between negative and positive direction residual shear is omitted.

Figure 6A shows the curves for the case of assuming a fully mobilized residual force present along the pile shaft before the test (a somewhat extreme condition). Note, also, that the residual toe force is just a consequence of the interaction and the balance between shaft and toe force-movements relations. Here, the shaft shear is plastic, but the toe response not—it is never plastic. Note the halving of the distance marked "a"; fully mobilized plastic shaft resistance is equal in negative and positive directions. Thus, the "FALSE" distribution represents a distribution for twice the true shaft resistance. This makes it easy to determine the "true" force distribution and the toe force engaged in the test. For the pull test, it is even easier. The force distribution is known in two points, the pile toe and the pile head and both are zero. The shaft distribution from the pile head to the pile toe follows the rules of effective stress. If the soil is not homogeneous, the "true" curve between the head and toe can simply be adjusted to measured force records.

Figure 6B shows the similar set of force distributions for the case of not fully mobilized residual force—more often than not the case in reality. The case is special in the sense that the force distribution is due to negative direction shear force all the way to the pile toe. Without knowing whether or not the residual force is fully mobilized, the "true" distribution can only be estimated. However, if, following the recommendation of Hunter and Davisson, the push test is combined with a pull test establishing the total shaft resistance, the analysis can be reliably concluded.

Figure 6C shows the rather special case of a push test being performed following the unloading of a pull test. The residual force is the force distribution after the unloading, which left the pile with a zero toe force and a axial force increasing from the pile toe upward with the shaft resistance in the positive direction up to a level where the shear direction changes to negative, then, reducing to zero at the pile head. The residual force shown is assumed to be not fully mobilized. Had it been fully mobilized, the measured distribution within the zone of positive direction shear would have been zero.

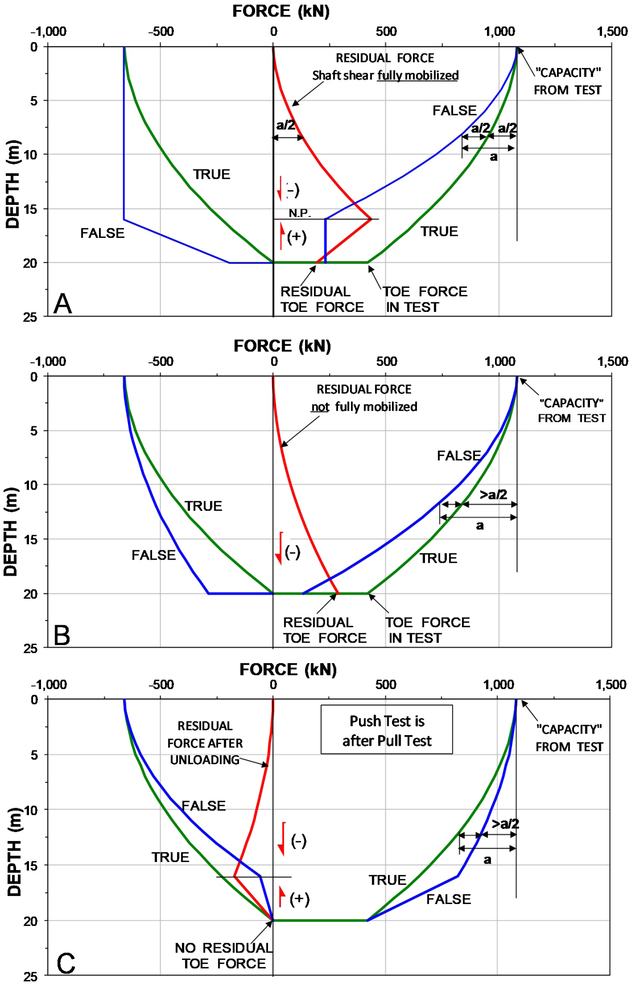

Figure 6. False and "true" force distributions for different assumed residual force distributions

Note that if a push test would have been performed after the unloading of the pull test, the “FALSE” and “TRUE” push curves of the previous figures would have traded places. Choosing a such sequence of loading is unlikely for an actual loading test on instrumented piles. However, as a thought, it serves to demonstrate the how ignoring unloading and reloading events can mess up the analysis of the force distribution of a static loading test.

Gregersen *et al.* (1973)

Hunter and Davidson (1969) did not measure residual force, but they strongly indicated that it was a fact in need of being considered and they also suggested ways to correct the results of a static loading test from the distortion of the shaft and toe resistances because of presence of residual force. Three years later, the Norwegian Geotechnical Institute presented a mile-stone paper reporting a series of full-scale tests, where the residual force was actually measured (Gregersen *et al.*, 1969). The study involved a 280-mm diameter, 16 m long instrumented precast concrete pile. Prior to the installation of test pile, it was subjected to free-standing axial loading to calibrate the gage-readings to axial force. The test pile was then driven into a normally consolidated deposit of loose sand.

Figure 7 shows the distribution of SPT N-index and cone stress, q_c, at the site and the axial force before starting the loading test (that is, the calibrated axial force as affected only by the free-standing weight of the pile) and at the maximum test load (plunging failure). The diamond points indicate the axial force distribution immediately before the test and the plus-sign points indicate the distribution measured for the maximum load applied to the pile head. The curve marked “True Resistance minus Residual Force” is the change of force induced by the test. It would normally have been thought of as the actual force distribution curve. There are still numerous papers presenting test results that mistakenly believe that the zero force in the pile is the gage reading taken immediately before starting the test.

Figure 8 shows the load-movement curves of the test comprising the load-movement of the pile head and the pile toe and pile shaft forces vs. the pile head movement. The static loading test included a series of unloading-reloading events (Figure 7 force distribution graph is from the end of the third loading event). The shaft resistance is for each plotted point the difference between the load applied to the pile head and the toe force. The zero reading is the condition before driving. Note that the test started with a residual toe force and for each unloading-reloading event, the residual toe force increased. The dashed curves are back-calculated continuous curves fitted to the test records by means of hyperbolic t-z and q-z functions pivoting around a Target Point at 8 mm movement calculated using the UniPile software (Goudreault and Fellenius 2014). The unloading-reloading

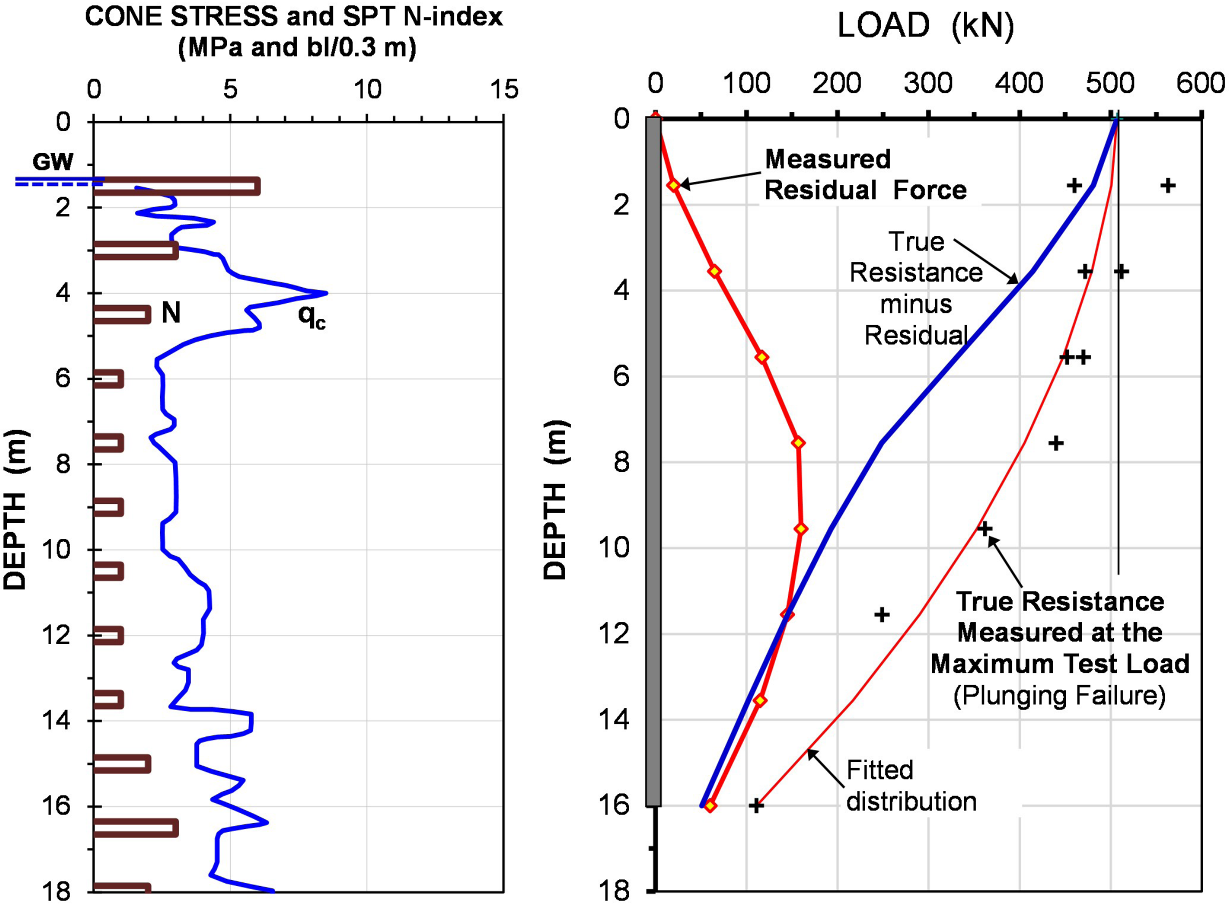

Figure 7. Soil profile and force distribution (data from Gregersen *et al.*, 1973)

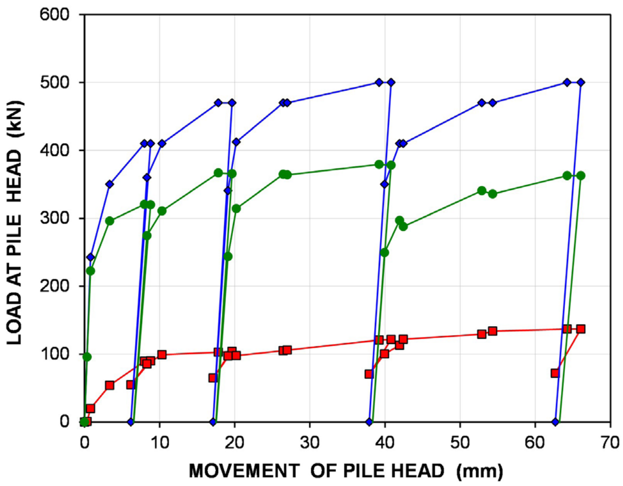

Figure 8. The load-movement of the static loading test (data from Gregersen *et al.*, 1973)

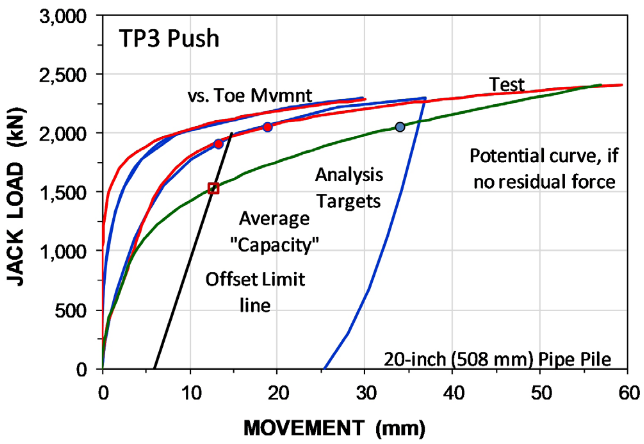

Figure 9. TP3 Load-movements in push test on TP3. Actual and simulation fit plus a potential curve for a test on the pile not affected by residual force

events, unfortunately, caused the axial pile forces to be less precise because the events will have resulted in changes due to hysteresis effects of the pile and the soil. The authors also mention that as the test proceeded, the reading became scattered and a zero drift was suspected to have occurred.

A back-calculation simulation showed that, at the 8-mm movement for the Target Point, the shaft resistance correlated to a beta-coefficient of 0.24 and a toe stress of 1.1 MPa. At the maximum load, the fit to the "True Resistance" at the much larger movement, about 40 mm, gave a beta-coefficient of 0.30 and a toe stress of 1.5 MPa.

The two papers—Hunter Davisson (1969) and Gregersen *et al*. (1973)—were the first to direct attention to the important effect of presence of residual force and the necessity to take it into account when assessing the results of static loading tests.

The build-up of residual force is a complex issue. The interaction between the toe spring and the shaft response will build in residual force, somewhat dependent on the flexibility of the pile and the soil. Bored piles are thought to be unaffected by this, but here, the reconsolidation after construction may result in imposition of negative skin friction accumulated to residua force. Both pile types will be affected by residual force if an ongoing subsidence exist at the test site. Negative skin friction will then start to build up along the pile elements down to an equilibrium plane, EP and then be counteracted—balanced—by positive shaft resistance below the EP plus a build-up of toe resistance.

"Capacity" of Pile With and Without Presence of Residual Force

Hunter and Davisson (1969) concluded that presence of residual force in a pile will not affect its capacity. They probably had in mind "capacity" defined as a single-point ultimate resistance on the pile-head load-movement curve. The quoted statement is not true, however, because the presence of residual force will cause the load-movement response to appear stiffer and, thus, give the appearance of a larger "capacity". This is demonstrated in Figure 9, showing, for TP3, the back-calculated pile-head and pile-toe load-movement curves and simulated curves made to fit them—the simulation applied the effective stress parameters gave the "True" TP3 distributions, Curves 7 and 8, shown in Figure 5. The fit was obtained by assuming a rather stiff initial stress-movement response of unit shaft as well as toe resistance and performed using the UniPile software (Goudreault and Fellenius 2014). The fit was achieved by assuming a beta-coefficient of 0.30 for a 8 mm element movement rising to 0.40 at a 60 mm movement and a toe stress of 5 and 7 MPa at toe movements of 8 and 60 mm, respectively. These value are larger than those back-calculated for the precast concrete pile (Gregersen *et al*., 1974), reflecting the fact of the sand being compact to dense, as opposed to loose.

The graph also includes the load-movement curve calculated for no presence of residual force (by using a less stiff shaft and toe response). The adding of the Davisson Offset Limit line, which intersection with the pile-head load-movement curve is often taken as indication of the pile "capacity", shows that the presence of residual force would, indeed, affect the assessment of the test in terms of a "capacity" produced by any other definition than "plunging failure"; here about 1,500 kN as opposed to 2,000 kN. As the parameters of stress-movement response of the pile elements interact and allow for many different interactive assumptions, many similar different "potential" curves can be produced all showing smaller initial stiffness than the actual curve, but all would show a Davisson offset limit smaller than that for the test curve.

The comparison shows that the residual force has stiffened up the pile and made a foundation supported on similar piles experience smaller deformation as opposed to a pile that has no residual force, but is otherwise equal. Again, the two piles would have the same plunging load, however.

Piles installed by Impact Driving versus Vibratory Driving

The tests reported by Hunter and Davisson (1969)included both impact driven piles and vibratory driven piles only casually addressed by Hunter and Davisson (1969). It is often expected

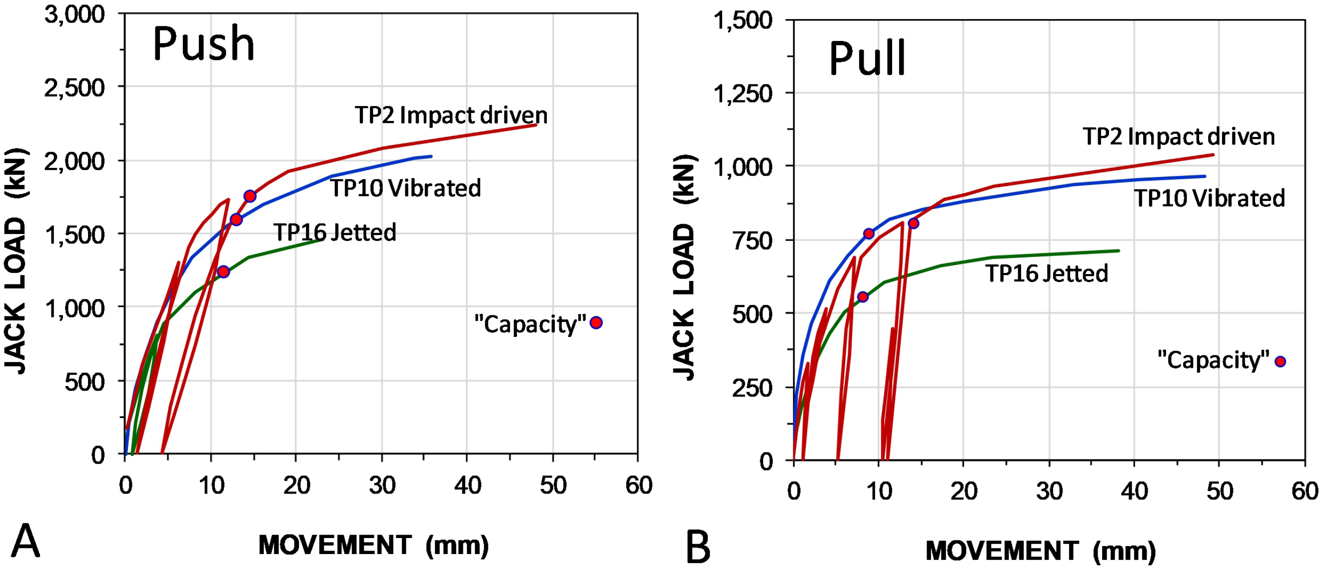

Figure 10. Load-movement response between impact driven, vibrated, and jetted 16-in pipe-piles

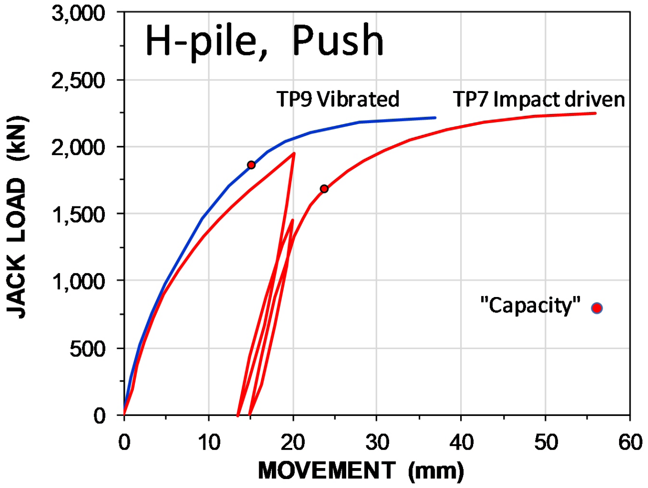

Figure 11. Load-movement response between impact driven and vibrated H-piles

that vibrated piles would have a smaller capacity than impact driven piles. This is not what can be deduced from the Lock and Dam 4 tests, however. Figure 10 compiles the load-movement results of the impact driven, vibrated, and jetted piles and shows no significant change in response between the impact driven and vibrated piles. There is a definite reduction for the jetted pile, however. Mansur and Hunter (1970) also included results from a static push test at the site on an H-pile, TP9, a pile similar to TP7 that was vibrated and Figure 11 shows a comparison between the load-movement response of these two piles. Again, there's no significant difference.

Conclusions

Hunter and Davisson (1969) brought the fact of presence of residual force to the attention of the profession. They concluded that residual force remaining in the pile after driving and after compression testing must be accounted, for if a true representation of load transfer is to be obtained. However, the suggestion that a push tests should be coupled with a subsequent pull test, while having substantial technical merit, it is only rarely implemented due to costs. Consequently, presence of residual force in driven piles is not often considered in the assessment of the results of a static loading test. The approach shown in Figure 6 will then provide some assistance to a judgment-based assessment.

The two papers showed that the driving of a pile leaves the pile with a residual force and that this force increases due to the subsequent loading and unloading of the static loading test. Together, the two papers showed clearly that an instrumented test pile must have means to determine the residual force, or the back-analyzed force distribution and that not recognizing or not properly assessing the presence of residual force will result in concluding that the pile has larger shaft resistance and smaller toe resistance than actually the case. If the test and erroneous back-analysis is applied to a piled foundation design involving effect of general subsidence, such as downdrag and, for long piles, drag force concern, costly incorrect design decisions will result (e.g., Fellenius and Jacobs 2023).

The construction of bored piles does not leave the pile with presence of appreciable residual force and, in assessing the results of a static test, residual force is usually assumed negligible. However, bored piles constructed in subsiding soil will experience a build-up of residual force that, then, needs to betaken into account. A loading test on a bored pile can employ the bidirectional method, which provides measurements of the axial force at a depth in the pile, usually near the pile toe, and allows for knowing accurate values of axial force at two points (the second one is the zero load at the pile head), which provides a considerable support for the assessment of the force distribution determined by the pile instrumentation.

Hunter and Davisson (1969) concluded that shaft resistance mobilized in the push tests was somewhat higher than that observed during pull tests. The force distribution graphs presented in the paper do not support this conclusion, however. In fact, the authors' use of the post-pull and post-push forces appear to support the opposite, that the resistance in push and pull are about equal when considered in terms of the full force-movement response, the t-z and q-z functions.

The project also launched Tom Davisson into a distinguished career of piled foundation studies and he pioneered much of the current state-of-the-art of static and dynamic testing of piles, including the need for always having a load cell to determine the applied load. Because such cells were not readily available at the time, he manufactured and made commercially available a very accurate and field-worthy load cell, which quality I can vouch for having been the owner of two of them.

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