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Bearing of Uniform Pile Versus Tapered Pile: A Full-Scale Study

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ABSTRACT: *Anecdotal observations of axial response of uniform and tapered piles and model-scale tests have suggested that tapered piles provide higher bearing than uniform piles of equivalent dimensions. However, there is minimal reliable full-scale comparative data. Records of three previous full-scale tests comparing the response to load of equivalent uniform and tapered piles in Sweden, Iran, and Italy were analyzed, along with results of recent instrumented full-scale test piles in Mobile, Alabama, USA. The results of all tests showed that tapered piles developed substantially larger shaft resistance, at least doubling that of the uniform piles along the tapered length and, despite the smaller toe size, the bearing of equal-size tapered piles exceeded that of uniform piles by up to 20% at comparable settlements. Back-analysis using UniPile6 software confirmed that the increased shaft resistance due to the taper could be represented as a "donut" effect. Lessons were learnt about how not to arrange details of a test.*

KEYWORDS: *Uniform piles, Tapered piles, Static loading test, Dynamic test, Shaft and toe resistances, Force converted from strain, t-z and q-z functions, CPT-sounding*

SITE LOCATION: Geographic Database

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INTRODUCTION

Foundations placed on soft soil, usually clay or silt, have been supported on piles for more than two thousand years. For the longest time, only tapered piles—timber piles—were available. Uniform cross section steel pipes or steel beams used as piles emerged about two hundred years ago. About a hundred years ago, the driven precast pile appeared. Anecdotally, it was "known" that the timber pile had larger bearing than the same size (pile butt) and length of the alternative pile. The reason, it was stated, was that, unlike steel and concrete, wood drained the soil, enabling it to consolidate and gain strength. Until recently, the taper itself was considered to have negligible effect on the pile bearing. However, since the mid-1900s, and mostly for piles driven in sand or coarse silt, it has been stated that tapered piles provide larger bearing than equal size or equal surface area uniform piles.

Piled foundations comprising tapered piles are now regularly used in many areas due to this higher bearing and also due to reduced material costs. For example, tapered steel pipe piles are common in Eastern USA and tapered spun piles are frequently used in Switzerland and Northern Italy, especially when associated driving vibrations can be accepted (G. Togliani, 2025, personal communication).

The larger bearing of the tapered pile compared to an equivalent-sized uniform pile is anecdotal, because there are only few full-scale correlations in directly comparative tests on uniform piles; three are quoted in this paper. To meet the need for case

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records, where uniform and tapered piles are directly compared, Browning Enterprise, Inc. sponsored a test series in Mobile, AL, comprising full-scale, side-by-side, static loading tests comprising three tapered steel pipe piles (TSFP) and two uniform piles (Fellenius, 2025b; SACL, 2025).

THE ANALYSIS OF PILE RESPONSE TO APPLIED LOAD

Shaft and toe resistances depend on two aspects. First, both are proportional to effective stress and they depend on relative movement between the pile and the soil. Unit shaft resistance is expressed by the ratio between the shear force and the effective stress, called "beta-coefficient (ß)", and unit toe resistance, similarly, by the toe-coefficient, called Nt. The ß- and Nt- coefficients depend on the site geology, i.e., the manner of soil generation (sedimented or residual), whether they are calcareous or carbonaceous, the general mineralogy, etc., and on rotation of principal stresses, the particular shear- and E-moduli, and, indeed, on pile taper. Second, the coefficients are also proportional to the mobilized movement between the pile surface and the soil, usually assumed to occur right next to the pile surface (i.e., the soil is assumed to not move due to the pile imposed movement. In reality, movement does not occur directly at the interface surface, but within a shear deformation zone around the pile. That is, the movement reference lies away from the pile). Whether or not the soil is preconsolidated or preloaded plays a part, but how so is almost always unknown. However, this effect is considered limited to the initial part of the force-movement curve of the pile elements (Fellenius, 2026).

Determining what effective overburden stress relation to use can be quite complex, as the effective stress analysis has to consider the variation of density, depth to the groundwater level, potential pore pressure gradient in the soil layers, potential fills, loaded areas, and excavations and distance of the pile to these latter occurrences.

Both shaft and toe resistances are a function of the movement between the pile elements and the soil. Yet, it is common to represent the resistance, be it shaft or toe, by a single value, an ultimate resistance that is independent of movement and also of surrounding soil stress. Because shaft resistance normally develops an approximately plastic response after an initial movement, as a characterization, an ultimate shaft resistance does have informative value. Moreover, shear resistance is governed by the effective stress in the surrounding soil. Therefore, a shaft resistance must always be related to effective stress and magnitude of movement between the pile and the soil. Toe resistance rarely develops plastic condition and, as a characterization, ultimate toe resistance is meaningless. Both shaft and toe resistances need to be determined in concert with their specific movement relation and the effective stress in the soil.

The shaft and toe resistances movement relations are called t-z and q-z functions describing resistance versus movement. As to the shaft resistance, initially, the ß-coefficient vs. movement curve rises steeply, almost linearly, and, then, it either becomes constant (plastic—ultimate shaft resistance), or shows a transition to a gradual increase (strain-hardening) or decreases gradually (strain-softening). As to the toe resistance, the N_t-coefficient versus movement usually shows a gentle rise from zero to infinite movement, always strain-hardening—there is normally no ultimate toe resistance unless a value at a specific movement is so denoted.

The β- and N_t-coefficients depend on the soil characteristics, which can vary immensely from site to site, and on the construction procedures (driven, bored, material, etc.), and correlations are not well established. Therefore, no analysis of

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response of a pile to an applied load is possible without correlation to experience, preferably, back-analysis of actual tests. For soil conditions being similar along the pile and at the pile toe, the ratio between the N_t- and the *ß*-coefficients, $N_t/ß$ usually ranges from about 40 to 100 in cohesive soil and from 100 to 150 in granular (Fellenius, 2004; 2026).

For a uniform pile, the shaft resistance expressed by the *ß*-coefficient is governed by the mobilized shear force with minimal change to the soil. However, for a tapered pile, the movement of the pile introduces a lateral component and a compression of the soil that adds to the shear resistance. The effect of the compression due to the taper can be accounted for by increasing the ß-coefficient or by an add-on separate value correlated to the taper by different ways. For example, Nordlund (1963) proposed a calculation based on the rotation of principal stress associated with the taper angle. Kodikara and Moore (1993) proposed a simplified similar analysis. Hatah and Shafaghat (2015) performed numerical analyses. Fellenius (2004; 2026) suggested to address the effect to the taper with a "donut" approach. That is, the projected size difference—the "donut" area—between the top and bottom of any unit length of the pile can be treated as a donut-shaped pile toe that adds resistance. This "donut" contribution can be calculated by means of applying a donut N_t coefficient to the projected area, as suitable for the soil layer.

The most common objective of a back-analysis of test results is to obtain the parameters that determine the movement (settlement) of a single pile or a group of piles supporting a specific sustained load, or of piles of lengths and sizes that differ from the test piles in some way or either.

Back-calculation analysis of the load response of a pile element comprises fitting the strain-gage calculated force and movement to those measured at the gage level. Each fit involves selecting first a specific point, i.e., a "Target Force" and associated "Target Movement". Then, effective stress conditions are applied to fit a calculated force-movement to the target force-movement points (values). The next step is to choose a t-z (or q-z) for the pile element and adjust it in a series of trial calculations until calculated force-movement curve and measured agree. An adjustment of the target force may be found necessary as the fitting progresses.

The analysis of loading test results starts with fitting calculations to the measured pile-toe element. After achieving a satisfactory fit for the toe-gage force-movement, the action is repeated for the next gage level up, keeping the input that gave the fit to the pile toe element, etc., until, finally, the measured and calculated pile-head load-movement agree. The so-obtained various target forces (N_t- and, then, *ß*-coefficients) and movements (t-z and q-z functions) constitute the theoretical analysis parameters expressing the pile response.

The analysis is quite direct as no heavy algorithms are included. However, it is too complex for a hand calculation, even with spreadsheet assistance other than for very simple cases. It is, therefore, necessary to employ a suitable software. Interacting with the UniPile6 software (www.unisoftGS.com) will make the process simple and fast, be the pile uniform or tapered.

RESULTS OF LOADING TESTS ON TAPERED PILES

Several model tests and numerical analyses have been published that compare the response of tapered and uniform piles. For example, Robinsky and Morrison (1964) reported tests performed in a sand box that showed taper piles mobilizing considerable greater shaft resistance than straight-sided piles. In other laboratory model test series, El Naggar and coworkers

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performed static loading tests on 1.2 m long model piles, tapered and uniform, in sand in a chamber equipped with an air bladder that could produce horizontal stress on the pile shaft. They found that that the shaft resistance of the tapered piles was greater than that of the uniform piles (Wei and El Naggar, 1998; El Naggar and Wei, 1999; El Naggar and Sakr, 2000; and Khan et al., 2008). Paik et al. (2010) also performed model tests, finding similar results, specifically that that the taper may also enhance unit toe resistance. Ibsen and Barari (2025) tested 2 m long piles installed by jacking into sand. Gupta and Rajagopal (2015) and Shafaghat and Khabbaz (2020) presented brief reviews of the aforementioned references and others.

Fellenius and Ataee (1999) criticized the relevance of the various model tests, stressing the fact that while they produced results of qualitative values, such as indicating that taper enhances shaft resistance, the quantitative results, such as ratio of enhancement, resistance distribution, and evaluated soil parameters, are not directly applicable to response of full-scale piles.

If presence of the taper had no effect, one would expect that a uniform pile and a tapered pile, if having the same surface area, would show the same total shaft resistance. However, the toe response of the tapered piles would be smaller due to its smaller toe area.

The anecdotal contention of greater bearing for tapered piles is supported by the results of several full-scale static loading tests on tapered piles, showing good bearing performance, e.g., Dougherty (2017), Fellenius et al. (2000), Horvath and Trochalides (2004), and Shafaghat and Khabbaz (2020). However, the references do not include comparison to uniform piles.

Indeed, all the aforementioned papers, and many others not mentioned, share a weakness: the absence of full-scale tests for use in direct comparisons and in support of theoretical calculation for equal conditions. Case histories that provide direct comparison of load-movement response of tapered pile versus uniform pile are rare. I only know of four. The first is from Massarsch et al., 1997, testing vibratory driven piles. The test included static loading tests on 9 m long, 200 mm open-toe steel pipe and a 500 to 150 mm conical concrete pile driven in sand in Sweden (Massarsch et al., 1997). The taper was 19 mm/m; 1.11°. The tests showed that the tapered pile produced significantly larger bearing and that the vibratory driving increased the shaft response due to larger compaction effect developed by the tapered section as opposed to the uniform. However, the uniform and tapered piles are too dissimilar to warrant a detailed response comparison.

Tests in Iran

The second full-scale case, presented by Ghazavi and Ahmadi (2008), compared the response of uniform and tapered piles in full-scale tests in Iran on two, 12.5 m long, square cross section, driven, precast concrete piles. The soil description was described as being "cohesive". The paper included no mention of the depth to groundwater table. For input to the effective stress analysis, it was assumed to be at 1 m depth. One pile was uniform 400-mm diameter and the other was a 570-mm diameter, 12.5 m long pile tapered along the full length to a 200 mm toe diameter, i.e., a taper of 7.5 mm/m; 0.5°. Thus, the piles had essentially equal shaft area, but the ratio of toe area of the taper pile to the uniform pile was 12 %. The reported load-movement curves, shown in Figure 1, indicated that the tapered pile developed considerably larger bearing than the uniform pile. The piles were tested twice, first at 35 days after driving and then, again, 254 days later. The gray curves show the results of UniPile simulation fitted to the curves.

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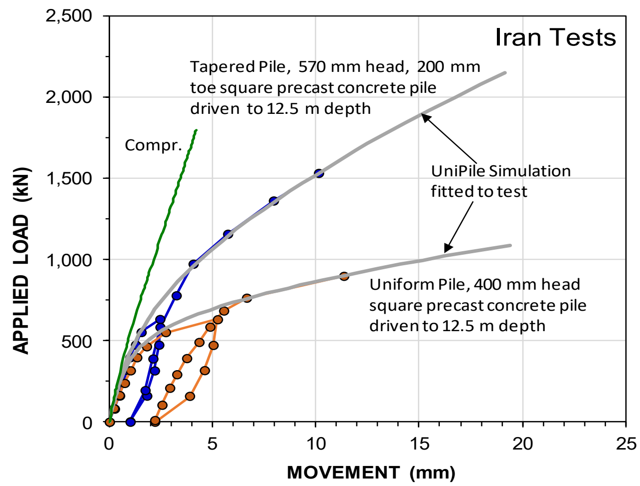

Figure 1. *Comparison between 12.5 m long tapered and uniform square precast piles with UniPile simulations.*

The limited information prevents a systematic back-analysis of the tests for meticulous assessment of the difference in response of the uniform and tapered pile shafts. However, it is still possible to obtain qualitative analysis results useful for a comparison of uniform versus taper response. My personal experience of back-analyses of loading tests on uniform piles in cohesive soil suggests that the simulated shaft resistance be per a hyperbolic t-z function with a target resistance of $ß = 0.25$ at 5 mm movement and a hyperbolic t-z function with coefficient of 0.95 (equal to 90 % of the resistance at large movement; theoretically infinite). The same t-z function was used for both piles. The toe resistance fit, also same for both piles, was a Gwizdala q-z function with an $N_t = 13$ toe resistance and function coefficient of 0.6. Thus, the ratio between the target N_t- and $ß$-coefficients, $N_t/ß$, was 52. Figure 2 shows the t-z and q-z functions assumed for the UniPile6 interactive calculations. For reference, a reasonable fit for the uniform pile, although not quite as good, would also be possible with input of similar functions but with other coefficients; the assumed ß-coefficients controls the choice of N_t-coefficient for the target input. Details on t-z and q-z functions are available in Fellenius (2025a).

For the fit to the tapered pile to the measured the load-movement curve, the analysis imposed using the same $ß$- and N_t-coefficients and the same q-z function as used for the fit for the uniform pile with input of a "donut" coefficient, N_t, of 33. To emphasize, the only difference between the two simulations was applying the "donut" method to the taper projection.

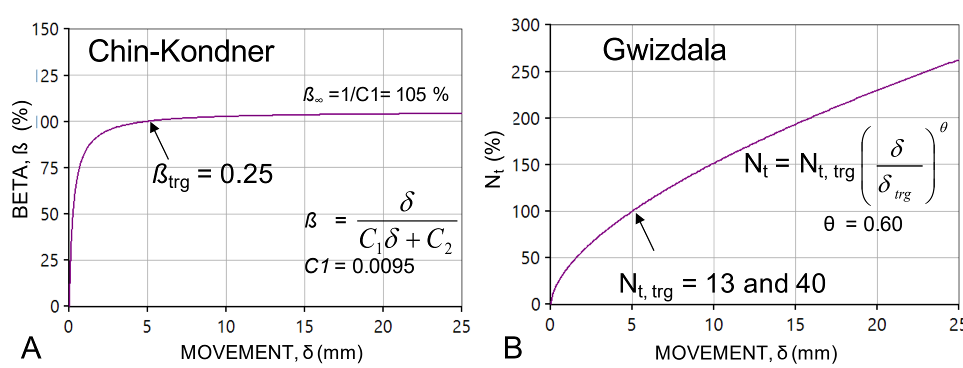

Figure 2. *The t-z and q-z functions applied in fitting the simulations to the measured curves from the Iran tests (UniPile6 input per equations given in Fellenius, 2026).*

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The UniPile6 software enables extracting the shaft resistance and axial force distribution for any applied load of the simulated response for the uniform and tapered piles. Figure 3A shows the shaft resistance of the piles for movement beyond about 8 mm, indicating that the shaft resistance of the tapered pile had mobilized more than twice that of the uniform pile for equal movement. Figure 3B shows the distribution of axial force in the two piles. The toe resistances are proportional to the respective toe areas.

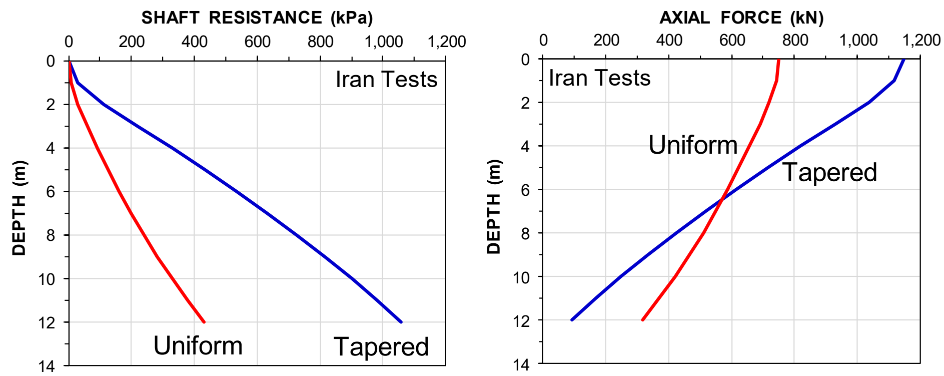

Figure 3. *Distribution of shaft resistance in uniform and tapered piles.*

Porto Marghera Tests

The third full-scale case is from static loading tests in Porto Marghera, near Venice, Italy, on two pairs of spun piles, 10 m and 15 m long, respectively (Gambini, 1973). Each pile pair comprised one uniform and one tapered pile. The tests were conducted in push followed by pull, which enabled determining the shaft and toe resistances separately. The piles were driven through an about 5 m thick mixture of loose fine soil deposited on about 5 m of fine sand followed by mixture of loose fine soil. Figure 4 shows the CPT diagram from a mechanical cone pushed at the test site. The groundwater table was at 1 m depth.

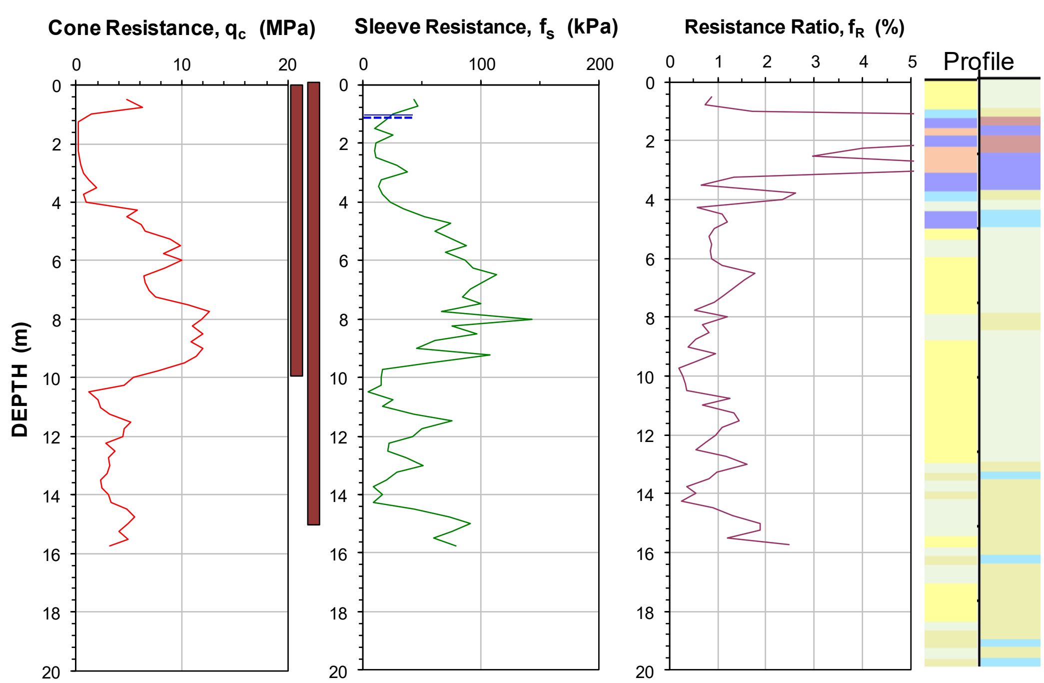

Figure 4. *CPT diagrams for the Porto Marghera test site (Gambini, 1973).*

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The 10 m uniform pile had 330 mm diameter and the 10 m tapered pile had a 390 mm head diameter, reducing to a 240 mm toe diameter. The 15 m uniform pile had 400 mm diameter, and the 15 m tapered pile went from a 460 mm head diameter to a 240 mm toe diameter. For both piles, the taper was 15 mm/m; 0.85°. The total shaft area of both tapered piles was about equal to that of the matching uniform pile. The pile toe areas were 855 cm^2 and 1,257 cm^2 for the uniform piles and 452 cm^2 for the tapered piles, i.e., the ratios of toe areas of taper pile to uniform pile were 53 and 36 %, respectively.

Figure 5 presents the results of the loading tests, comprising head-down tests on the four piles followed by pull tests. The separation of the pull test load-movement curves may be due to the difference in pile surface area. The pull tests on the 15 m piles incorporated an unloading-reloading event and this distortion may be why no similar difference occurred. The gray curves with no symbols show the results of UniPile simulation fitted to the curves.

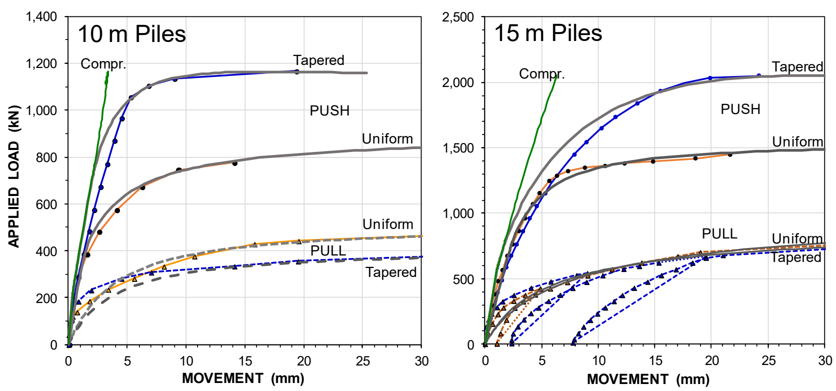

Figure 5. *Comparison between 10 m and 15 m long tapered and uniform spun piles (Gambini, 1973).*

This test series enables separation of shaft and toe resistance. The first analysis step comprised fitting a UniPile6 interactive analysis to the load-movement of the 10 m uniform pile pull test, which gave a target of ß-coefficient for 5 mm pile element movement, then, keeping that t-z function for the 10 m pile push test in addressing the pile toe response, i.e., finding the target N_t-coefficient for 5 mm movement and the q-z function that gave the fit to the full curve. The fit for the initial part is not as good, which is often found for piles with some presence of residual force. The input is shown in Figures 6 A and 6D and it was the same for both pile types. Of course, for the pull tests, there is no "donut" effect.

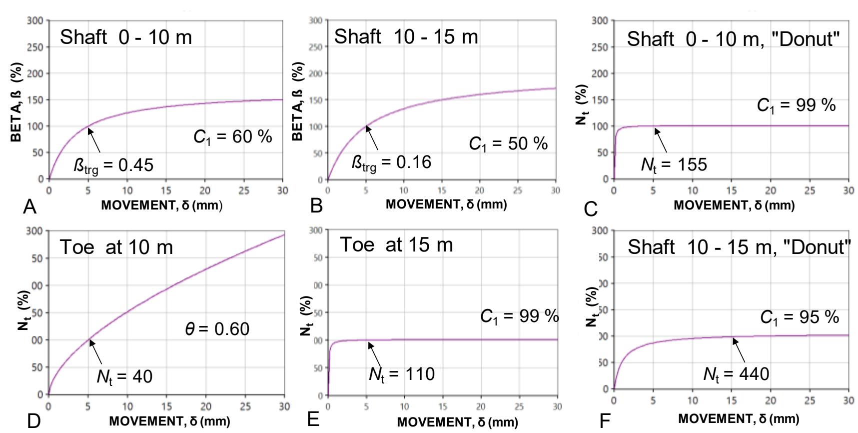

Figure 6. *The t-z and q-z functions applied in fitting the simulations to the measured curves, Porto Marghera tests.*

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Next came addressing the push tests. The same shaft input was used for both pile types, shown in Figures 6A and 6B. The toe input for the 10-m and 15-m uniform piles differed between the 10 m and 15 m depths, but was again the same for both pile types, Figures 6B and 6C. The "donut" input for the 10 and 15 m long piles is shown in Figures 6C and 6F.

The tests on the 10 m piles resulted in *ß*- and N_t-coefficients for the 5 mm target movement of 0.45 and 40, respectively. The analysis imposed using the same ß- and t-z function for the uniform and tapered piles, and leaving the difference between the load-movement curves to be fitted by means of the "donut" effect. Note, the use of the same input other than the "donut" effect does not prove that the uniform and tapered shaft shear and toe resistance responses are equal. The tests on the 15 m piles resulted in *ß*- and N_t-coefficients for the 5 mm target movement between 10 - 15 m depth of 0.16 and 110, respectively. Thus, the ratio, N_t/β was 690, which appears to be unlikely large. Imposing that the 15 m long piles should have the same ß- and N_t-coefficients in the 0 - 10 m depth as the 10 m piles might not be realistic.

Eyeballing the curves and considering the fact that the surface area of the two pile types were about equal, the taper shape appears to have close to doubled the shaft resistance at the 10 and 15 m pile lengths as shown in Figure 7A. Figure 7B shows the axial force distributions. The dot symbols are the values derived directly from the test records and the curves show the distributions determined in the UniPile simulations for large movements and 1,400 kN applied load, extrapolated for the uniform pile.

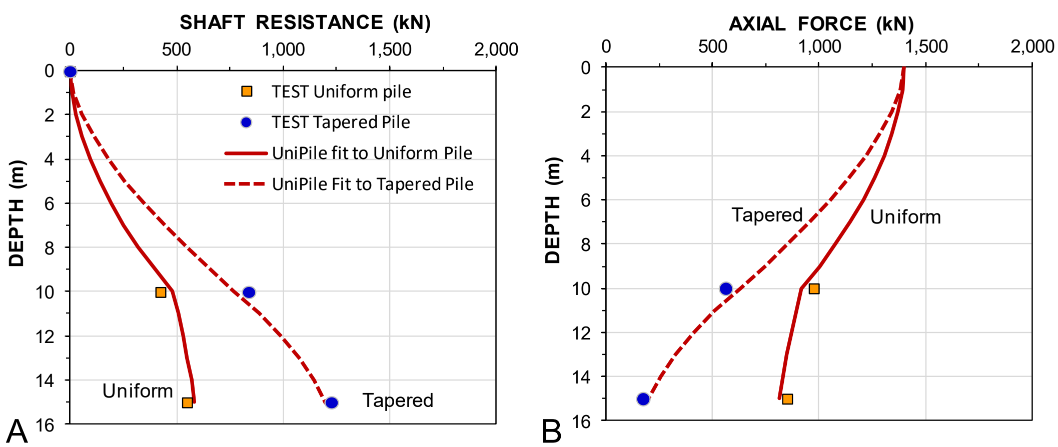

Figure 7. *Shaft resistance and axial force distribution from tests and from back-analysis.*

Monselice Tests

The fourth test series comprises a static loading test carried out in 2018 on a pair of 12 m long spun piles in Monselice, 50 km away from the Porto Marghera site (Togliani, 2025, private communication). One pile was uniform and one tapered. The diameter of the uniform pile was 330 mm and the tapered pile diameter was 420 mm at the pile head and 240 mm at the pile toe; both piles had the same total surface area. The piles were driven through an about 8 m thick mixture of fine soil followed by an about 2 m thick layer of clay deposited on sand. Figure 8 shows the CPTU diagrams from the test site. The groundwater table was at 4 m depth.

Figure 9 presents the results of the head-down loading tests on the two piles. The gray curves show the results of UniPile simulation fitted to the curves. A target *ß*-coefficient of 0.40 for a 5 mm movement and a Chin-Kondner t-z function with a

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coefficient (C_1) of 0.0098 (ß = 0.410 at infinite movement) fitted the result of the test on the uniform pile. For the tapered pile, the fit applied the same input of β and toe N_t-coefficients and the same t-z and q-z functions as used for the uniform pile. The compression effect of the taper was modeled by input of a "donut"-function with a target toe coefficient, N_t, of 130 and a Chin-Kondner hyperbolic q-z function with a function coefficient of 0.0085 at a 5-mm target movement (large-movement N_t-coefficient of 170). The respective functions are shown in Figure 10. The pile toe q-z response followed a Gwizdala function with a coefficient, θ, of 0.40. The N_t-coefficient was 55 at a target movement of 5 mm. Thus, the N_t/β ratio was 138. The "donut" N_t/β-ratio was 425.

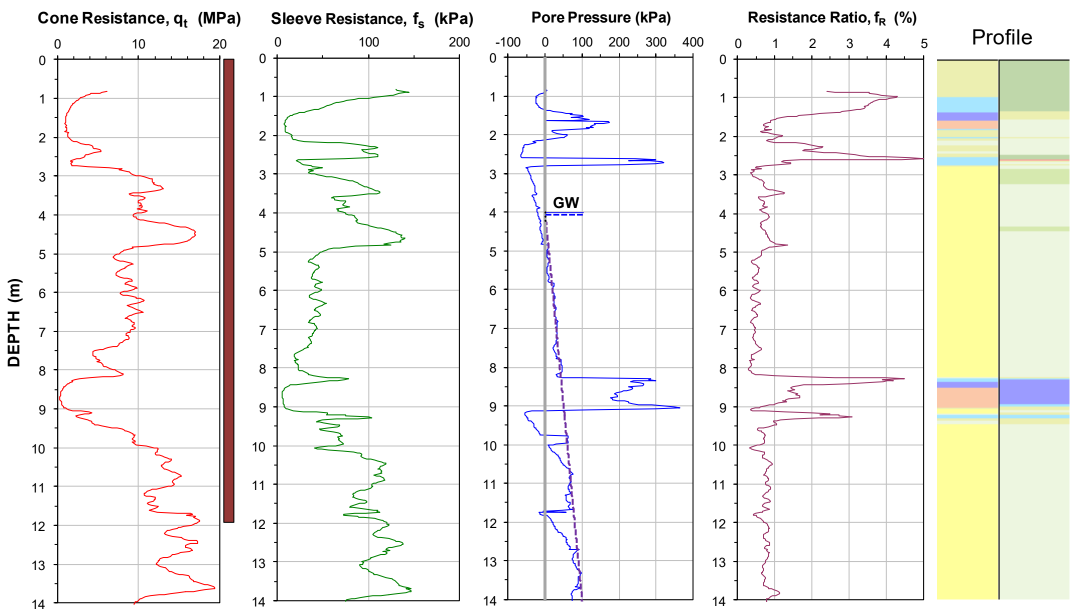

Figure 8. *CPTU diagrams for the Monselice test site (Togliani, 2025).*

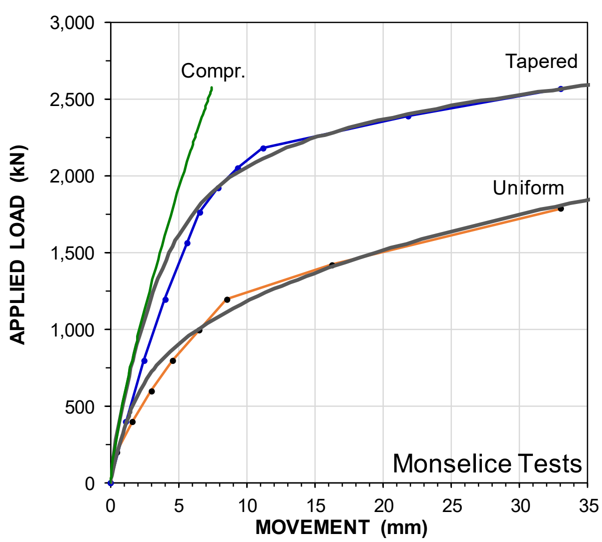

Figure 9. *Comparison between 12 m long tapered and uniform spun piles (test data from Togliani, 2025).*

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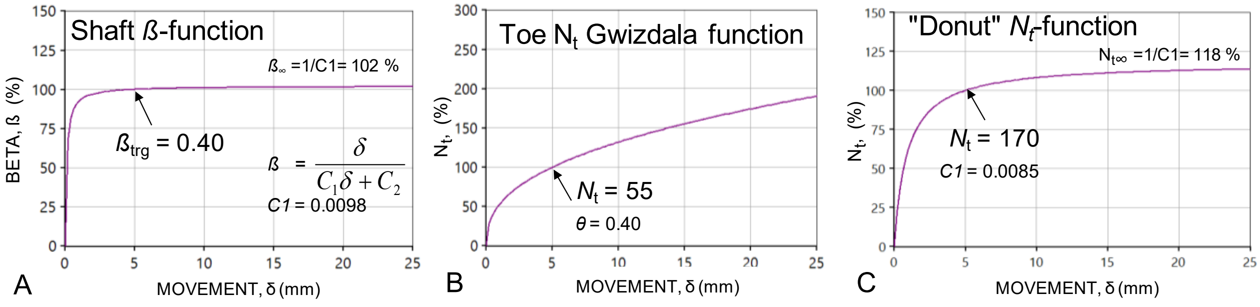

Figure 10. *The t-z and q-z functions applied in fitting the simulations to the measured curves, Monselice.*

Figure 11A shows the shaft resistance and the axial force distributions of the uniform and tapered piles as extracted from the UniPile6 output for movement beyond about 10 mm and at a 1,400 kN applied load. The values indicate that the tapered pile mobilized more than twice the shaft resistance of the uniform pile. Figure 11B shows the distribution of axial force in the two piles. The calculations indicated that for the uniform and tapered piles to move beyond about 10 mm required applying about 1,500 kN and 2,400 kN, respectively. The toe resistances are proportional to the respective toe areas.

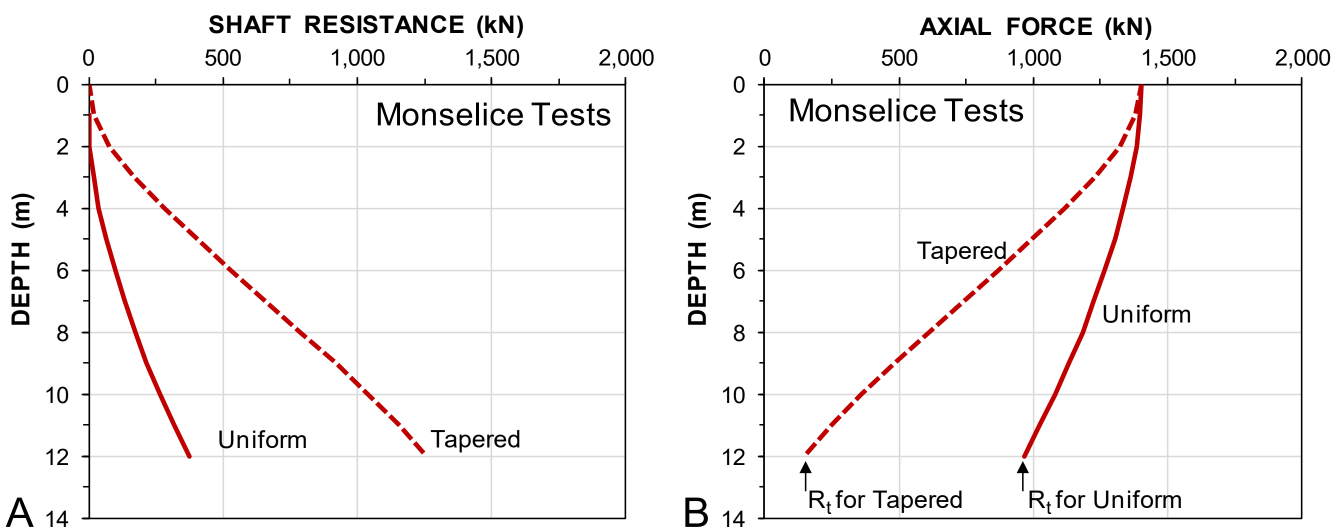

Figure 11. *Shaft resistance and axial force distribution from tests and from back-analysis, Monselice.*

Full-Scale Tests in Mobile, AL

Piles, Instrumentation, Soil Profile, and Loading Tests

On March 26. 2025, five test piles, TP1 - TP5, were driven in Mobile, AL, to 17.4 m of predetermined depth. The piles were concrete-filled, closed-toe, pipe piles with a 9.5 mm wall with 457 mm diameter. Piles TP1 and TP2 were uniform and Piles TP3, TP4, and TP5 were TSFP piles, i.e., with the same diameter down to 7.6 m above the pile toe, from where the section tapered to 203 mm toe diameter, i.e., a taper of 16 mm/m; 1.0°. The steel area, A_{steel}, of the 457 mm section was 169 cm^2. The shaft surface area of the tapered length was 83 % of the uniform pile and the pile toe area was 20 % of the pile toe area of the uniform pile.

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Pile TP5 was scheduled to include a bidirectional cell (hydraulic jack) placed just above the transition between the straight and the tapered sections. The purpose of the bidirectional test on TP5 was to test for potential locked-in residual force. However, as described later in this paper, the concreting operation adversely affected both the strain-gage instrumentation and the BD-cell in TP5, the bidirectional test pile. The latter to the point that the bidirectional test could not be performed on Pile TP5. A head-down test was performed, instead.

The piles were instrumented by means of vibrating-wire strain-gages Type Geovan Model GV-2410 and full-length compression telltale rods. The gages were placed on a rebar cage comprising four #5 bars (15.9 mm) held together with about 200 mm diameter rings spaced 2 m apart and equipped with spacers (bracings) to center the cage in the pile. The gages were placed as one or two diametrically opposed pairs at five levels in Piles TP1 - TP4 and six levels in Pile TP5 at the depth indicated in Table 1. (Pile TP5 gage depths are as field-adjusted due to the placement difficulties.) The two most important gage levels are the uppermost level (which were to serve as calibration gages for determining the EA-parameter of the pile cross section) and the pile-toe gage, which determines the pile-toe force (relying on the EA calibration).

Table 1. *Gage depths and pair numbers*

	TP1 - TP4		TP5	
Gage Level	**Depth (m)**	**No. of Pairs**	**Depth (m)**	**No. of Pairs**
SG6			0.52	2
SG5	0.42	2	6.42	1
SG4	6.42	1	8.27	2
SG3	9.41	2	9.82	2
SG2	14.42	1	14.07	1
SG1	16.89	2	14.62	2

But for an about 2 m thick zone of loose gravelly sand with 30 % fines content between 4.6 and 6.4 m depth, the soil consisted to 90 % of sand size grains, and the density was 1,850 kg/m3. The density over and below this zone was 2,050 kg/m3 and the consistency was compact to about 6.4 m depth, loose to about 16.4 m, and then dense. When the static loading tests were carried out, the groundwater table (GW) was at 5 m depth. Figure 12 shows results of a CPTU sounding performed at the site. The qt-graph is supplemented with the distribution of SPT N-indices.

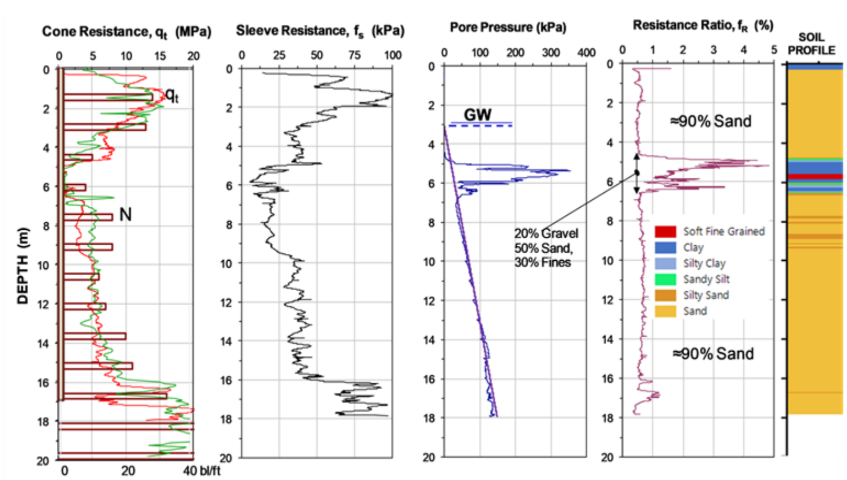

Figure 12. *Soil profile by CPT and SPT records.*

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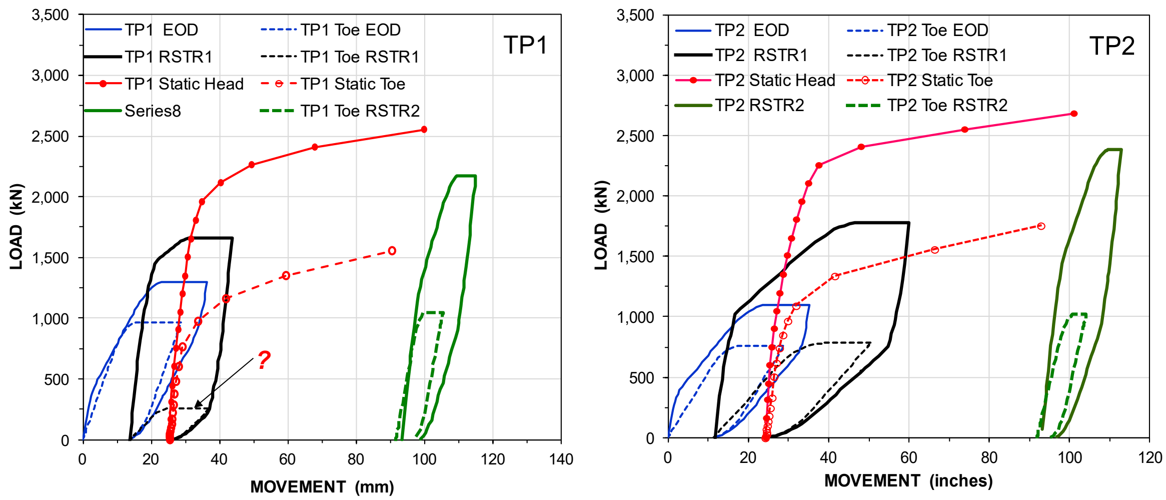
Dynamic Tests

The test piles were driven using an APE D30-32 open-end diesel hammer, with a rated energy of 69.9 kip-ft (94.8 kJ), to the 17.4 m predetermined depth. The pile driving was monitored using Pile Driving Analyzer (PDA) during initial driving and at restrike (RSTR1) on March 28. A second restrike (RSTR2) was performed on all test piles on April 29, 33 days after end of driving.

The CAPWAP determined load-movement curves are compiled in Figure 13A - 13C for Piles TP1 through TP5, respectively, together with the load-movement curves measured in the static loading tests, which were carried out 7, 14, 12, 13, and 18 days after the pile were installed. The CAPWAP determined load-movement curves plot consistently below those measured in the static loading test (red curves).



Figur 13A. *Piles TP1 and TP2. Load-movement curves of static test and CAPWAP.*

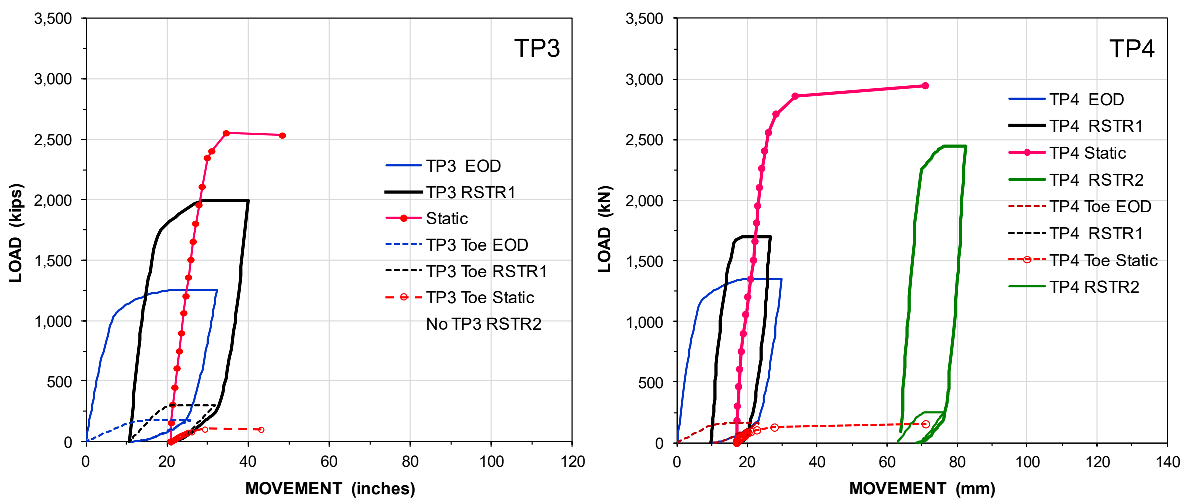


Figure 13B. *Piles TP3 and TP4. Load-movement curves of static test and CAPWAP.*

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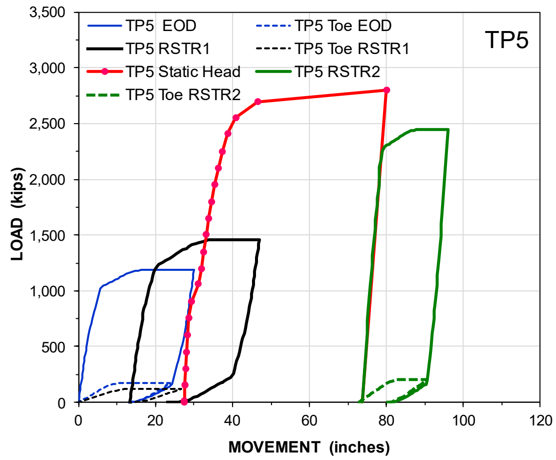

Figure 13C. *Pile TP5. Load-movement curves of static test and CAPWAP.*

The CAPWAPs indicated that there was a slight set-up between the End-of-Driving (EOD) and the one-day restrike (RSTR1) events. The CAPWAP results from the 30-day restrike (RSTR2) implied that the set-up continued during the full month additional wait time. However, considering that the adding of concrete had increased the pile mass by about four times, the RSTR2 CAPWAP results are not fully comparable to the RSTR1 CAPWAP results.

The notable finding is that for both the static and dynamic tests, the pile-toe resistance for the uniform piles (Piles TP1 and TP2) were significantly larger than that for the taper piles (Piles TP3 - TP5), as would be expected, of course. As the difference is much larger than the difference between total resistance, both the static and the CAPWAP results indicate that the shaft resistance of the taper piles was larger than that of the uniform piles despite the larger surface area of the latter piles.

Figure 14 compiles the force distributions of the EOD CAPWAP analyses. While the toe resistance of the uniform and the taper piles is compatible to the toe area of the taper pile being 20 % of that of the uniform pile, despite the reduced shaft area of the taper section (average area of the taper section being about 75 % of the full size section), the CAPWAP analyses indicated that the shaft resistance along the taper length was several times larger for the taper pile opposed as to the uniform pile.

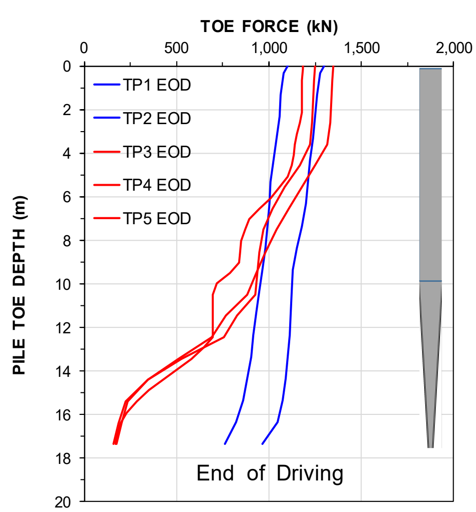

Figure 14. *CAPWAP-determined force distribution for Piles TP1 - TP5 at EOD.*

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The post static test restrike (RSTR2) blows were somewhat erratic with low energy forcing the CAPWAP analysis to address test records several blows into the restrike. A portion of the set up had likely then been shed off. Moreover, the restrike analyses are affected by variable impedance in the pile due, probably, to air pockets in the concrete and debonding between concrete and steel pile, causing strain incompatibility along the composite pile profile. However, the test objective was not to compare pile bearing from the static and dynamic analysis results. The difference in response between uniform and tapered piles is clearly illustrated and, in qualitative terms, the CAPWAP analyses showed agreement with the static loading results.

Static Loading Tests

The static loading tests were performed on April 4 through April 15, 2025, comprising 150-kN (34 kips) load increments with no intermediate unloading-reloading. The set-up time between initial driving and loading test were 7, 14, 12, 13, and 18 days for Pile TP1 through TP5, respectively. The load increments were applied every 16 minutes (the operator wanted to make sure on the prescribed 15 minute load holding). A separate load cell was used to monitor the applied loads. The reaction support was a loaded platform placed on two 16 ft by 5 ft timber mats. The free space between mat and pile was 1.3 m. The set-up included measurements to verify that the reference beam was unaffected by the transfer of load from the mats to the pile. The reaction load was from a loaded platform (concrete-block kentledge system) and the assigned kentledge weight was 3,000 kN. At the end of the second test (Pile TP3), the kentledge started to lift off when the applied load was about 2,600 kN and the pile-head movement was 13 mm. For the following tests, additional concrete weights were placed on the platform.

SACL engineers opted to terminate the concrete pour below the upper end of the steel pipe (pile head) to enable installing the telltale and arranging for monitoring the pile compression from inside the piles. This necessitated placing the jack to load on the pile rim, which, as addressed later, resulted in a progressive loss of adhesion between the steel pipe and the concrete core (delamination, debonding) as the test progressed, compromising the strain measurements.

Moreover, the schedule called for the piles to be grouted with a fluid grout pumped through a grout hose discharging at the bottom of the piles after installation. The instrumentation cage was then to be lowered into the grouted pile. However, instead of grout and grouting equipment, ordinary concrete was delivered to the site. As the project schedule did not allow for delays, the engineers decided to use the delivered concrete. As the instrumentation cage could not be pushed into this stiff consistency concrete, the cages were placed in the empty pipe before placing the concrete in the pile. For unknown reasons, no slump test or cylinders were prepared from the concrete and, therefore, the concrete strength is unknown.

The pouring of the concrete down the pipe was feared to have damaged the gages. However, the gage attachment proved to be sturdy enough to take the abuse, and all gage pairs survived the pouring of the concrete. The strain records were consistent. The data represented the strain imposed in the concrete at the gage location—though the strains did not quite represent the axial force at the gage location. First, the records indicated that air pockets might exist throughout the pipe. Second, the unfortunate placing of the jack on the rim of the steel pipe, instead of on the concrete, significantly impaired the strain-gage measurements. In loading a pipe rim, the steel pipe laterally expands; this expansion, albeit minute, causes a loss of adhesion between the steel and the concrete, gradually progressing down the pile as the load increases. While the strain-gages would then give values of the strain in the concrete, the ever-so precise records of the concrete strain will now not reliably reflect the average strain in the pile nor provide a correct value of the force at the gage level.

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The delamination caused the uppermost gage level, SG5, to become useless at first load increment—regrettably so, because this gage was intended to serve as "calibration gage", that is, to give the conversion from strain to force via the E_sA parameter derived from the force-strain records. (Force is calculated as strain times E_sA, where E_s is the secant modulus. For relation between the E_s and E_t, see Fellenius, 2025.) Moreover, as the axial force down the pile increased, delamination was introduced to the deeper place gages and it became progressively larger as the test proceeded. This removed the reliability of the strain measurements and the data progressively ceased to reflect the average strain, compromising the conversion of strain to force. Because most of the force in the pile load then was in the steel pipe, the test pile compressed more than a pile that, in contrast, would have had full interaction between steel and concrete.

Figure 15 shows the resulting load-movement curves of all test piles (records are from the end of each load increment). Labels TP1 and TP2 denote uniform piles and labels TP3 - TP5 denote taper piles. The curves show that, for movement larger than about 5 mm, the taper piles carried close to 20 % more load than the straight piles.

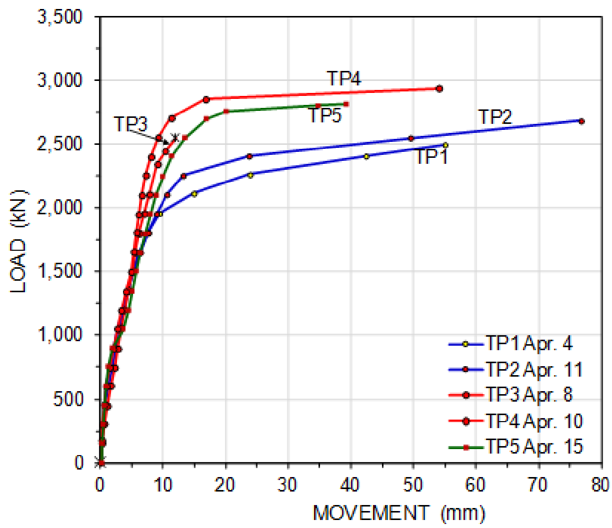

Figure 15. *Load-movements for the five test piles.*

Figure 16 shows the applied load vs. strain for the piles. Most strain records appear strange. As mentioned, the records of SG5 are of no use. Had SG5 been measuring correctly, it would essentially have shown a straight line with a slope indicating the E_tA-parameter of the pipe and concrete combination. As SG3 and SG4 appear to develop a reasonable slope, they might at first glance appear to be delivering reliable records. However, the two curves are too close to each other, indicating an unreasonably small change of axial force between the two levels. A reasonable E_tA-parameter is 7.5 GPa, corresponding to an E_s-modulus of 30 GPa considering steel-pipe area, gage cage, and guide-pipes. A 10 GPa E_sA-parameter would infer an E_s-modulus of 47 GPa. Clearly, such a value would be too large.

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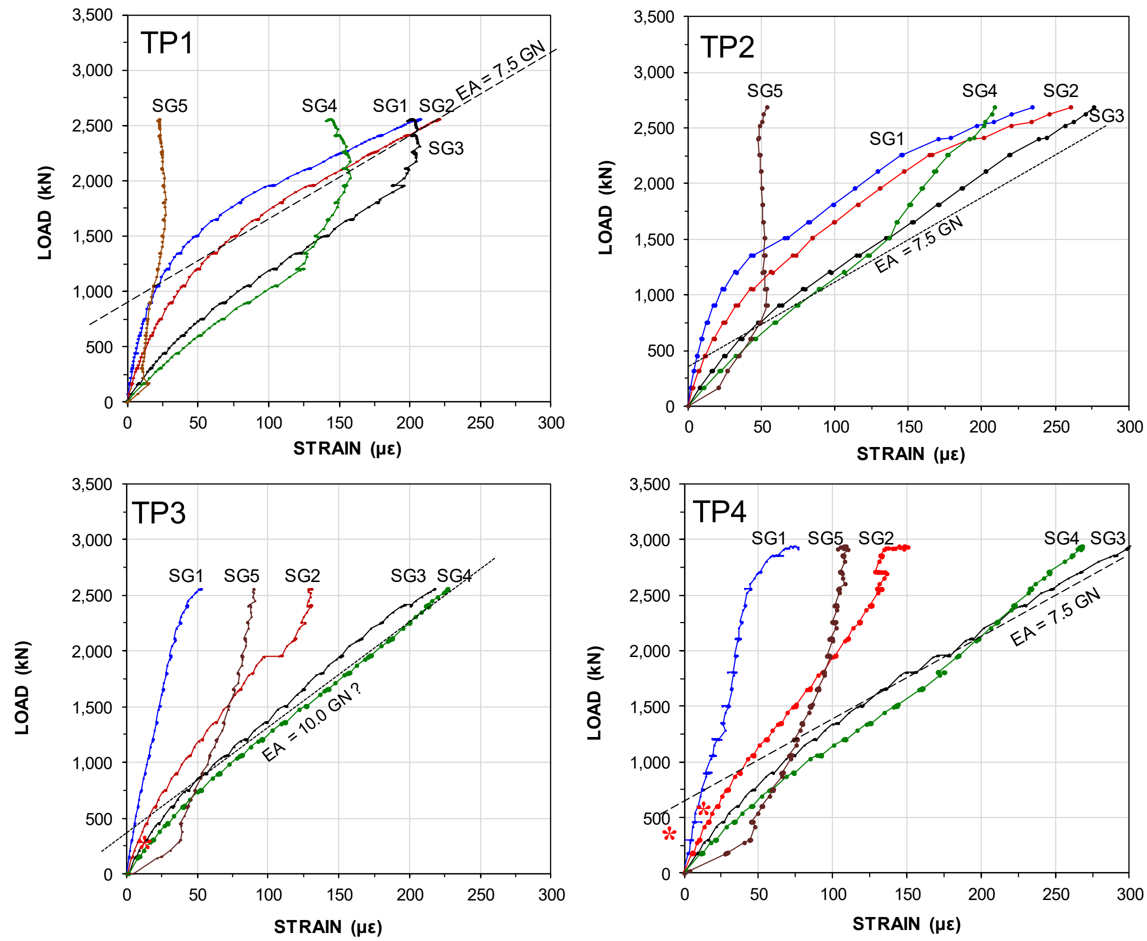

Figure 16. *Applied load vs. measured strain for Piles TP1 and TP2 (uniform) and TP3 and TP4 (tapered).*

To obtain a more representative E_sA-parameter, the strain records can be plotted as change of load over change of strain (i.e., tangent EA-parameter, E_tA) versus strain; the plotted values will usually converge toward a more or less constant value. However, there are two important conditions for this to be true: first, the soil response (shaft resistance) must be fully mobilized and truly plastic. If the shaft resistance is strain-hardening or strain-softening, the E_tA-Parameter will be correspondingly larger or smaller, respectively. This is why a calibration gage level, such as Gage SG5, independent of the soil shear, is necessary. However, depending on the uniformity of the concrete as placed and/or the mineral of the ballast material, sometimes a reducing E-modulus for increasing stress, i.e., a downward slope, may appear even for the calibration gage level.

The tangent method for determining the E_tA-parameter is far from exact. It is a differential method, and small errors will be magnified and cause an inconsistent appearance that would appear flawed. To determine the E_tA-parameter at a gage level, the tangent method requires a well-executed test without unloading/reloading events and prolonged load-holdings, and there definitely must be no delamination between concrete and steel.

Figure 17 shows the tangent EA-Parameter versus strain, displaying no distinct parameter. The EA = 7.5 GN from the load-movement graphs appears a reasonable "compromise", although the graphs do not truly suggest this value.

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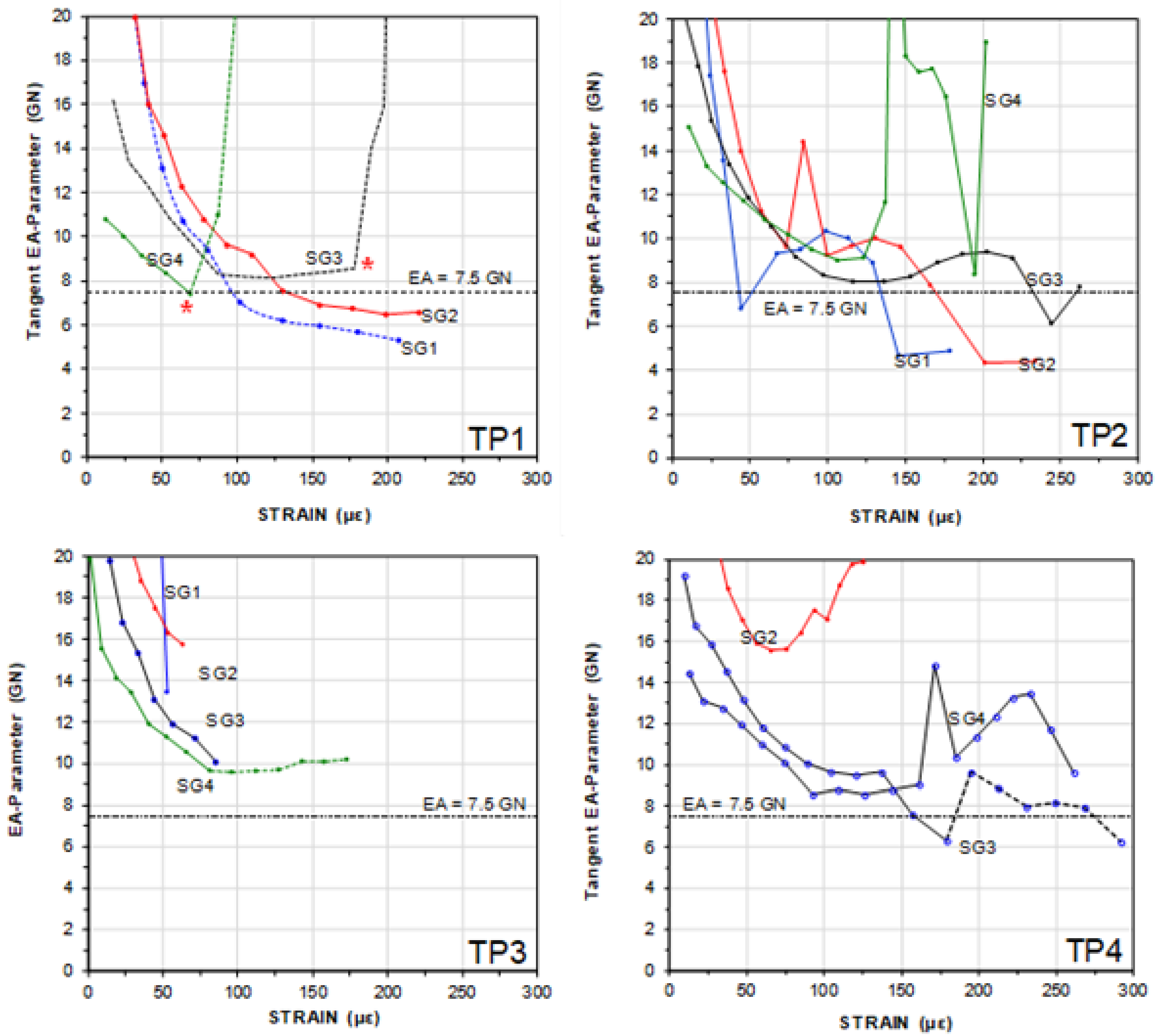

Figure 17. *Change of load vs. change of strain (EA-parameter).*

Figure 18 shows the force distributions of Piles TP1 through TP4 calculated from the gage records, applying EA = 7.5 and proportional values for SG2 and SG1. For the uniform piles, TP1 and TP2, the force distributions make sense. SG4 was affected by the delamination, while SG3 values appeared realistic except for the last three in TP1. The numbers for the toe-gage, SG1, also appeared realistic. In contrast, for the tapered piles, TP3 and TP4, either value of SG2 and SG4 is false or both are. Moreover, the SG1 numbers are unrealistically low. It appears that the concrete in the tapered piles was affected by air pockets or a similar anomaly resulting from the dumping of the stiff concrete over the instrumentation cage. The concrete strain, albeit accurately measured by the gages, does not likely reflect the true axial force in the tapered piles. After several back-and-forth calculations, it became clear that the strain records (except for, possibly, SG1 in TP1) would be best excluded from the back-analysis of the pile response to the applied load.

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Test and Analysis Results

The procedure was applied to the test records to obtain a final fit of calculated to measured applied load, pile-toe force, shaft resistance, and pile compression versus movement for the test piles. However, as mentioned, because of the erratic strain records, mainly due to suspected air pockets near the gage levels, the back-analysis disregarded all gage records but for SG1 in TP1. Figures 19A and 19B show the measured and fitted back-analyzed pile-head movements for TP1 and TP2 and for TP3 and TP4, respectively. Blue curves are plotted SG-values, and red curves are simulated using UniPile6.

Figure 19A includes the simulated curve for the 9.4 m depth and the SG3 curve at that depth. If the latter were correct, in fitting the calculated, and strain-gage independent, pile-head load-movement curve, to the measured, it would indicate an unreasonably low shaft resistance below 9.4 m depth and, consequently, an unreasonably larger shaft resistance above.

The SG1 force-movement of TP4 (Figure 19B) appears to be unrealistically small. Rather than fitting a curve to the gage records, the graph shows the simulated SG1 force calculated applying the input for the uniform pile (TP1), and with the actual TP4 toe area, as the more realistic curve.

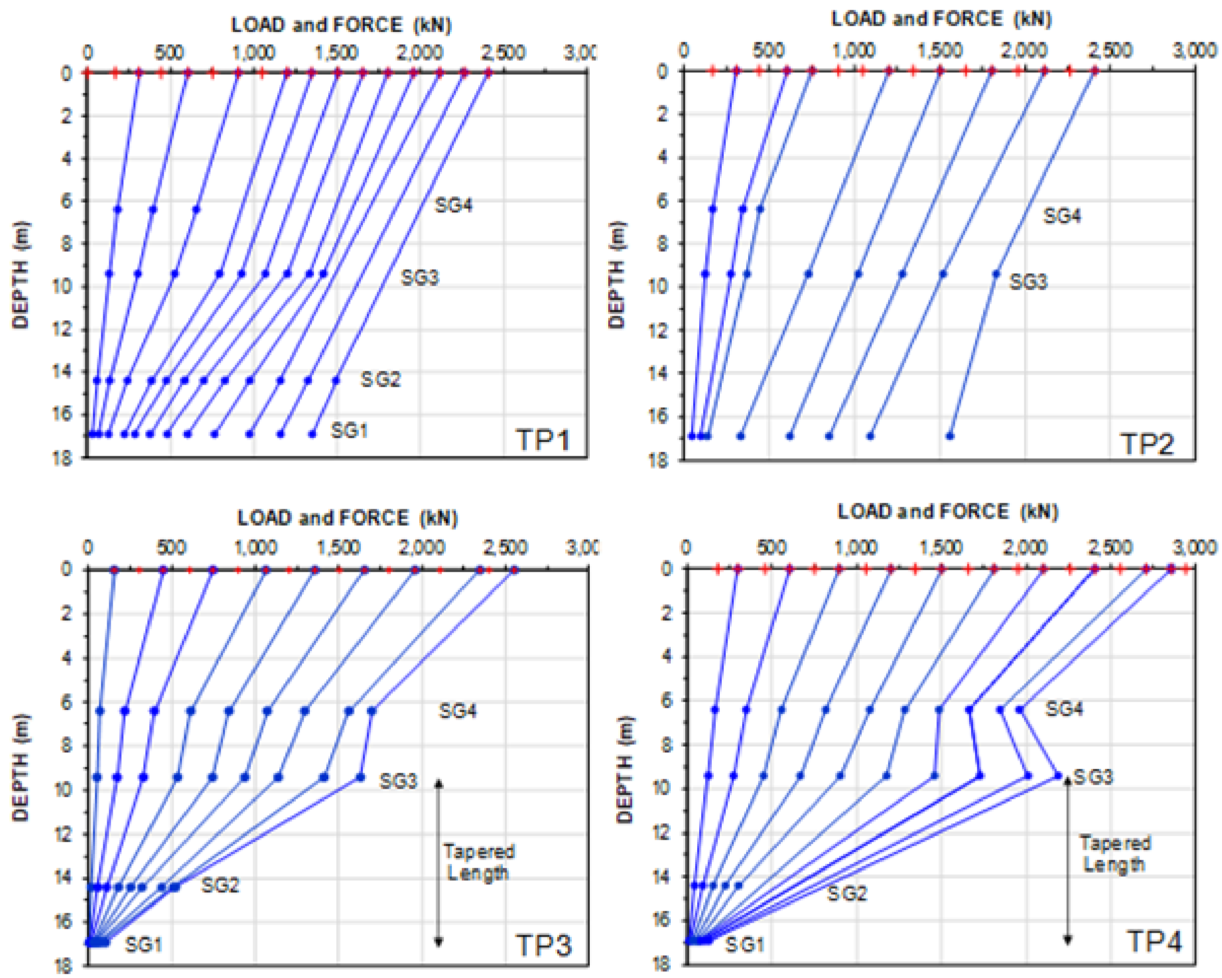

Figure 18. *Force distributions.*

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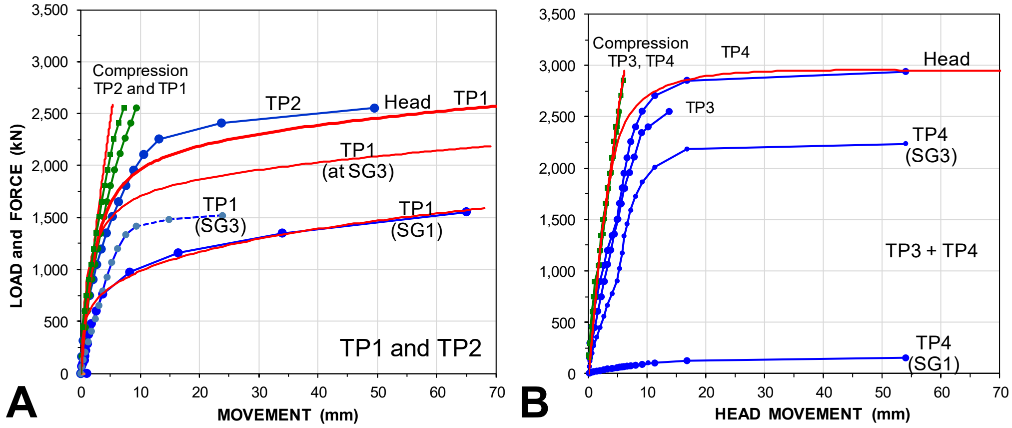

Figure. 19. *Pile-head load-movement curves and force-movement curves for the test piles.*

Both graphs include measured and simulated pile compression. Note that for TP1 and TP2, the measured compressions are significantly larger than the calculated ones. This suggests that the concrete was not fully participating in conveying the axial force down the pile due to delamination and that, consequently, the steel pipe carried most of the applied load and, accordingly, compressed more.

The fit to the tapered pile (TP4) applied the same target values of *ß*-coefficients and t-z/qc functions as used for the uniform pile (TP1) and obtained the fit by adding shaft resistance by means of an N_t-coefficient applied to the "donut" area. The q-z function for the "donut" was set equal to the t-z function.

Figure 20 shows the final target coefficients and t-z/q-z functions employed in UniPile6 to fit the simulated load- and force-movements to measured. The *ß*-targets were chosen with subjective reference to the CPTU distribution (c.f., Figure 3) for the soil layers defined by the gage depths, but the shaft response was simplified to employing the same t-z function for the entire length of the pile. The N_t-target and q-z function were fitted to the SG1 records in TP1. The ß-coefficient of 0.40 applied to the soil at the piles toe and the N_t-coefficient of 22 combine to a $N_t/ß$ ratio of 55, which is rather low. This could be due to the presence of residual force. However, an accurate evaluation of the effect of residual force would require measuring it, but the test unfortunately failed. A pull test, such as that for the Monselice test, would have helped in assessing the test for residual force.

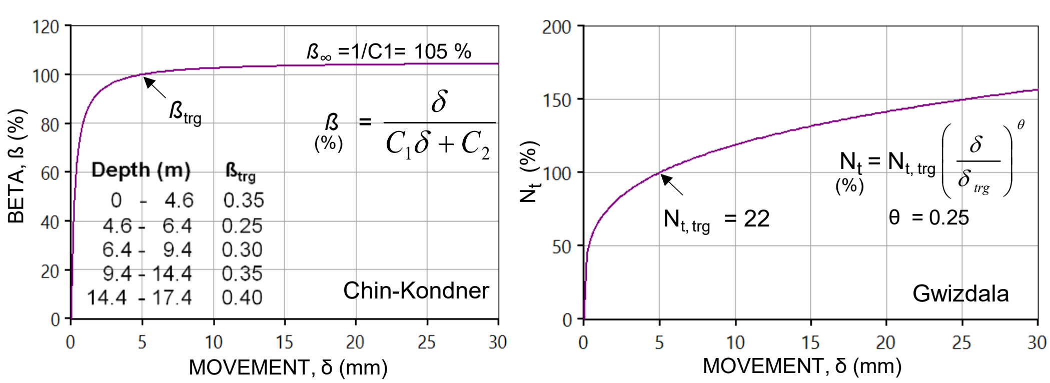

Figure 20. *The t-z and q-z functions and target coefficients used to achieve the fit between calculated and measured load and force response.*

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The simulation for the uniform piles, TP1 and TP2, was based on the fit to the SG1 and the pile-head load-movement records of TP1 applying *ß*-coefficients.

The fit to the measured TP1 pile-head load-movement is very good. However, the fit could have been achieved using a different set of ß-coefficients. Indeed, a slightly changed choice of *ß*-coefficients and t-z function would have resulted in a similarly good fit to the TP2 curve.

The t-z function indicates an essentially plastic response of the soil, a not uncommon observation for compact sand. The q-z function has a significantly stiff initial portion as opposed to a more commonly seen, less steep curve expressed by a function coefficient, θ, equal to 0.5 or larger. This is an indication of the presence of residual toe force. If so, and known, the fitted N_t-coefficient would be smaller than the real. The effect of the presence of corresponding residual shaft force is disguised by the use of the same t-z function for the full length of the pile made necessary by the uncertainty of the SG2 - SG4 gage records and the loss of the bidirectional test on TP5.

Figure 21 compares UniPile-calculated force distributions for an array of applied load, same for both pile types, demonstrating the taper effect of increasing the shaft resistance more than offsetting the reduced toe area of the tapered pile. The simulation and fit of the UniPile calculation of the tapered piles employed an N_t-coefficient equal to 55 for the "donut" effect, combined with the same ß-coefficients as used for TP1 and the same N_t-coefficient (22) as found in the fit of the toe response of TP1. It is likely, however, that the driving of the tapered pile increased the toe response and, therefore, the N_t-coefficient for the tapered pile should instead be larger. The dashed curve indicates applying a distribution calculated with equal N_t-coefficients (N_t = 50) to the "donuts" and pile toe of the tapered pile in order to adjust to the associated, then, slightly reduced shaft resistance.

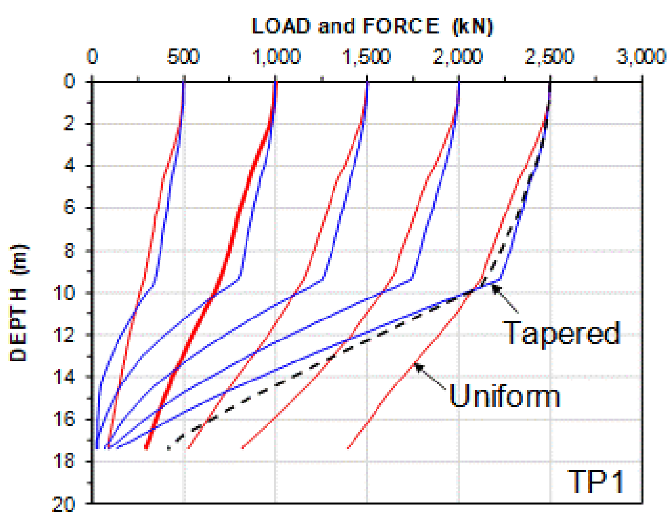

Figure 21. *Force distributions in uniform and tapered piles for different applied loads.*

Figure 22 applies the fitted parameters in calculating the shaft resistance of the uniform and tapered piles for movement beyond about 10 mm, showing that the 16 mm/m, 1.0°-taper resulted in a doubling of the shaft resistance.

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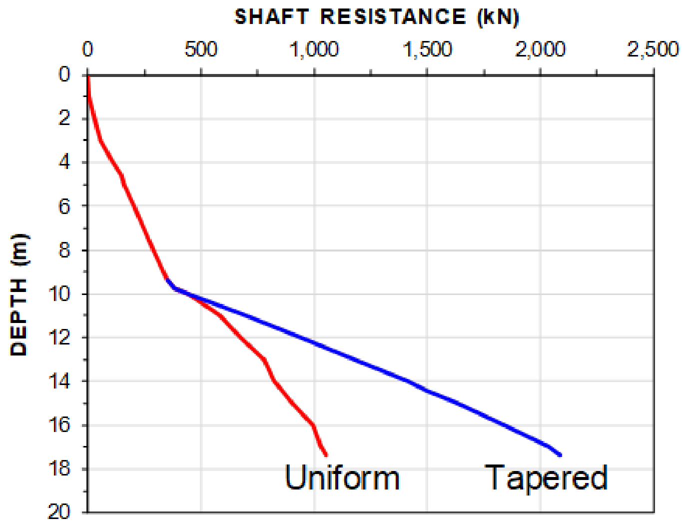

Figure 22. *Shaft resistance distributions in uniform and tapered piles for 2,500 kN applied load.*

SUMMARY

The four full-scale tests confirm the results of the many model tests in regards to the fact that a tapered pile develops a significantly enhanced pile bearing as opposed to an equivalent-sized uniform pile.

As a pile is moved relative to the soil, shear resistance develops in relation to the effective stress best expressed in a ß-approach. For tapered piles, additional resistance develops due to the imposed lateral movement and compression induced by the taper. The "donut" method was useful in back-analyzing the latter effect. However, the full-scale test records from the Iranian and Italian tests do not allow for a detailed analysis of just how the taper mobilizes and adds shaft resistance. For this, test piles must be instrumented to (successfully) measure axial force along the pile and, at least, separate shaft resistance from toe resistance with due attention to the potential presence of residual force.

The Mobile, AL full-scale tests showed that the tapered (TSFP) 18 in piles achieved the same and somewhat larger bearing as the 18 in uniform piles, confirming the findings of the model tests and outcome of the aforementioned three previously performed full-scale tests.

The 1°-taper of the TSFP resulted in a doubling of the shaft resistance along the tapered length as compared to the uniform pile along the same length and depth.

It is likely that further larger bearing of the tapered piles in comparison to uniform piles would result if the tapered piles were installed using vibratory driving.

All strain gage-pairs survived the dumping of the stiff concrete into the strain-gage cage.

Placing the applied load on the rim of the pipe pile resulted in rendering the records of the uppermost gage pair useless and caused delamination of concrete and steel at the lower gage levels, severely compromising the strain records as the test progressed.

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Placing stiff concrete in the piles as opposed to using the assigned grout resulted in trapping air pockets in the pile, causing uneven concrete cross section areas at gage levels and strain incompatibility and strain records that indicated, if true, unrepresentative force distribution.

Placing stiff concrete in the piles as opposed to using the assigned grout also resulted in loss of means to pursue the bidirectional test (TP5) and establish any presence of residual force in the test piles.

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