Modelling the Effects of Pile Diameter

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Abstract

The most commonly used program for the analysis of piles under static lateral loading is LPILE (2012). The program uses the nonlinear Winkler springs recommended by API to model soil-pile interaction. The p-y curves were developed from field tests with pile diameters in the range 0.324m - 0.67m. When these p-y curves are used to analyze load tests on larger diameter piles, the computed load-deflection curves underestimated the stiffnesses of the test piles. This effect is referred to as the pile-diameter effect. In this technical note a very different approach is presented to evaluating the pile diameter effect. Both LPILE and a continuum based finite element program VERSAT-P3D were calibrated to simulate closely the results of two lateral load tests on small diameter piles at two different sites. VERSAT-P3D modelled the volume of the pile and LPILE did not. Each program was used to develop load displacement curves for increasingly larger pile diameters up to 2.0m. An important finding for practice is that there was no pile diameter effect for displacements up to 60mm. LPILE can be used with confidence in practice in this displacement range. Thereafter the load deflection curves from LPILE became softer and the pile diameter effect became evident.

Keywords: **soil-pile interaction, pile diameter effect, calibrating p-y curves, continuum modelling of piles, coping with pile-diameter effect.**

Introduction

The most commonly used program for the analysis of piles under static lateral loading is LPILE (2012). The program uses nonlinear Winkler springs to model soil-pile interaction: the p-y curves of Reese et al. (1974) for sand, based on field test data from tests on 0.324m diameter piles and the p-y curves proposed by Matlock (1970) for soft clays, based on data from tests on 0.67m diameter piles. When these p-y curves are used to analyze load tests on larger diameter piles, the computed load-deflection curves underestimate the stiffnesses of the test piles. This effect is referred to as the pile diameter effect. The effect increases with pile diameter and is more pronounced for clays than sands. In this short note it is not possible to review the many and varied proposals to deal with this problem. However Lam (2009) has presented an excellent detailed survey of pile diameter effects including a valuable critical assessment of the major proposals for dealing with the problem. These proposals usually involved changing the assumptions on which the current p-y curves are based. Such as assuming that the modulus of subgrade reaction was diameter dependent (Pender 1993) rather than independent as held by Terzaghi (1955) and Vesic (1961) and affirmed by API (2007), or altering the specification of y_{50}, the deflection at half the ultimate soil resistance from y_{50} = 2.5 ε_{50} D to y_{50} = 8.9 ε_{50} D, where ε_{50} is the strain corresponding to half the maximum stress difference and D is the diameter (Stevens and Audibert, 1979). Lam took the view that the pile diameter effects problem arose from the neglect of additional soil resistance that comes into play with the bending and rotation of large diameter piles. He recommends adopting the proposal of Lam and Martin (1986) to include rotational springs along the pile shaft and the base and a base shear term. They showed that these springs improved predictions of pile-deflection curves. Another approach to correcting the API model to account for pile dimensions may be the use of the Strain Wedge Model (SWM) to improve the API p-y curves to account for 3-D soil-pile interaction (Ashour et al., 1998; Ashour and Norris, 2000 and Heidari et al. (2014). The SWM procedure has not yet been applied to the pile diameter problem.

In this technical note a very different approach is presented that takes into account the significant uncertainty associated with predictions based on the API p-y curves. Murchison and O'Neill (1984) conducted a major evaluation of the reliability of predicted pile response to lateral loading in sand based on the API p-y curves for sand and O'Neill and Gazioglu (1984) conducted a similar evaluation of the API p-y curves for clay. They found that the reliability of predictions of pile response to lateral loading based on these p-y curves was quite low. Therefore the first essential step in evaluating the capacity of the program LPILE to model the effects of pile diameter at a given site is to calibrate the p-y curves using data from a small diameter test pile at the site. This step removes concerns about the reliability of the p-y curves. Therefore it is reasonable to assume that any discrepancy in matching data from large diameter pile tests is due to the fact that LPILE does not model the volume of the pile. To quantify the pile diameter effect, it is necessary to have load-deflection data from large diameter piles in the same site as the calibration pile. Since field test data is not available, the necessary data was developed by continuum analysis of the larger diameter piles.

The 3-D finite element program VERSAT-P3D (Wu 2006, Finn and Wu 2013) was selected for these analyses because it models the volume of the pile. An elastic-plastic soil model was used where the elastic part was modelled as equivalent linear using strain dependent moduli and damping ratios. VERSAT-P3D was also calibrated to the site using the test pile data. A comparative study of the LPILE and VERSAT-P3D analyses of larger diameter piles resulted in a recommendation for dealing with pile-diameter effects in practice.

Calibration of LPILE and VERSAT-P3D

The effects of pile diameter were explored at two different sites; a site described by Christensen (2006), and a second site described by Rollins et al. (2006). LPILE and VERSAT-P3D are calibrated for each site using the results of experimental load tests on single piles described by Christensen (2006) and Rollins et al. (2006).

Christensen's Site

Christensen (2006) conducted an experimental field study of single piles and two pile groups of slender piles at a site in Salt Lake City, Utah and has presented a detailed description of the soil profile and associated properties for the site. Christensen also presented details of LPILE analyses carried out to replicate the experimental results. As a starting point for the properties to be used in the LPILE analyses, Christensen used information reported by Snyder (2004) for the site and altered these site properties to include a new 2.4m deep overlying sand layer that was absent from the Snyder (2004) study. The soil friction angle and modulus of subgrade reaction of the upper sand layers were then adjusted by Christensen (2006) so that the LPILE analysis replicated his experimental data. After achieving a satisfactory match between the experimental results and the LPILE analyses, Christensen (2006) then undertook some sensitivity analyses and found that the parameters used in layers at depths greater than ten times the pile diameter had “relatively little effect of the final calculated results”. The properties used by Christensen (2006) in replicating the experimental data in LPILE analyses are shown in Table 1. The same model properties were used for LPILE analyses in the present study.

The layering of the soil strata presented in Table 1 represents the different soil types identified in the soil profile and is not the layering used in the numerical analyses by LPILE for which 100 layers were developed from the soil profile of the site. Indeed, all LPILE analyses presented as part of this study use 100 soil layers. For the layers identified as sand in Table 1, the p-y curves adopted for LPILE analyses were the calibrated curves developed by Reese et al. (1974). For the layers identified as clay the calibrated p-y curves of Matlock (1970) were adopted.

The corresponding soil parameters for the VERSAT-P3D analyses are shown in Table 2. VERSAT-

P3D uses a special 4-beam pile element to model the volume of the pile. A pile cross-section, either round or square is modelled as square for simplicity, and the four beam elements of each pile section are arranged at the corners of the pile section. The four beam elements are tied rigidly together at the nodes so as to act as a single pile element.

The most important parameter used in VERSAT-P3D is the maximum shear modulus, G_{max}. The determination of G_{max} values was based on the CPT-q_c data for the site and was evaluated using the relationship proposed by Mayne and Rix (1993), given by Equation 1.

$$G_{max} = 1634 \times q_c^{0.25} \times \sigma_v'^{0.375} \quad (1)$$

where q_c is the cone bearing capacity and σ_v', the effective vertical stress, both expressed in kPa units.

The modulus reduction curves used in the VERSAT-P3D analyses were the average curves recommended by Seed et al. (1986) for sand and the PI=50 curve by Vucetic and Dobry (1991). The yield stress of the sand was taken as $\sigma_v'\tan\phi$ and as the undrained cohesion, c_u, in clay.

The pile properties were taken directly from Christensen's single pile test. These were: pile length = 16.6m, pile diameter = 0.324m, pile area = 0.01m^2, pile I = 0.000143m^4, pile Young's modulus = 200MPa. The soil layers in Table 2 were subdivided into 20 sublayers for the VERSAT-P3D analyses. Further subdivision of the layers was found to not result in significantly different results.

The results of the calibration study are presented in Figure 1, which shows that the load-displacement responses from LPILE and VERSAT-P3D analyses and the actual test data. The two simulations are almost identical to each other and to the test data. The two programs provide a reliable basis for exploring the effects of pile diameter.

Figure 1.

It is also of interest to check how well the bending moment curve predictions from both programs agree, and how these in turn agree with the recorded moments from the experimental results. Figure 2 shows bending moments predicted by the two different programs for a lateral load of 108kN and the recorded moments from the experiment for comparison. A very good match was achieved between the VERSAT-P3D and LPILE models and the experiment at all load levels, of which Figure 2 is a good representative example.

Figure 2.

Rollins' Site

As part of a study investigating the effects of pile spacing on the response of pile groups, Rollins et al. (2003, 2006) conducted an experimental field study of single piles at a site in Salt Lake City, Utah. The geotechnical properties of the site were measured and described in detail in Rollins et al. (2003, 2006). The soil profile and associated properties for the site are different from those described in the experiments of Christensen (2006). Rollins et al. (2003) present a detailed description of the site investigation carried out at the site including the variation of G_{max} with depth. Rollins et al. (2006) created an LPILE model with appropriate p-y curves for test piles at the site. The LPILE parameters for use in the present study were taken directly from Rollins et al. (2006), and the corresponding soil parameters for the VERSAT-P3D analyses of the Rollins site are shown in Table 3. The predicted load-displacement responses from LPILE and VERSAT-P3D analyses of Rollins et al. (2006) test pile are shown in Figure 3 together with the original experimental data. The pushover curves are almost identical for all three cases.

Figure 3.

Analysis of Pile Diameter Effects

Christensen's Site

A pair of programs is now available, VERSAT-P3D using the FE method, and LPILE using the API p-y curves, both of which have been calibrated to give accurate simulations of the pile load test data described by Christensen (2006). The results of this calibration have been presented previously in Figures 1 and 2.

The calibrated programs were used to develop load-deflection curves for different pile diameters ranging from 0.2m to 2.0m. The individual pile diameters tested in both models were 0.2m, 0.5m, 0.75m, 1m, 1.25m, 1.5m, 1.75m and 2m. The solid lines in Figure 4 represent the results from the VERSAT-P3D analyses. The dotted lines show the results from the LPILE program. Up to 45mm of lateral displacement both programs give approximately similar results. As the displacement increase beyond 45mm, the LPILE load-displacement curves begin to fall away from the VERSAT-P3D curves and at displacements greater than 60-70mm the differences are becoming significant, especially for pile diameters greater than 1.25m. The predicted displacements of the two models are within 10% for displacement levels up to approximately 70mm.

Figure 4.

Pile diameter versus load levels for a common displacement

The relationship between load level and pile diameter from VERSAT-P3D analyses was found to be well defined by a simple linear relationship when plotted on a double-log plot as shown in

Figure 5. The linear relationship can be described, for each displacement level, by Equation 2.

$$load = d^{1.58} \times e^{c} \tag{2}$$

where *load* is the load in kN, *d* is the pile diameter in m and e^c is the exponent of a constant that depends on displacement level. It is equal to 6.27 for 0.02m displacement; 6.50 for 0.03m displacement; 6.78 for 0.05m displacement; 6.96 for 0.07m displacement. The parameter *c* defines the curve to be used for estimating the displacement for a given load or the load to achieve a specified displacement of a pile with a given diameter *d*. The *c* for intermediate values of displacement is obtained by interpolation.

Figure 5.

Rollins' Site

The calibrated programs were used to develop load-deflection curves for different pile diameters ranging from 0.2m to 1.5m for the Rollins site, as was previously done for the Christensen site. The individual pile diameters tested in both models were 0.2m, 0.5m, 0.75m, 1m, 1.25m and 1.5m. In a similar style to Figure 4, the solid and dashed lines in Figure 6 represent the results from the VERSAT-P3D and LPILE analyses, respectively. As was seen in Figure 4, the lateral displacements output from both programs are similar, and as the displacement increases beyond about 60mm the LPILE load-displacement curves begin to fall away from the VERSAT-P3D curves and the differences become significant, especially for pile diameters greater than 1.25m.

Figure 6.

Pile diameter versus load levels for a common displacement

As in the case for the Christensen site, the relationship between load level and pile diameter from VERSAT-P3D analyses was again found to be well defined by a simple linear relationship when plotted on a double-log plot as shown in Figure 7. The data from Figure 5 are plotted here again for comparison. The linear relationship can be described, for each displacement level, by Equation 3.

$$load = d^{1.54} \times e^{c} \tag{3}$$

Equation 3 differs from Equation 2 in that that exponent of d is 1.54 (as opposed to 1.58). The exponent *c*, a constant that depends on displacement level, has the following values; 6.14 for 0.02m displacement, 6.39 for 0.03m displacement, and 6.65 for 0.05m displacement. The parameter *c* defines the curve to be used for estimating the displacement for a given load or the load to achieve a specified displacement of a pile with a given diameter *d*. The *c* for intermediate values of displacement may be obtained by interpolation.

Figure 7.

Discussion of Results

The computed load-deflection curves at each pile diameter for both for the LPILE analyses and VERSAT-P3D analyses are within 10% up to about 60mm. The curves plotted in Figures 4 and 6, show very small differences. This is partly due to plotting a limited number of data points, and although both programs give very similar results they are not exactly the same. Within this scope of differences there is no evident effect of pile diameter. The ratio of loads predicted by both programs at a given displacement is essentially unity. Beyond about 60mm displacement the load-displacement curves begin to diverge and the LPILE analyses become less representative of the effects of soil-pile interaction. A potential explanation is offered by Lam and Martin (1986) and Lam et al. (2009), that for the larger diameters and displacement levels, the bending and rotation of the large diameter piles is not well represented by the API curves and additional springs need to be used to account for the effect of the bending and rotation of the larger diameter piles.

A clear picture of the effect of pile diameter on the load-displacement curves is given in Figures 4 and 6. These curves for each site studied have been described by exponential equations, where the dependent variable is the diameter and the exponential exponent is a function of displacement. However, the most useful representation of the results is in Figure 7, which shows that for each site there is a linear relationship between the ratio of load to diameter for a given displacement level. This linear relationship offers the opportunity to develop the full load-diameter relationship with a limited number of data points, extrapolated from test data for perhaps two smaller diameters.

However, from the point of view of practice the key finding from the study is that if LPILE p-y curves are calibrated on a small diameter test pile at the site of interest then, LPILE can be relied upon to give reliable estimates of the load-displacement curves of larger diameter piles at displacements up to 60mm. In many practical problems, this is an adequate displacement range, especially for working loads.

Conclusions

When using LPILE to develop load-displacement curves for a project, it is imperative to calibrate the program to the site by data from a load-deflection test. This calibration is required to counter the unreliability of the p-y curves as pointed out by Murchison and O'Neill (1984) and O'Neill and Gazioglu (1984).

The computed load-deflection curves at each pile diameter for both the LPILE and VERSAT-P3D analyses are almost identical up to about 60mm. Beyond about 60mm displacement, the load-displacement curves begin to diverge and the LPILE analyses become less representative of the effects of soil-pile interaction.

The relationship between the ratio of load to diameter was found to be linear in double natural logarithm space, and this allows the development of the load-diameter curve for a given displacement based on two small diameter test piles.

This finding has led to a practical 4-step procedure for developing the load-deflection curves of large diameter piles up to about 1.25m for pile head displacements less than 60mm using LPILE. The steps are:

1. Drive a small (say, 0.2m-0.4m) test pile at a representative location on site.
2. Develop the load-deflection curve of the test pile in a lateral loading test.
3. Calibrate the program LPILE to accurately model the experimental load-deflection curve.
4. Calculate the load-deflection curves of the large diameter piles using the calibrated LPILE program.

Acknowledgements

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Table 1. Soil properties used in LPILE from Christensen (2006).

Layer depth (m)	Soil type	γ' (kN/m^3)	Shear strength (kN/m^2)	ϕ	k (kN/m^3)	ε_{50}
0 - 2.1	Sand	16.7		40	75×10^3	
2.1 - 2.4	Sand	6.8		40	42×10^3	
2.4 - 2.7	Clay	9.1	41		27×10^3	0.01
2.7 - 3.7	Clay	9.1	50		140×10^3	0.01
3.7 - 4.6	Clay	9.1	40		27×10^3	0.01
4.6 - 6.3	Sand	8.1		38	26×10^3	
6.3 - 8.0	Clay	9.1	57		140×10^3	0.01
8.0 - 16.1	Sand	6.7		33	150×10^3	

Table 2. Soil properties used in VERSAT-P3D.

Layer depth (m)	# of sub-layers	G_{max} (kN/m^2)	γ (kN/m^3)	Soil strata*	ϕ
0 - 2.1	3	29615	16.7	Sand	40
2.1 - 2.4	1	15884	6.8	Sand	40
2.4 - 2.7	1	7000	9.1	Clay	35
2.7 - 3.7	2	7000	9.1	Clay	35
3.7 - 4.6	2	8076	9.1	Clay	35
4.6 - 6.3	3	17769	8.1	Sand	38
6.3 - 8.0	2	6461	9.1	Clay	35
8.0 - 16.1	4	22615	6.7	Sand	33

Table 3. Soil properties used in VERSAT-P3D (Rollins et al. site).

Layer depth (m)	# of sub-layers	G_{max} (kN/m^2)	γ (kN/m^3)	Soil strata*	ϕ
0 - 1.34	3	21455	14.9	Clay	
1.34 - 1.65	1	13979	14.93	Sand	36
1.65 - 3.02	2	24211	16.5	Clay	
3.02 - 3.48	1	18538	14.93	Sand	36
3.48 - 4.09	1	24211	16.5	Clay	
4.09 - 5.15	2	20564	14.93	Sand	38
5.15 - 9.80	4	10029	14.9	Clay	
9.80 - 11.9	2	26845	16.5	Clay	

Figure Captions

Figure 1. Calibration of the VERSAT-P3D and LPILE models.

Figure 2. Bending moments from VERSAT-P3D and LPILE analyses (lateral load of 108kN), and Christensen's recorded experimental data for comparison.

Figure 3. Calibration of the VERSAT-P3D and LPILE models for the Rollins site.

Figure 4. Pushover curves for all considered pile diameters.

Figure 5. Relationship between pile load and diameter for a given displacement.

Figure 6. Pushover curves for all considered pile diameters for the Rollins site.

Figure 7. Relationship between pile load and diameter for a given displacement for both sites.

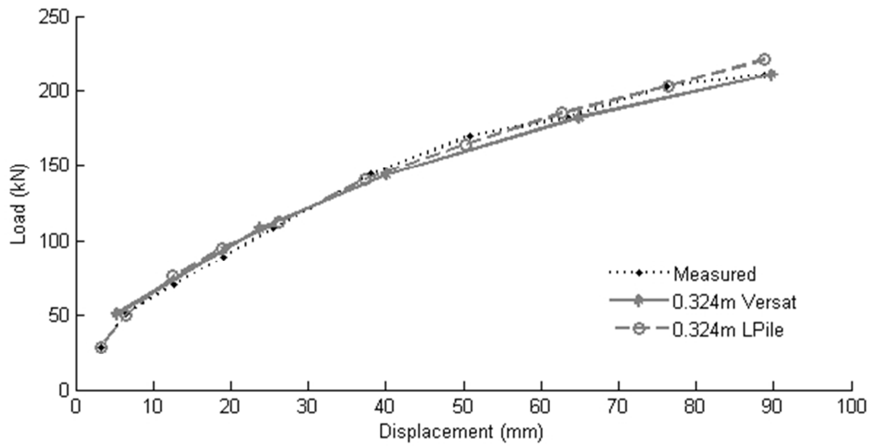

Figure 1. Calibration of the VERSAT-P3D and LPILE models.
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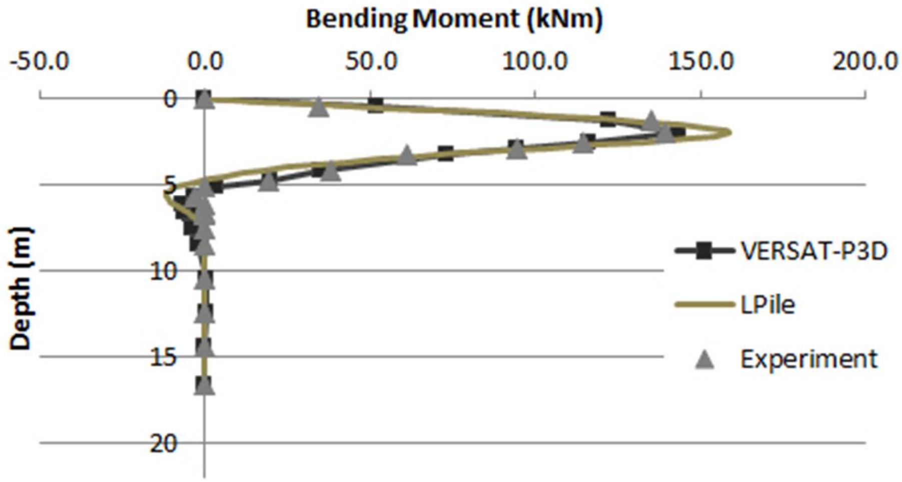

Figure 2. Bending moments from VERSAT-P3D and LPILE analyses (lateral load of 108kN), and Christensen's recorded experimental data for comparison.
124x65mm (96 x 96 DPI)

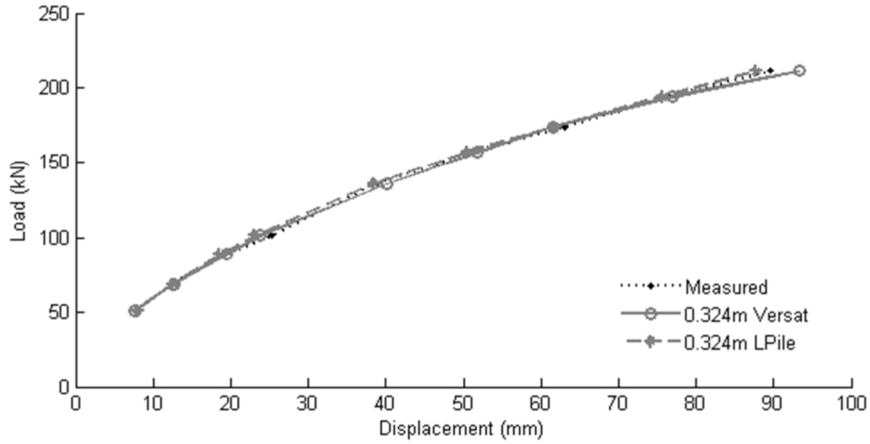

Figure 3. Calibration of the VERSAT-P3D and LPILE models for the Rollins site.
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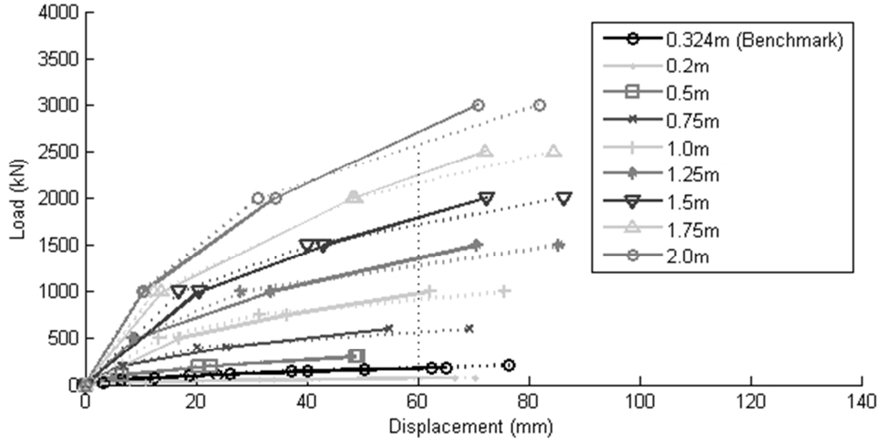

Figure 4. Pushover curves for all considered pile diameters.
181x84mm (96 x 96 DPI)

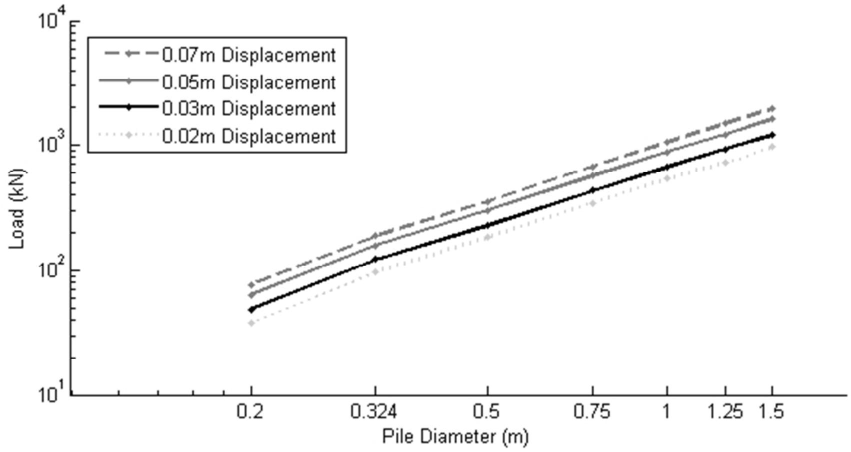

Figure 5. Relationship between pile load and diameter for a given displacement.
181x84mm (96 x 96 DPI)

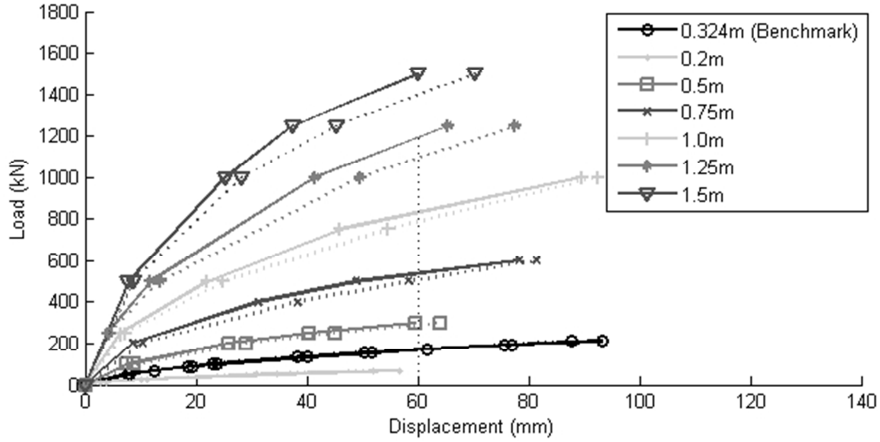

Figure 6. Pushover curves for all considered pile diameters for the Rollins site.
181x84mm (96 x 96 DPI)

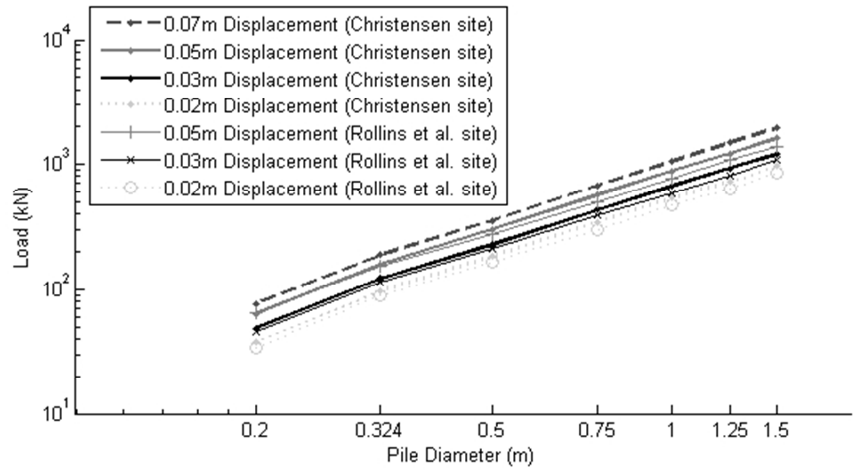

Figure 7. Relationship between pile load and diameter for a given displacement for both sites.
181x84mm (96 x 96 DPI)