Pile driving behaviour for wind farm in Bruce County, Ontario

Prapote Boonsinsuk & Siva Nadarajah
AMEC Earth and Environmental, a Division of AMEC Americas Limited, Scarborough, Ontario, Canada

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ABSTRACT
As part of a wind farm project in Bruce County in Ontario, over 40 wind turbines had to be supported by piled foundations due to the presence of thick soft soil strata overlying dense soils. Over 1500 steel HP 310 x 110 piles were driven, some more than 30 m deep, to achieve the design pile axial capacities in both compression and tension. Prior to driving the piles, the pile capacities were evaluated by static pile capacity analysis using the borehole data obtained at each wind turbine location. The subsurface soil conditions were investigated by Standard Penetration Test and Dynamic Cone Penetration Test. The minimum pile embedment depth (i.e., anticipated pile lengths) at each wind turbine location was established in order to achieve the design pile compression and tension capacities. Pile driving criteria based on Hiley formula were then developed.

During actual pile driving, a number of piles had to be driven much deeper than the anticipated pile lengths as indicated by the resistances from Standard Penetration Test (SPT) and Dynamic Cone Penetration Test (DCPT), particularly when no hard soil layer (e.g., thick layer of hard clay or very dense sand, bedrock, etc.) was present at anticipated pile tips. This paper describes the behaviour of pile driving in comparison with the results of Standard Penetration Test (SPT) and Dynamic Cone Penetration Test (CPT). A suggestion for estimating pile lengths from static pile capacity analysis and SPT / CPT results is provided.

RÉSUMÉ
Dans le cadre d'un projet de parc éolien dans le comté de Bruce en Ontario, plus de 40 turbines éoliennes ont dû supporter par les fondations sur pieux dû à la présence des strates de terre molles au-dessous des terres fermes. Plus de 1500 pieux en acier de type H310 ont été enfoncés dans la terre - certains de plus que 30 m en profondeur, pour réaliser les capacités axiales de conception du pieu, en compression ainsi qu'en tension. Avant que les pieux aient été enfoncés, les capacités du pieu ont été évaluées par l'analyse de capacité de pieu statique en utilisant les données de forage obtenues à chaque location où les turbines éoliennes se situent. Les conditions sous-terraines du sol ont été étudiées par l'Essai de Pénétration Standard (SPT) et l'Essai de Pénétration Dynamique au Cône (DCPT). La profondeur d'ancrage minimale du pieu (c.-à-d., longueur prévue du pieu) à chaque location où les turbines éoliennes se situent a été établie afin que les capacités de conception du pieu, en compression ainsi qu'en tension, soient atteintes. Les critères d'enfoncement de pieu basés sur la formule Hiley ont été ensuite développés.

Pendant l'enfoncement actuel du pieu, un certain nombre de pieux a dû être enfoncé plus profond que longueur prévue telle qu'indiquée par les refus de SPT et DCPT, particulièrement quand la présence d'un banc de terre dense n'existe pas (par exemple une strate épaisse d'argile dure ou de sable très dense, de roc, etc.) à la base anticipée du pieu. Cet article décrit la conduite de l'enfoncement de pieu en comparaison avec les résultats des SPT et DCPT. Une suggestion est fournie pour l'estimation des longueurs de pieu, utilisant les résultats de l'analyse de capacité de pieu statique et de SPT/DCPT.

1 INTRODUCTION

A wind farm project consisting of more than 100 wind turbines, each with a capacity of 1.65 MW and a hub height of 80 m (Photograph 1), has been developed in Bruce County, Ontario, Canada. The wind turbines are installed approximately 350 m to 500 m apart, resulting in a project area of about 10 km by 10 km (Figure 1). Due to the presence of thick soft clayey soil strata in some areas, over 40 wind turbines have to be supported by piled foundations (Figure 2). Steel H 310 x 110 piles which are commonly used in Ontario have been chosen and designed with an allowable capacity of 900 kN in compression and 350 kN in tension.

The performance of the driven piles in Bruce County, Ontario, with respect to actual pile lengths driven and the subsurface soil conditions, together with other aspects of pile driving, have been discussed earlier by Boonsinsuk et al (2008). Typically, it has been found that the pile lengths actually driven to achieve the design pile capacities with the use of Hiley's Formula are longer than those estimated from static pile capacity analysis. Furthermore, piles can be driven significantly deeper than the practical refusal depths indicated by Standard Penetration Test (SPT) and Dynamic Cone Penetration Test (DCPT). Such performance of driven piles makes it difficult to estimate, within a few metres in accuracy, the pile lengths required prior to installation.

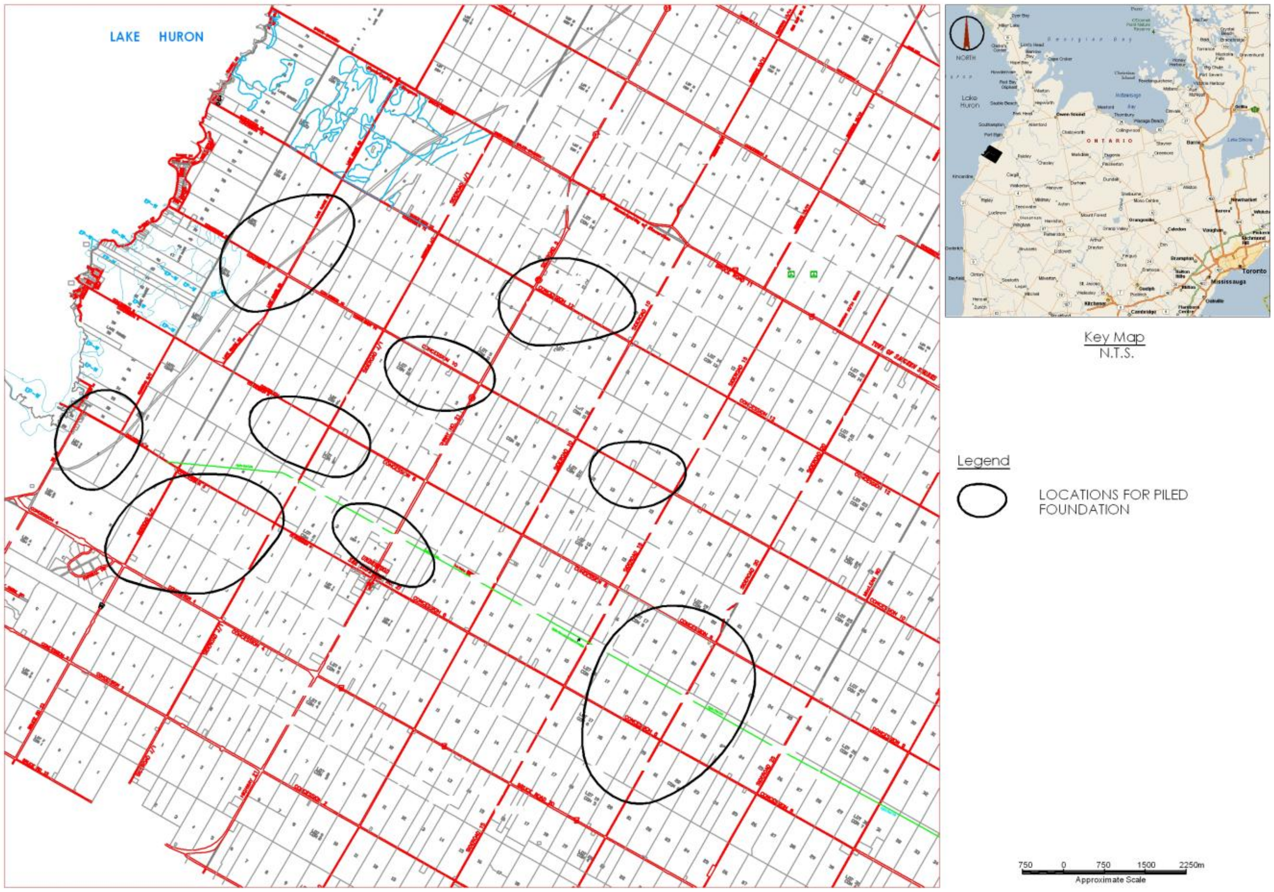

Figure 1. Site Location Plan

Photograph 1. Example of Wind Turbines already Erected

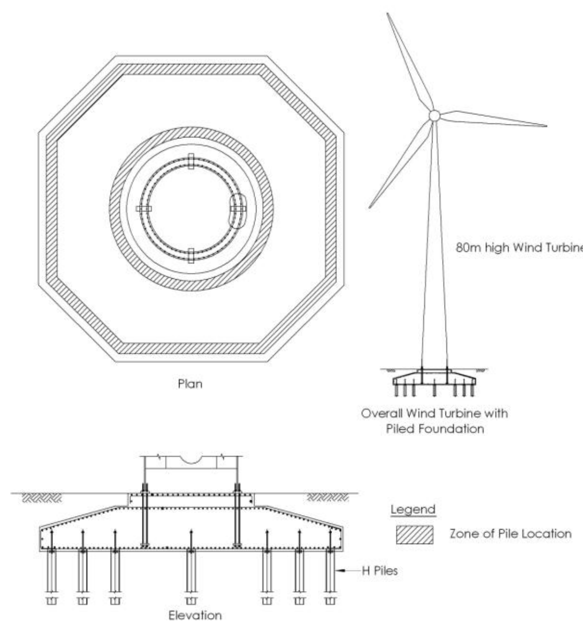

Figure 2. Piled Foundation for Wind Turbine

This paper presents the behaviour of driving piles in comparison with driving the split-spoon in SPT and the DCPT (CFEM, 2006). Actual pile depths driven to achieve design pile capacities are compared with the practical refusal depths indicated by DCPT and SPT. Such comparison leads to a simplified approach in predicting pile lengths for the soil conditions found in Bruce County, Ontario.

2 SUBSURFACE SOIL CONDITIONS

The geotechnical investigation program for a wind farm project is normally undertaken by the Project Owner with the aim for selecting the type of foundation for a design-build contract. As such, it is typical to drill and sample one borehole at each wind turbine to a minimum depth of about 18 m (subject to the geotechnical engineer's requirement), below which depth DCPT is conducted if the soil conditions at the end of the borehole are not competent. During detail design, additional boreholes may be advanced to deeper depths with SPT.

For the wind farm project at Bruce County, a minimum of one borehole was drilled to a minimum depth of 18 m in order to determine the subsurface soil conditions for foundation design. Typically, each borehole was drilled by hollow-stem augering whenever a soft soil stratum was encountered. Standard Penetration Test (SPT) using a hammer weight of 63.6 kg with a drop height of 0.76 m (ASTM D 1586) was carried out normally at 1.5 m depth intervals, together with intermittent field vane shear testing in soft clayey soils. The highest blow counts (N value) of SPT were usually limited to 50 blows per 0.3 m at any depth and subsequently the soil was augered deeper for additional SPT or the borehole was terminated (i.e., practical refusal) if sufficient borehole depth or auger refusal had been reached. For any soft soil stratum that was deeper than about 18 m as indicated by low SPT 'N' values, DCPT using the same hammer and the same 0.76 m drop height as SPT was conducted through the hollow stem augers until refusal to cone penetration (≥ 100 blows/0.3 m – practical refusal) was reached. Alternatively, the borehole was drilled deeper with SPT.

From the Quaternary Geology of Ontario (Southern Sheet), the site is covered by St. Joseph Till (Huron – Georgian Bay lobe) - "silt to silty clay matrix, clay content increases southward, clast poor". The seismicity of the site is relatively low.

For the soil conditions that require piles to support the wind turbines, the results of the subsurface soil profile can be categorized broadly as follows:

2.1 Thick Clayey Soil Overlying Very Dense Stratum ("Soft Soil Profile")

A typical soil profile in which a thick firm-to-stiff silty clay layer overlies a very dense stratum is shown in Figure 3. The majority of the SPT 'N' values range from 7 to 9 blows per 0.3 m while the field vane shear strength ranges from about 50 kPa to 60 kPa (firm to stiff in consistency – CFEM (2006)) with the sensitivity in the range of 1.6 to 1.8. The liquid and plastic limits of the silty clay are 25 and 15 respectively, with its natural water contents varying generally from 16 % to 22 %. DCPT conducted below the 18 m depth through hollow stem augers reaches refusal (100 blows per 0.3 m) at a depth of about 31 m. The soil profile shown in Figure 3 is referred in this paper as "soft soil profile" (in relation to pile driving effort) with the knowledge that the majority of the silty clay is "firm to stiff" in consistency and with the intention of differentiating the "soft soil profile" from the "soft to dense soil profile" described in Section 2.2. Groundwater levels are typically 4.5 m to 15.0 m below the ground surface without artesian conditions.

The majority of soil conditions encountered at the site fall in this "soft soil profile" category.

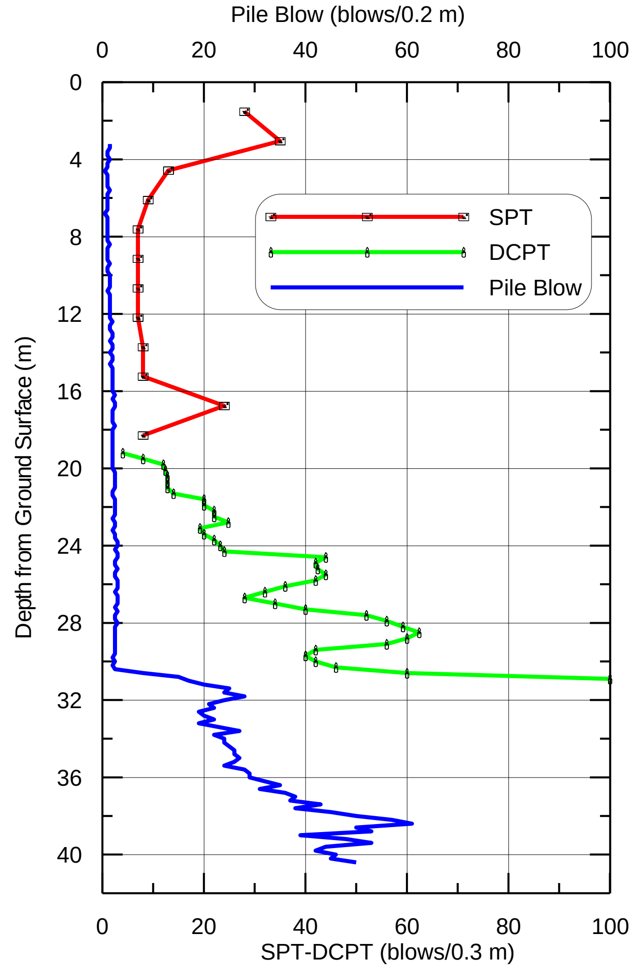

Figure 3. Typical "Soft Soil Profile" (Site T-14)

2.2 Clayey Soil Overlying Thick Very Dense to Compact Sand ("Soft to Dense Soil Profile")

Figure 4 shows an example of a soil profile where a firm-to-stiff clay overlies a relatively-thick, very dense sand which subsequently becomes less dense (i.e., "compact" in degree of compactness). Such a soil profile is referred to in this paper as "soft to dense soil profile" with respect to pile driving effort. In this example, a 7.5 m thick, firm-to-stiff clay layer with a field vane shear strength of 29 kPa is underlain by a 6 m thick, very dense sand with SPT 'N' values of higher than 50 blows per 0.3 m.

However, the very dense sand becomes less dense below a depth of about 13.5 m, without the evidence of “sanding in” which will loosen the sand due to groundwater inflow during drilling. Groundwater levels are typically 4.5 m to 15.0 m below the ground surface without encountering any artesian conditions.

A few wind turbines are located in this soil “soft to dense soil profile” category, with various thickness of the very dense stratum underneath the firm-to-stiff clay layer.

3 STATIC PILE CAPACITY ANALYSIS

Based on the soil conditions encountered at each wind turbine supported by piles, the static pile capacities in both compression and tension of a single pile are analysed by using conservative soil parameters which are varied for sensitivity analysis. For a single pile, the ultimate pile capacity (Q) in static conditions is normally expressed by

$$Q = Q_p + Q_s \qquad [1]$$

where

Q_p = point resistance = $A_p\, q_s$

A_p = area of pile tip

q_s = unit end bearing by Terzaghi bearing capacity equation

Q_s = shaft resistance = $\sum (\Delta L)\,(a_s)\,(s_u)$

ΔL = increment of pile length

a_s = area of pile length for ΔL in contact with soil

s_u = unit shaft resistance

A factor of safety of 2.5 is applied to Q for compression. For tension, a minimum factor of safety of 5.0 for shaft resistance is considered. Both side friction/adhesion and end bearing between the soils and the H 310 pile are calculated in order to determine the pile length that will achieve the design pile capacities (i.e., 900 kN in compression and 350 kN in tension for H 310 x 110). As a result, the minimum pile length and the range of anticipated pile lengths are established for each wind turbine location. In general, the minimum pile length at the site and loading conditions is governed by the design compression capacity.

The static pile capacity analysis results in specifying the minimum pile length/depth and the estimated range of pile lengths/depths to be driven at each wind turbine location.

4 ACTUAL DRIVEN PILE DEPTHS

Two pile driving rigs were used, i.e., Berminghammer B-4505 with a maximum rated hammer energy of 73,550 Joules and a Pileco D30-32 with a maximum rated hammer energy of 85,350 Joules. Prior to driving piles, Hiley Formula was initially used to calculate the set required and subsequently verified and revised, if necessary, by using a Pile Driving Analyzer on the first few piles driven. Such a practice is common in driving piles in Ontario. The ultimate pile capacity considered in the Hiley Formula was 2,700 kN (with a factor of safety of 3, i.e., 3 times the 900 kN design pile capacity in compression as typically used in Ontario). The piles were driven first to the minimum pile lengths specified for tension capacity and subsequently to the required set for compression capacity.

For the soil profile consisting of firm-to-stiff clay overlying a very dense stratum as indicated by DCPT, described as “soft soft profile” in Section 2.1, the pile depths actually driven to achieve the required pile capacities are typically deeper than the depths of DCPT refusal, as shown in Figures 3, 5a and 5b. In Figure 3 (Site T-14 in Figure 5b), one of the piles shown has been driven to more than 40 m depth which is much deeper than the 31 m refusal depth of DCPT (not all the piles within the same turbine location were driven to this depth).

As for the soil profile consisting of firm-to-stiff clay overlying very dense to compact sand (“soft to dense soil profile” - Section 2.2), the ranges of the actual pile depths driven below the first SPT ‘N’ value that exceeds 50 blows per 0.3 m (as measured in the borehole – Figure 6a) are shown in Figure 6b. Figure 4 shows one of the piles driven to the design capacity at about the same depth as the borehole termination depth, indicating that the borehole depth is sufficient for foundation design.

The actual pile depths driven to achieve the required pile capacities could vary significantly even within the same wind turbine foundation footprint (of less than 20 m in diameter) as shown in Figures 5b and 6b which exhibit the range of pile penetration depths within the same wind turbine location.

5 PILE DRIVING BEHAVIOUR

It is common that to estimate pile lengths using the borehole data consisting of SPT and/or DCPT results is difficult to achieve an accurate result which is required for construction quantity control. The use of steel H piles allows the driven pile length to be extended by welding a new section, although the number of welded pile sections should be limited for pile integrity. Cutting an excessive pile length is wasteful.

It should be noted that the piles for this project are driven to achieve the design capacities, not to “practical refusal” typically used when there is a thick very hard layer (e.g., bedrock) at the pile tips. As such, the piles are not driven to “practical refusal depth” controlled by pile damage criterion (i.e., set that will cause pile damage), DCPT, and/or SPT. The piles are therefore driven to depths that are typically shallower than the depths that could damage the piles.

The pile penetration depths actually driven to achieve the design pile capacities are compared with the DCPT and SPT results in the following sections.

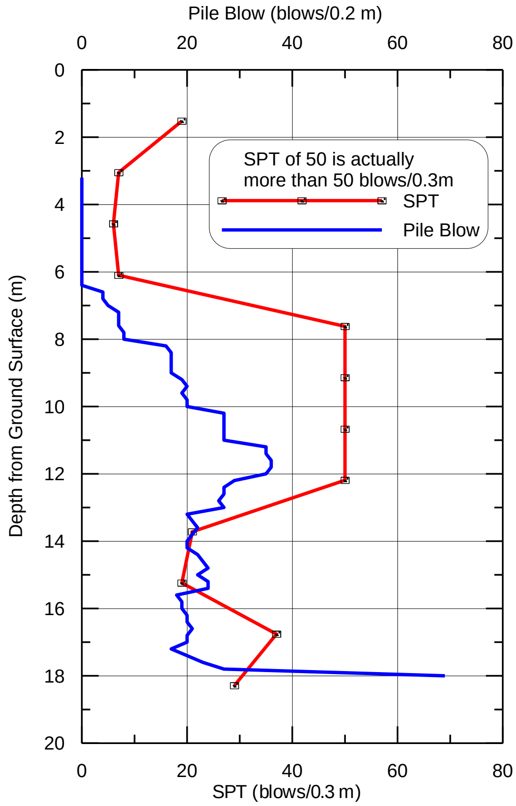

Figure 4. Example of "Soft to Dense Soil Profile" (Site T-38)

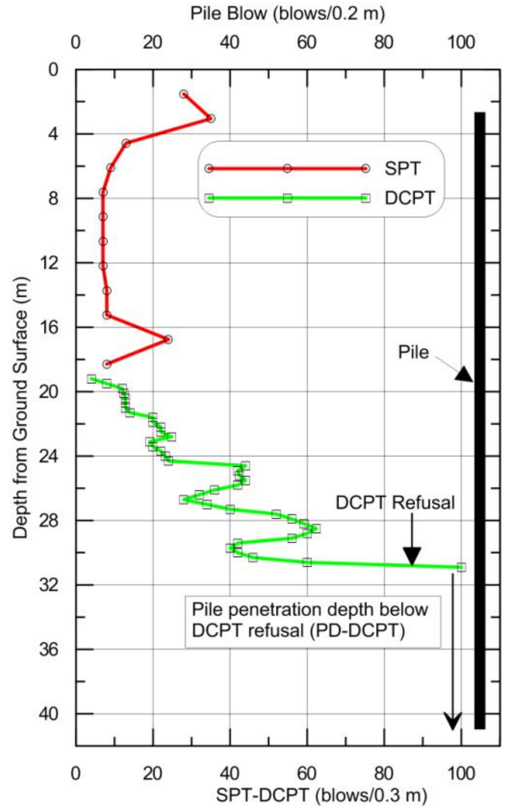

Figure 5a. Example of Driven Pile Depth in "Soft Soil Profile" (Site T-14)

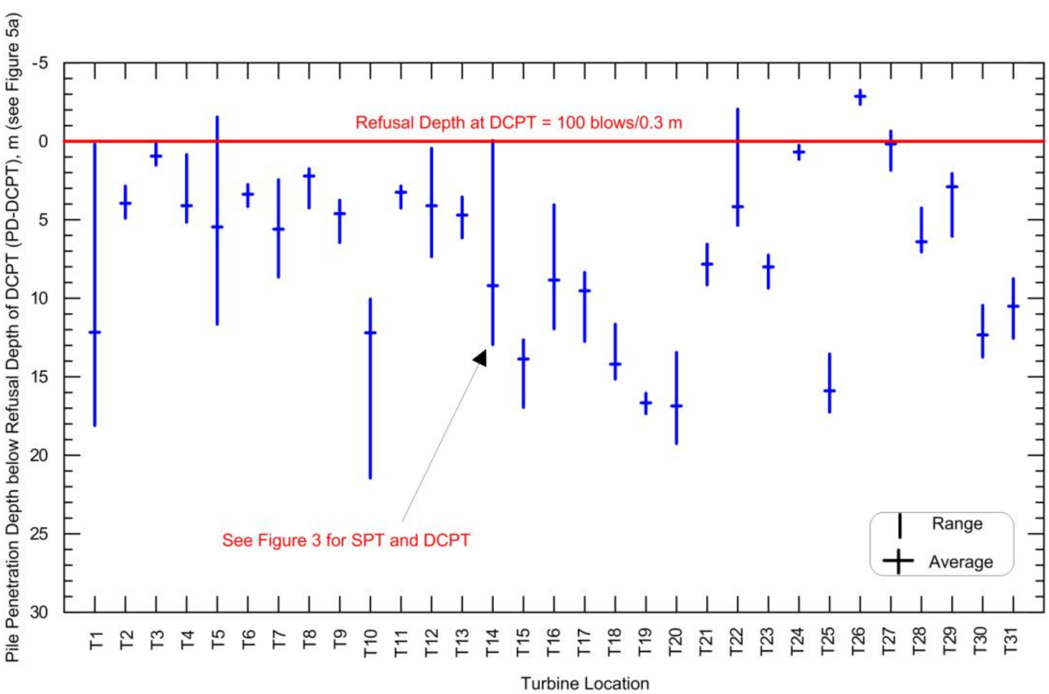

Figure 5b. Actual Pile Depths vs Refusal Depths of DCPT

("Soft Soil Profile")

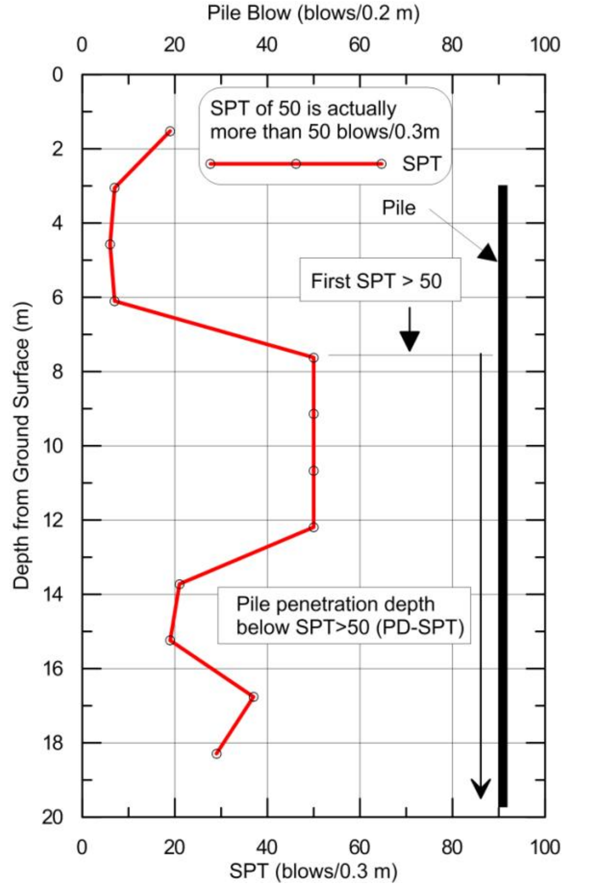

Figure 6a. Example of Driven Pile Depth in "Soft to Dense Soil Profile" (Site T-38)

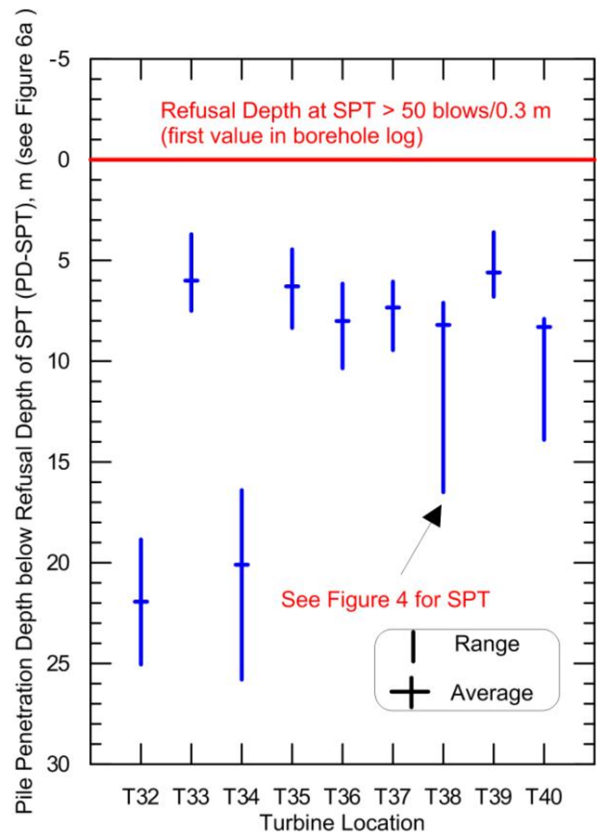

Figure 6b. Actual Pile Depths vs Refusal Depths of SPT ("Soft to Dense Soil Profile")

5.1 Pile vs DCPT

DCPT could penetrate the soil below a drilling depth of about 18 m to the DCPT refusal depth at about 31 m as exemplified in Figure 3. In order to achieve the design pile capacities, the H 310 x 110 piles have to be driven to depths ranging from about 31 m to 41 m (Figures 3, 5a and 5b).

In general, the majority of the piles driven to design pile capacities are deeper than the depths of the DCPT values that are equal to 100 blows per 0.3 m (practical refusal). About half of the piles installed are driven within 5 m below the DCPT refusal depths, while the rest exceed the 5 m depth below the DCPT refusal depths. The maximum difference between the actual pile depths and the DCPT refusal depths is 10 m to 22 m as shown in Turbine No. 10 in Figure 5b. The DCPT refusal depth is therefore not necessary the refusal depth of pile.

Even within the same turbine location, the driven pile lengths are typically different among the adjacent piles and normally vary by up to 5 m for the piles driven within the pile cap width of less than 20 m in diameter.

The differences between the driven pile depths and the refusal depths of DCPT are likely due to the differences in driving criteria and driving energy used.

5.2 Pile vs SPT

When comparing the actual driven pile depths with the "practical refusal" depths of SPT (i.e., SPT N values equal to or higher than 50 blows per 0.3 m), the driven pile depths to achieve the design pile capacities are within 5 m to 10 m below the first refusal depth of SPT as shown in Figures 6a and 6b. It should be reminded that the typical soil profile as shown in Figure 4 consists of a firm-to-stiff clay overlying a very dense sand (SPT N values of 50 blows per 0.3 m or higher) with 5 m to 10 m in thickness. The very dense sand layer is typically underlain by a compact sand layer with SPT N values of equal to or less than 30 blows per 0.3 m. The piles have to be driven through the very dense sand layer in order to achieve the design pile capacities, particularly in tension. Therefore, the actual driven pile depths that are within 5 m to 10 m below the first SPT refusal depth as shown in Figures 6a and 6b simply indicate that the piles have to be driven through the very dense sand in order to achieve the design capacities and should be considered as in relatively-good agreement with the soil profile determined by SPT as exemplified in Figure 6b.

The fact that steel H piles can be driven through very dense sand for a distance of about 5 m to 10 m should be considered during design since the pile refusal depth is not necessary the SPT refusal depth. Damage to the piles could however occur in hard driving through the thick, very dense sand layer. For this site, driving piles relatively deep into the thick, very dense sand layer did not cause any pile damages as verified during pile driving. Otherwise, pre-drilling would be needed to drive the piles to the minimum depth required.

6 ESTIMATED PILE LENGTH

To estimate the pile length required to achieve the design pile capacities, a static pile capacity analysis can be carried out using the available borehole information. If the borehole depth investigated is less than the pile depth that would achieve the design pile capacities, the soil conditions below the investigated depth have to be conservatively assumed (and subsequently verified by actual driven pile depth). For this project, the soil type below the borehole depth investigated is assumed to be the same as that encountered at the termination of the investigated depth which is normally a hard or very dense soil stratum. Such an assumption is based on past experience for driven pile depths at the project site and the site quaternary geology consisting of till deposits. The static pile capacity analysis is then carried out by using conservative soil strength parameters to estimate the pile length required for achieving the design pile capacity in both compression and tension. The soil strength parameters are varied for sensitivity analysis, resulting in a range of estimated pile lengths.

Alternatively, additional deeper boreholes can be drilled to determine the actual soil conditions. However, this is rather costly and may not provide representative soil conditions for pile lengths which have been found to vary substantially within the same wind turbine foundation footprint, a distance of less than 20 m (Figures 5b and 6b).

For presentation, the estimated pile lengths and the actual driven pile lengths can be compared using the following equation:

$$F = \frac{\text{Actual Driven Pile Length}}{\text{Minimum Estimated Pile Length}} \quad [2]$$

Using Equation 2 and the minimum estimated pile length, the range of F for the piles is shown in Figure 7 for boreholes terminated by DCPT and Figure 8 for boreholes terminated by SPT. Both DCPT and SPT lead to good estimation of pile lengths for the majority of the wind turbine locations, i.e., F is equal or close to 1.0. Significant variations can occur in some locations, i.e., F is much higher or lower than 1.0. As an average for the entire project site, F is about 1.3 for DCPT and 1.1 for SPT.

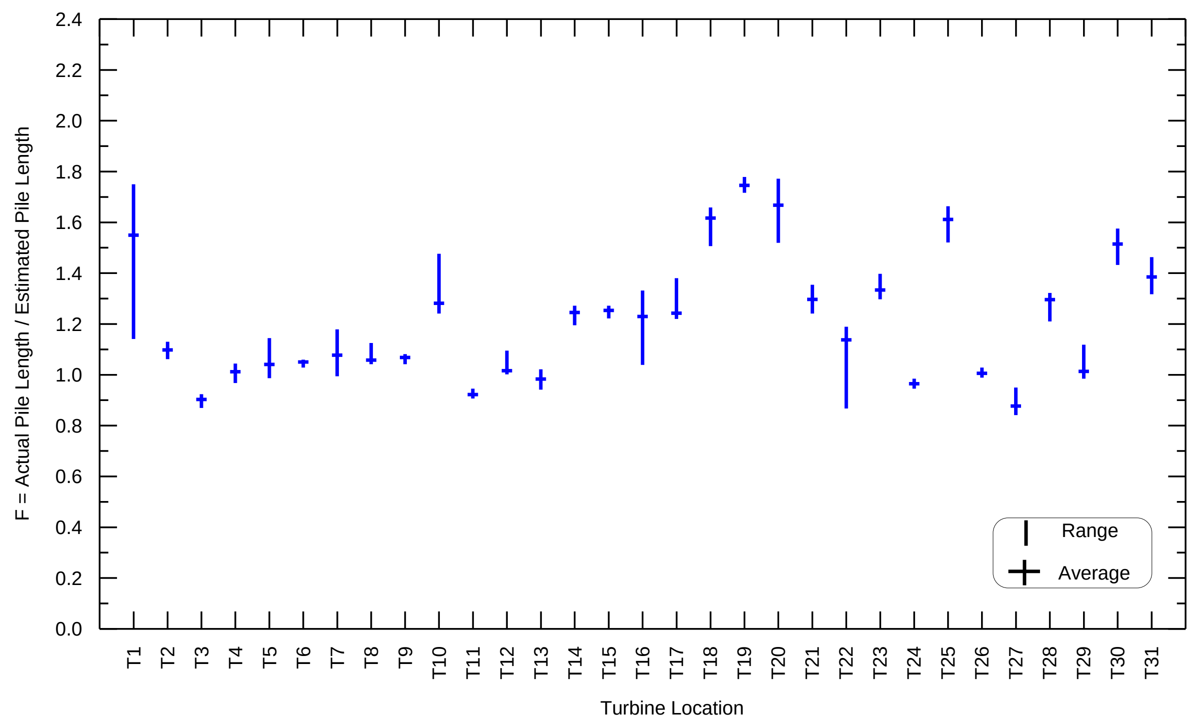

Figure 7. Variation of Estimated and Driven Pile Length - DCPT

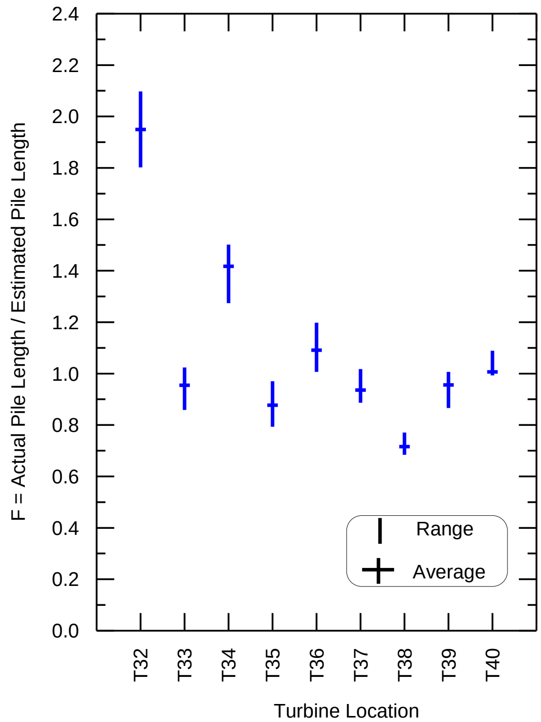

Figure 8. Variation of Estimated and Driven Pile Length - SPT

7 CONCLUSIONS

From the results of driving over 1500 piles at Bruce County in Ontario, the following conclusions can be made with respect to pile lengths actually driven to achieve the design pile capacities:

- Steel H piles can be driven deeper than the practical refusal depths indicated by the cone in Dynamic Cone Penetration Test (DCPT) and the split-spoon sampler in Standard Penetration Test (SPT), possibly due to the much higher driving energy generated by pile driving rigs and the stronger structure of steel H piles. For soil profiles without a thick hard/very dense soil stratum or bedrock at anticipated pile tip depths, it is therefore difficult to estimate pile lengths to be driven.
- To estimate pile lengths to be driven, a static pile capacity analysis can be used with assumed conservative soil parameters. A sensitivity analysis should also be carried out using a range of soil parameters in order to estimate a reasonable range of pile lengths to be driven.
- If soil conditions below borehole depths are assumed in order to estimate pile lengths required for the project, the assumptions should be based on site specific knowledge of soil conditions and past pile driving experience. The assumptions have to be verified by actual pile driving and/or additional site investigation.
- Driving piles with the use of Hiley Formula as normally used in Ontario should always be verified by pile load testing, e.g., Pile Driving Analyzer or static pile load testing, prior to driving production piles.
- For boreholes that are terminated by DCPT, the estimated pile lengths using a conservative static pile capacity analysis should be increased by 10 % to 30 %.
- For boreholes that are terminated by a number of SPTs, the estimated pile lengths using a conservative static pile capacity analysis should be increased by about 10 %.
- Notwithstanding the suggested increase in the estimated pile lengths, it is possible that a significant variation from the estimated pile lengths could still occur in some locations.
- For driving piles in soil conditions without a thick hard/very dense soil stratum for embedding pile tips, the construction contract should be flexible to accommodate the actual pile lengths driven to achieve the design pile capacities.

ACKNOWLEDGEMENTS

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