Experience in driving over 1000 piles in Bruce County, Ontario

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ABSTRACT
As part of a wind farm project developed by Enbridge 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. Over 1000 steel H 310 piles were driven, some more than 30 m deep, to achieve the design pile axial capacity in both compression and tension. For design, the pile capacity was evaluated by static pile capacity analysis using the borehole data obtained at each wind turbine location. The subsurface soil conditions were investigated by the Standard Penetration Test and dynamic cone penetration. The minimum pile embedment depth at each wind turbine location was established in order to achieve the design pile compression and tension capacity. Pile driving criteria based on Hiley formula were then developed.

A few pile driving hammers were used in driving the piles from the fall of 2007 into 2008. A Pile Driving Analyzer (PDA) was utilized to evaluate the performance of each pile driving hammer, confirm pile driving criteria, and verify design pile capacity. The experience gained in interpreting borehole data, analyzing pile capacity and specifying pile driving criteria, will provide a good basis for similar projects in the future.

RÉSUMÉ
Plus de 40 turbines éoliennes qui font partie d'un projet de parc d'éoliennes dévelopé par la compagnie Enbridge au comté de Bruce en Ontario, ont des fondations sur pieux dû à la présence des strates de terre molle. Plus de 1,000 pieux H en acier ont été enfoncés dans la terre, quelques uns plus de 30m en profondeur, pour atteindre les capacités axiaux de pieux en compression ainsi qu'en tension. Durant la phase de conception, les capacités de pieux ont été évaluées selon la méthode de Capacité de Pieu Statique, en utilisant les données de sondage obtenues à chaque location de turbine éolienne. Les conditions de sous-terrain ont été etudiées en utilisant les méthodes d'Essai de Pénétration et de Pénétration Dynamique au Cône. Le profondeur minimal de fonçage de pieux a été établi à chaque location de turbine éolienne afin que les capacités de pieux conçues en compression et en tension soient atteindre. Critères pour fonçage de pieux donc ont été développés, fondés sur la Formule de Hiley.

L'utilisation de quelques marteaux de fonçage de pieux était en cours entre l'automne de 2007 et 2008. Un Analyseur de Battage de Pieux a été utilisé afin d'évaluer la performance de chaque marteau, de confirmer les critères de fonçage de pieux, ainsi que de vérifier les capacités des pieux. L'expérience acquise en interprétant les données de sondage, en analysant les capacités de pieux et en spécifiant les critères de fonçage de pieux, fourniront une bonne fondation pour les projets similaires qui suivent.

1 INTRODUCTION

A wind farm project developed by Enbridge in Bruce County, Ontario, Canada, consists of more than 100 wind turbines, each with a capacity of 1.65 MW and a hub height of 80 m. The wind turbines are installed approximately 350 m to 500 m apart, such that the project site covers an area of about 10 km by 10 km (Figure 1). An example of the wind turbines already erected at the project site is shown in Photograph 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, the pile lengths of which exceed 30 m in some turbine locations. Each piled foundation (Figure 2) has been designed by considering the pile group behaviour to support the high moment on the foundation caused by the wind load, resulting in the number of piles for each foundation to be less than 40 piles. Nevertheless, over 1000 piles are required for the wind farm project.

In order to limit the type and size of pile for construction control, H 310 x 110 and H 310 x 79 steel piles are selected, based on their availability and common usage in Ontario. The design allowable pile capacity for H 310 x 110 is 900 kN in compression and 350 kN in tension, and for H 310 x 79 is 900 kN in compression and 250 kN in tension.

This paper describes the static analysis of the capacity of a single pile during design and the results of driving the piles to achieve the pile design capacity. The experience gained in driving a large number of piles over a variety of soil conditions as described in this paper should provide a good case record for future similar projects.

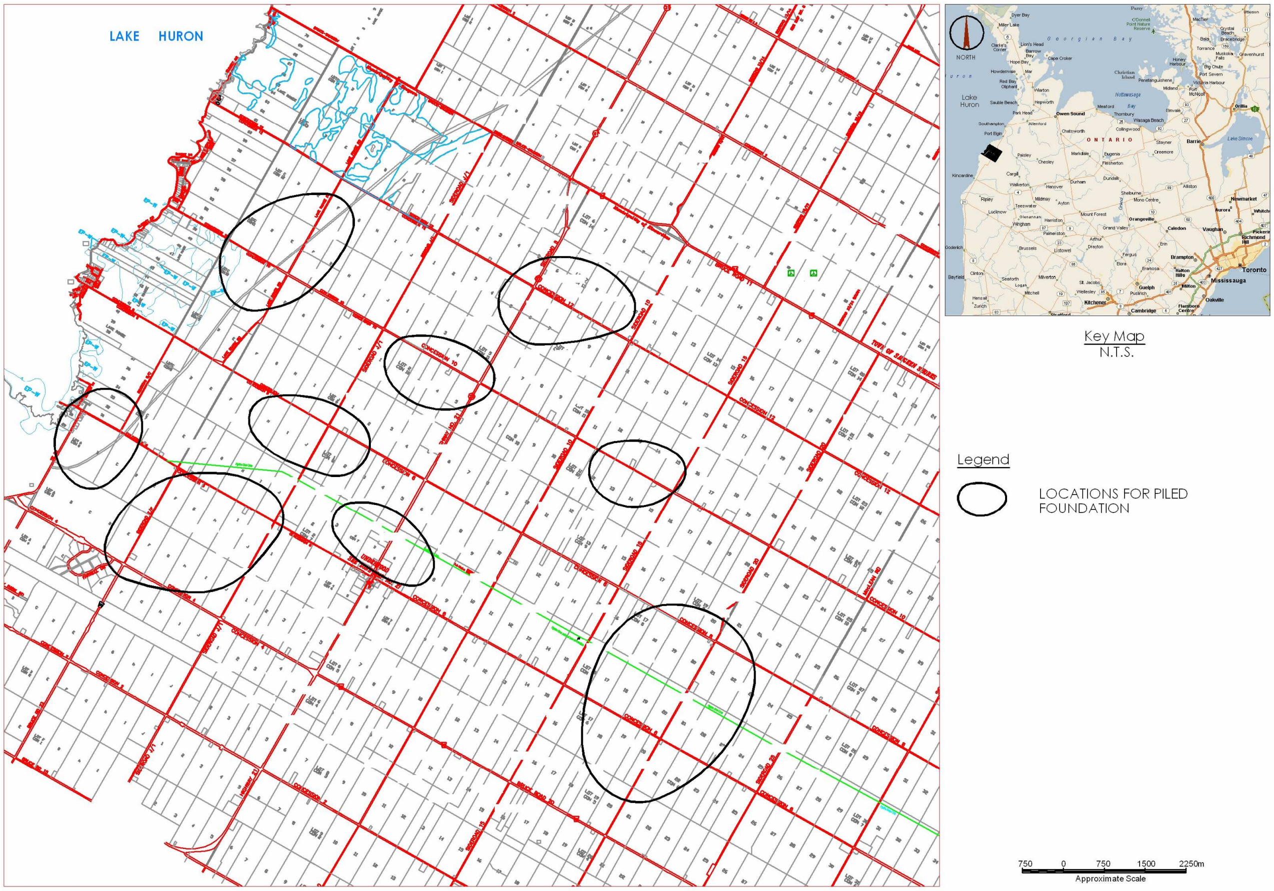

Figure 1. Site Location Plan

Photograph 1. Example of Wind Turbines already Erected

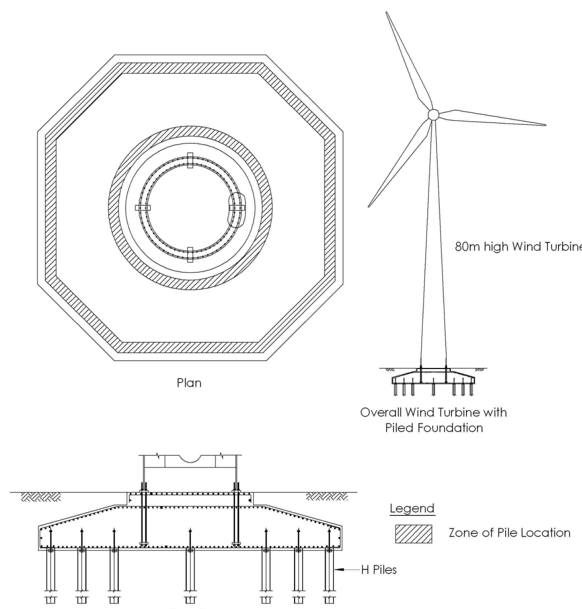

Figure 2. Piled Foundation for Wind Turbine

2 SUBSURFACE SOIL CONDITIONS

For each wind turbine location, a minimum of one borehole was drilled to a minimum depth of 18 m in order to establish the subsurface soil conditions for foundation design. Each borehole was drilled typically by hollow-stem augering whenever a soft soil stratum was encountered. Standard Penetration Test (SPT) was carried out at regular depth intervals, together with field vane shear testing in soft clay strata. For any soft soil stratum that was deeper than about 18 m, a dynamic cone penetration test (DCPT) using the same hammer and the same 0.75 m drop height as SPT was conducted through the hollow stem augers until refusal to cone penetration (100 blows/0.3 m) was reached.

The results of the subsurface soil investigation can be categorized broadly, with respect to the soil conditions that require piles to support the wind turbines, as follows:

2.1 Thick Soft Clayey Soil Overlying Hard Stratum

A typical soil profile where a thick soft silty clay soil overlies a hard stratum is shown in Figure 3. At this borehole location, the field vane strength of the soft clay ranges from about 50 kPa to 60 kPa 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 %. The dynamic cone penetration test (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 majority of the soft soil profiles encountered at the site fall in this category.

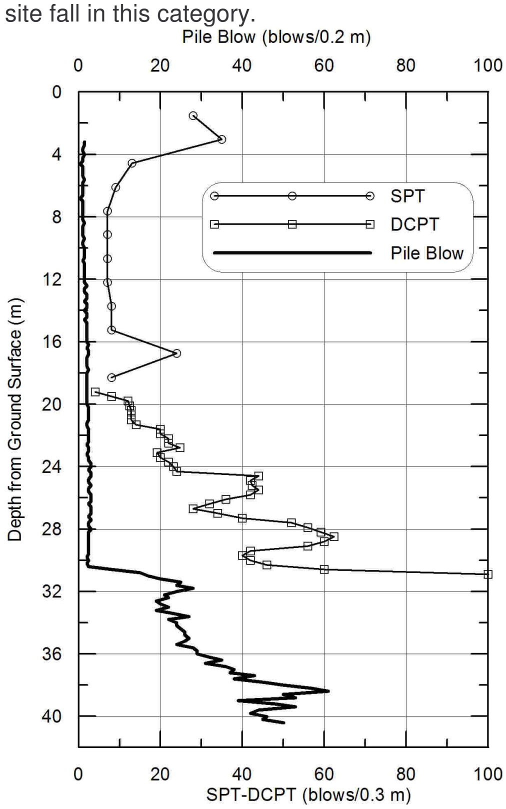

Figure 3. Typical Soft Clay Profile

2.2 Soft Soil Overlying Very Dense to Compact Sand

Figure 4 shows an example of a soil profile where a soft clay overlies a relatively-thick, very dense sand which subsequently becomes less dense (i.e., compact relative density). In this example, a 7.5 m thick, soft clay with a field vane 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 being loosened due to groundwater during drilling.

A few wind turbines are located in this soil profile category.

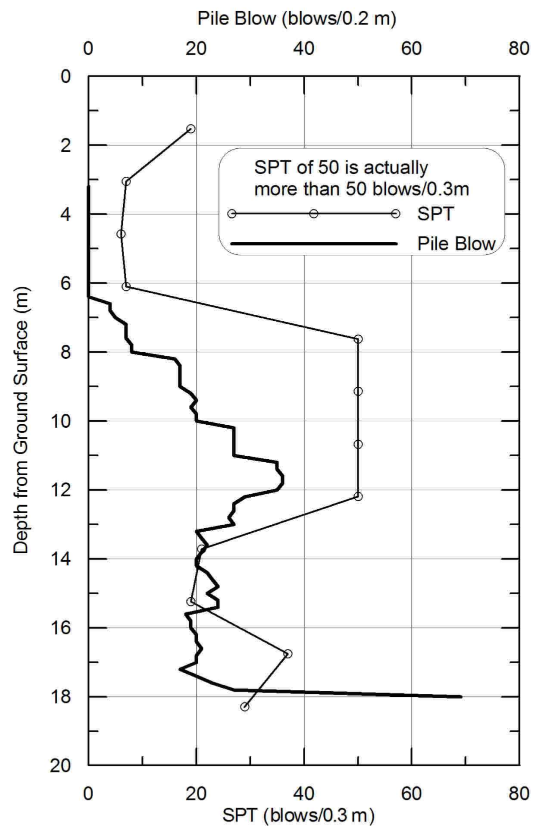

Figure 4. Example of Soft Clay Over Very Dense Sand Profile

3 STATIC PILE CAPACITY ANALYSIS

Based on the soil conditions encountered at each wind turbine to be supported by piles, the static pile capacity in both compression and tension of a single pile is analysed by using conservative soil parameters which are varied for sensitivity analysis. 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 capacity (i.e., 900 kN in compression and 350 kN in tension for H 310 x 110 / 250 kN in tension for H 310 x 79). As a result, the minimum pile length is established for each wind turbine location. The minimum pile length to be driven is mainly governed by the design tension capacity. In other words, even if the pile has been driven to achieve the design capacity in compression (as typically used in deriving pile driving set criteria), the pile may have to be driven deeper in order to achieve the minimum pile length required to achieve the design capacity in tension.

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

4 PILE DRIVING AND CAPACITY VERIFICATION

Pile driving began in fall 2007 and extended to early 2008. Two pile driving hammers were used, i.e., Berminghammer B-4505 with a maximum rated hammer energy of 73,550 Joules and Pileco D30-32 with a maximum rated hammer energy of 85,350 Joules. The piles were driven from the base of the pile cap (i.e., concrete footing covering all driven piles) located approximately 3 m below the existing ground surface.

Prior to driving piles, Hiley Formula was used to calculate the set required. 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). In addition, the minimum pile embedment depths are specified for pile driving.

Pile driving was monitored full-time. The number of hammer blows per 0.2 m was recorded throughout each pile embedment length. The number and location of pile splices were recorded, together with any uncharacteristic pile behaviour during driving (e.g., twisting in pile, out-of-plumb, etc.). The pile driving records were reviewed by engineers on a daily basis.

For the first few piles driven by each pile hammer, a Pile Driving Analyzer (PDA) was used to verify the transferred pile driving energy and determine pile resistances to driving in terms of strain and acceleration. Subsequently, a CAPWAP (Case Pile Wave Analysis Program) analysis was performed to evaluate the mobilized pile capacity in both compression and tension. Both End of Initial Driving (EOID) and Beginning of Restrike (BOR) of driven piles were tested by the PDA.

The PDA and CAPWAP results were used to verify the design pile capacity of driven piles, and modify the minimum pile embedment lengths and the pile driving set criteria where necessary.

In general, the results of PDA and CAPWAP analysis confirm the capacity of driven piles in both compression and tension. At each of the wind turbines tested by PDA, 3 to 5 piles were subject to the PDA test. The pile capacity in both compression and tension analyzed by PDA and CAPWAP shown in Figure 5 indicates that the pile capacity in compression (end bearing plus side resistance) substantially exceeds the design 900 kN pile capacity. Similarly, the pile capacity in tension as analyzed by PDA and CAPWAP considerably exceeds the design 350 kN pile capacity in tension. If the pile capacity as analyzed by PDA and CAPWAP is significantly less than the design values, the pile driving criteria are revised, generally resulting in driving the piles deeper.

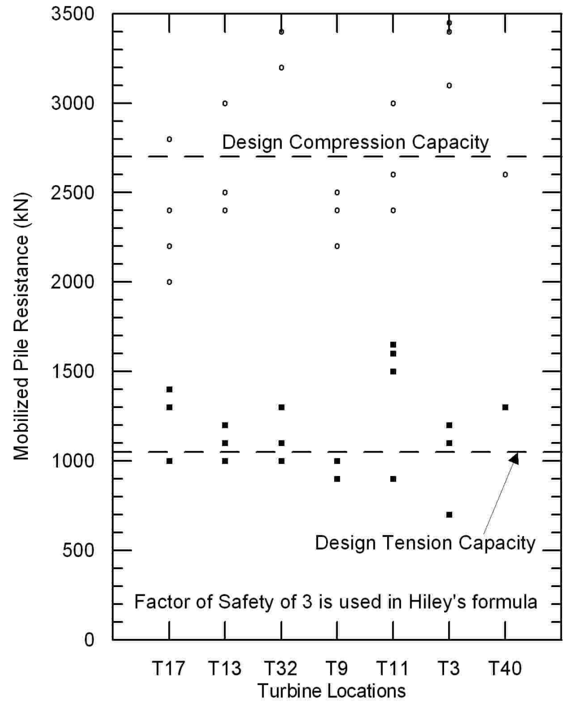

Figure 5. Mobilized Pile Resistance from PDA Tests

5 PILE DRIVING BEHAVIOUR

From driving a large number of steel H piles at Bruce County in Ontario, the following pile driving behaviour can be observed:

5.1 Actual Driven Pile Depths

For the soil profile consisting of soft silty clay overlying a hard stratum as indicated by dynamic penetration testing (DCPT) described in Section 2.1, the pile depths that are driven to achieve the required pile capacity are typically deeper than the depths of DCPT refusal, as shown in Figure 6. Such a trend is anticipated due to the fact that the cone (about 50 mm in diameter) used in DCPT is actually much smaller than the H 310 piles (about 310 mm by 310 mm in pile end area) and the energy in driving the cone is much smaller than that used in driving the H 310 piles, i.e., 475 Joules per blow for DCPT compared with approximate 40,000 to 50,000 Joules per blow for driving H 310 piles. The pile blow counts do not generally follow the trend of the DCPT blow counts as exemplified in Figure 3. By using conservative soil strength parameters, the estimated pile depths based on the static pile capacity analysis prior to pile driving are generally agreeable with the actual pile depths driven.

It should be noted that drilling deeper boreholes instead of DCPT could provide a more accurate estimate of pile depth. However, the actual driven pile depths for piles located within a few metres away could be quite different as shown in the range of the actual driven pile depths at each wind turbine location in Figure 6. In some cases, the difference in driven pile depths within the same wind turbine location, which is less than 20 m diameter in the piled foundation footprint, is more than 10 m.

Regardless of the depth of the borehole and the number of boreholes drilled within the footprint of a wind turbine tower, there could be a significant difference of actual pile depths driven to achieve the required pile capacity. Such a fact makes it difficult to accurately estimate pile penetration depths.

As for the soil profile consisting of soft soil overlying very dense to compact sand (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 are shown in Figure 7. An example of the actual pile blow counts and pile depth driven compared with the SPT 'N' values measured in the borehole is illustrated in Figure 4. In general, the pile blow counts increase with high SPT 'N' values and vice versa. The piles can be driven below the soil stratum with high SPT 'N' values and limited stratum thickness, although there may be a significant number of damaged piles.

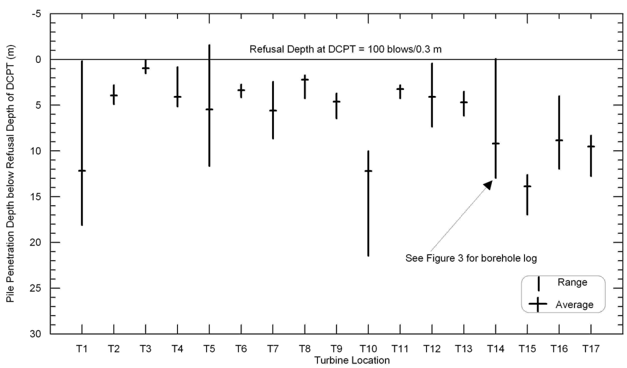

Figure 6. Actual Pile Depths vs Refusal Depths of DCPT

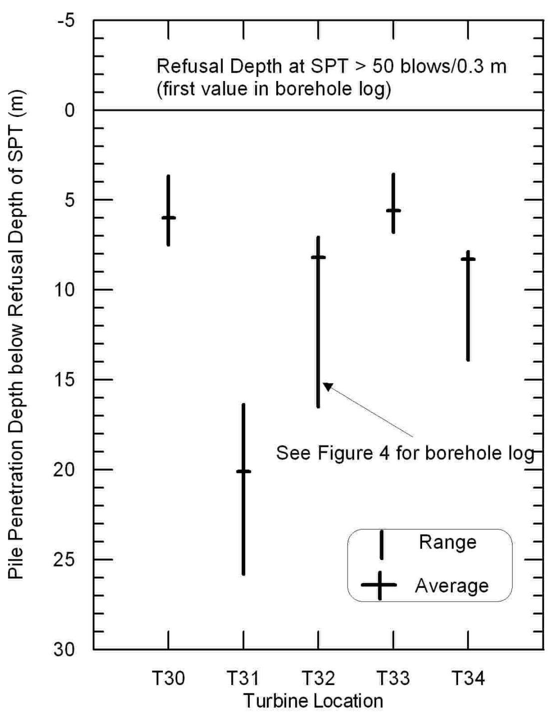

Figure 7. Actual Pile Depths vs Refusal Depths of SPT

5.2 Variation of Driven Pile Depths within a Single Wind Turbine Foundation Footprint

As mentioned in Section 5.1, the actual pile depths driven to achieve the required pile capacity could vary significantly even within the same wind turbine foundation footprint. At one wind turbine location, some adjacent piles were driven to a depth of about 39 m while the remaining piles were driven to a much shallower depth of about 27 m as shown in Figure 8. Apparently, there is a significant natural depression of relatively-soft soil located immediately adjacent to a hard stratum. Such a phenomenon could also be caused by isolated boulders, although the boulders can not be accounted for the approximate 27 m long piles located side by side at a distance of over 4 m.

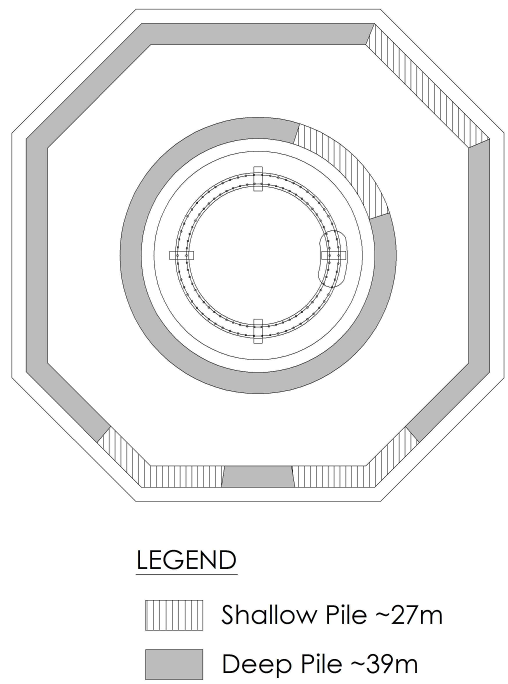

Figure 8. Variation of Driven Pile Depths within a Single Wind Turbine Footprint

5.3 Pile Damages

In driving the H 310 piles, the two main controlling factors are (a) to drive the piles to the required set in order to achieve the required pile capacity in compression, and (b) to drive the piles to the required minimum pile embedment depth in competent soils in order to mobilize sufficient pile capacity in tension. Such controlling factors demand that the piles are to be driven sometimes below the depth where the required set has already been reached. Hard driving of the piles at some locations is therefore necessary, particularly through very dense sand (e.g., Figure 4). The hard driving, together with the possible presence of boulders, leads to some pile damages.

An example where a relatively-high number of pile damages occurred is in the case of soft clay overlying very dense sand as shown in Figure 4. At this location, the range of pile penetration depths below the first SPT 'N' value that exceed 50 blows per 0.3 m is shown in Figure 7. The percentage of the damaged piles is about 10 % at this particular location.

For all the H 310 piles driven for the project, the percentage of damaged pile is less than 1.5 %. All damaged piles are replaced with new piles driven adjacent to the damaged piles.

One of the factors that could damage driven piles is the accumulated number of blows that the piles are subject to during driving. At the project site, comparing the accumulated number of pile blows between undamaged piles and damaged piles indicates no significant difference as shown in Figure 9. The majority of the H piles can be driven with a total number of pile blows up to about 1,900 blow counts without damage.

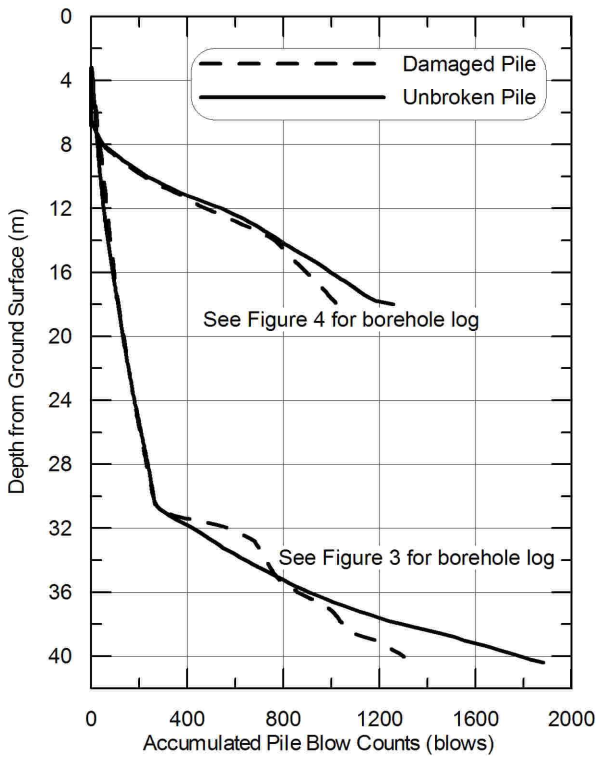

Figure 9 Accumulated Pile Blow Counts

6 CONCLUSIONS

Due to the presence of a soft silty clay stratum overlying a hard stratum, piled foundations are required to support the 80 m high wind turbines. The piled foundation has to be capable of supporting the wind turbine under high wind loads that cause high moments to the piled foundation. As a result, the piles required to support the wind turbine tower have to be subject to both compression and tension.

Piles for this wind turbine project are required to be driven: (a) to the required set in order to achieve the design pile capacity in compression, and (b) to the required minimum pile depth in order to achieve the design pile capacity in tension.

In order to satisfy the pile driving requirements, the piles have been driven significantly below the depth where refusal to dynamic cone penetration test (100 blows per 0.3 m) and refusal to Standard Penetration Test (exceeding 50 blows per 0.3 m) had been encountered during drilling boreholes.

Close monitoring of pile driving and periodic verification of driven pile capacity by PDA and CAPWAP are necessary to confirm the design pile capacity in both compression and tension.

Significant variation in pile embedment depths within the same piled foundation footprint (less than 20 m in diameter) makes it difficult, if not impossible, to accurately estimate the pile lengths to be driven. However, using the borehole information with DCPT/SPT data and conservative soil strengths in estimating the static pile capacity can lead to a reasonable range of estimated pile lengths required to achieve the design capacity in both tension and compression.

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