

## FRICION FATIGUE AND DRIVABILITY ANALYSIS OF OPEN ENDED PIPE PILES BASED ON CONE PENETRATION TESTING RESULTS

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### ABSTRACT

Pile foundation driveability is a function of several variables such as subsurface characteristics, hammer type, hammer efficiency, pile type, and plugging conditions. One important phenomenon occurring during pile driving, and yet not well documented and published, is the *friction fatigue*, where a reduction of shaft resistance is observed as the pile is driven to greater embedment. This paper introduces current soil models developed for the assessment of friction fatigue, and further presents a comparison between predicted driveability obtained from Wave Equation Analysis Program (GRLWEAP) and field driving records. From a literature survey, and review of technical articles, a widely-used soil model known as AH-01 has been selected to analyze the friction fatigue concept. Using a WEAP software, two driveability analysis were completed using the standard approach with setup factors, and adapting the AH-01 model into the WEAP input file. Driveability predictions were compared to the driving records corresponding to a 1676-mm x 44-mm open-ended pipe pile with a total and embedment lengths of 180-m and 119-m, respectively. Results from analyses and the comparison presented in this paper provide further information regarding existing methods for the incorporation of the friction fatigue concept to the driveability analyses, and contributes to a better prediction of driveability of open-ended pipe piles.

**Keywords:** Friction fatigue, Driveability, Open-ended pipe piles, Wave Equation Analysis, Static Resistance to Driving, SRD

## Introduction

Dynamic measurements during pile installation provide more dependable information as compared to results obtained from predictive models used for design. Despite uncertainties associated with a specific project site and foundation type, measured data provides a reliable understanding of the soil resistance and its distribution throughout the length of the pile. Back-calculations or back-analyses based on a series of measured data from a pile driving process could help to obtain reliable models to better predict events related to pile installation process in spite of all variability related to fitted models. One of the widely-used analysis regarding pile driving during the design phase is the “driveability analysis” where capacity, blowcounts, maximum stresses in the pile element, and transferred energy from the hammer to the pile element are predicted using mathematical models along with a software. Such analysis requires relevant information regarding soil, pile, and hammer properties combined with a deep understanding of the level of impact each one of these properties could have on the analysis.

One of the properties that could significantly impact the driveability prediction is the effect of the embedded pile length on the soil resistance distribution along the pile. This effect has been commonly studied under the *friction fatigue* phenomenon where the soil resistance is decreased along the pile shaft as the pile is driven deeper into the soil layers. Traditionally, instead of using the friction fatigue approach, driveability analyses were performed assuming an empirical soil setup factor for each layer. It was then assumed that during driving, regardless of the number of load cycles (i.e., hammer blows), the soil resistance would be the long term static resistance divided by the soil setup factor. For example, if the soil setup factor was 2 then the resistance during driving was assumed to be 50% of the long-term resistance. This approach has been satisfactory for land piles with moderate pile penetrations. Unfortunately, the setup factor was not well defined for marine clays, and varied between 2 and 10. Experience in a certain geology was needed to select the correct value.

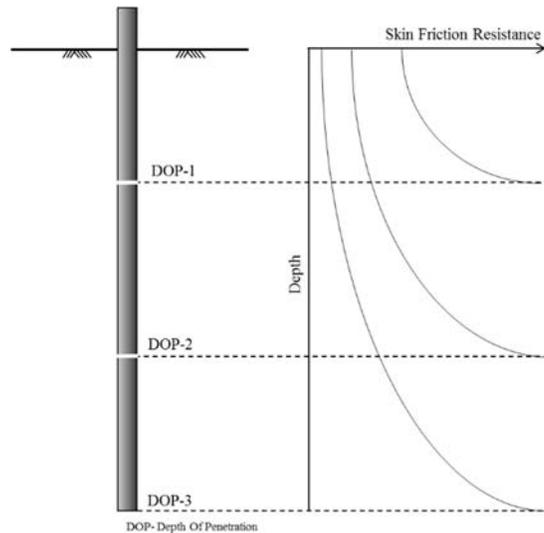
Appropriate mathematical approaches and formulations have been proposed and implemented to assess the friction fatigue. Throughout several studies, it has been proposed and assumed that the friction fatigue is more noted in granular soils (i.e. sandy soils) compared to fine grained soils (i.e. clay material), and the effect is further observed in dense to very dense sands compared to those results reported for loose sands, Schneider et al. (2010).

Throughout this paper, a brief background and review of existing studies related to friction fatigue is presented, the driveability analysis and its associated parameters are discussed in detail, a mathematical model proposed by Alm and Hamre (2001) (A&H) to assess the friction fatigue during pile driving is introduced, and the wave equation analysis program used for related analyses is described. Furthermore, a case study is presented where the driveability analysis was completed with and without considering the friction fatigue effect, and the results are compared to driving logs representing measured blowcounts obtained from the pile driving monitoring.

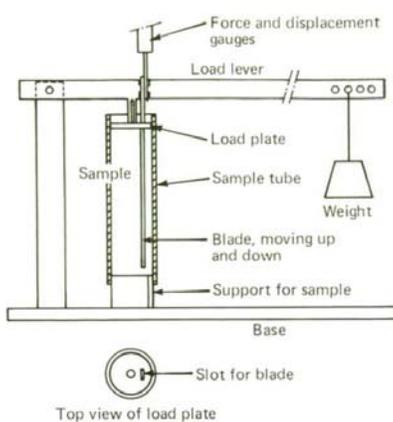
## Friction Fatigue

Hypothetically, the unit skin friction for a pile installed in a uniform material increases as the depth is increased, and consequently more resistance is encountered at higher depths which results in higher driving resistance (i.e. high blowcounts as the depth increases). However, throughout a series of observations Heerema (1979) concluded that the unit shaft resistance decreased during the driving process as the piles were driven to greater depths, Figure 1. The reduction of skin friction was primarily attributed to the cyclic shearing process that the soil surrounding the pile suffers during the driving process, and it was further introduced as the friction fatigue theory.

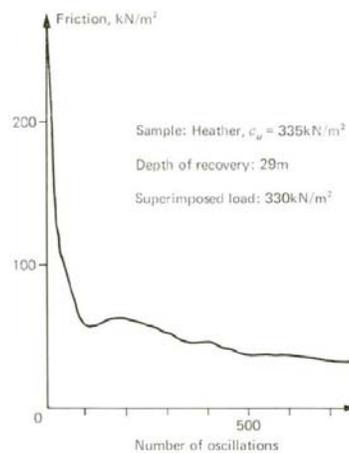
In addition to documenting observations made at a pile driving project, Heerema (1980) developed a laboratory device to further study the friction fatigue phenomenon, and simulate the interaction between the steel wall of the pipe pile and the soil material. For the laboratory test, a thin wall tube was recovered containing an undisturbed sample, and it was cut to a length of approximately 19-cm with vertical stresses applied to the soil sample from above and below using bearing plates. Using a relatively small opening in the upper plate, a 1.5-mm thick and 12-mm wide steel blade was pushed into the soil sample, and through an actuator cyclic, displacements were generated in the sample, Figure 2a. During this process, strain gages and accelerometers were connected to the steel blade to continuously record force and velocity measurements. Results from the laboratory tests showed that the initial shear strength of the soil was decreasing as the number of oscillations were increasing which further confirmed the observations reported by Heerema (1979), Figure 2b. It is interesting to note that in the traditional setup approach, the results of Figure 2b would have been interpreted to suggesting a soil setup factor of approximately  $300/40 = 7.5$ .



**Figure 1.** Schematics of skin friction resistance at different depths of penetration (after Heerema 1980)



a) Laboratory Apparatus



b) Laboratory Results

**Figure 2.** Evaluation of friction fatigue concept through laboratory testing (after Heerema, 1979)

After results presented by Heerema (1979 and 1980), other studies have evaluated the relationship between the friction fatigue and hammer blows (White et al. 2004, and White 2005), the ratio of the soil height above the pile tip and the pile diameter (Randolph et al. 1991), and the height of the soil above the pile tip (Alm and Hamre, 2001).

The research study presented by White et al. (2004) evaluated the effect of friction fatigue on displacement piles in sands using a centrifuge model instrumented with lateral stress sensors. The results from the experiment were combined with laboratory tests as well as field observations, and it was concluded that for a given installation method the lateral stress acting on the pile-soil interface at any depth can be expressed as a function of the cone penetrometer tip resistance ( $q_t$ ) and the number of cycles that the soil element is exposed to shearing. In the context of the research, White et al. (2004) associated the number of cycles with the hammer blowcounts during pile installation. In a subsequent work, White (2005) evaluated the combined effect of friction fatigue and the geological stress history of the soil surrounding the pile element to develop predictions of unit skin friction for displacement piles.

Open-ended pipe piles present additional challenges as far as end bearing and internal friction is concerned. For example, under plugged conditions the soil mass moves downward with the pile and end bearing develops over the fully plugged area. In an unplugged condition (i.e. where coring condition is presented), end bearing only occurs against the steel annulus, but friction resistance may occur inside of the pipe and partially considered for a driveability analysis. The plugged behavior is mainly observed under static loading conditions (Randolph et al. 1991) which differs from conditions where the pile is exposed to higher loading rates, particularly in the case of open-ended pipe piles installed for offshore projects. Under fast loading rate conditions, the increase in the effective stress acting on the soil plug is limited while the plug inertia is very high, which causes a significant reduction of resistance at the bottom of the pile. A one-dimensional analysis of the plugging conditions was presented by Randolph et al. (1991) and design charts were developed as a function of soil plug parameters and loading rate.

An important concept to consider before driving a pile is the prediction of the driveability which consequently impacts installation method, construction equipment selection, and hammer selection. Important parameters such as soil conditions, pile material properties, pile dimensions, the friction fatigue concept, and in the case of open-ended pipe piles the plugging conditions have notable impact on the pile driveability predictions. A&H presented a fitted model based on driveability studies of large diameter pipe piles installed in the North Sea. In order to reduce uncertainties associated with the selection of soil parameters, the strength parameters used for the determination of pile predicted capacities were determined using cone penetration results, and both unit skin friction ( $f_s$ ) and unit base resistance ( $q_b$ ) were correlated to the cone penetration test tip resistance ( $q_t$ ). From field logs and driving records, A&H concluded that the skin friction of a pile driven into soil layers will decrease exponentially from an initial skin friction ( $f_{s-i}$ ) to a residual value of ( $f_{s-res}$ ). The model fitted to the measured, and correlated data is presented by equation (1). A&H proposed the values and expressions presented in Table 1 to determine unit skin friction during driving ( $f_{s-res}$ ) and long-term unit skin friction ( $f_{s-i}$ ), classified based on soil type, and related to CPT data and effective vertical stress.

$$f_s = f_{s-res} + (f_{s-i} - f_{s-res}) e^{-kh} \quad (1a)$$

$$k = \frac{1}{80} \sqrt{\frac{q_t}{\sigma'_{v0}}} \quad (1b)$$

In Eq. 1a and 1b,  $f_s$  is the unit skin friction resistance during driving (also called Static Resistance to Driving, SRD) at a distance  $h$  above the pile tip,  $f_{s-res}$  is the residual unit skin friction resistance during driving which

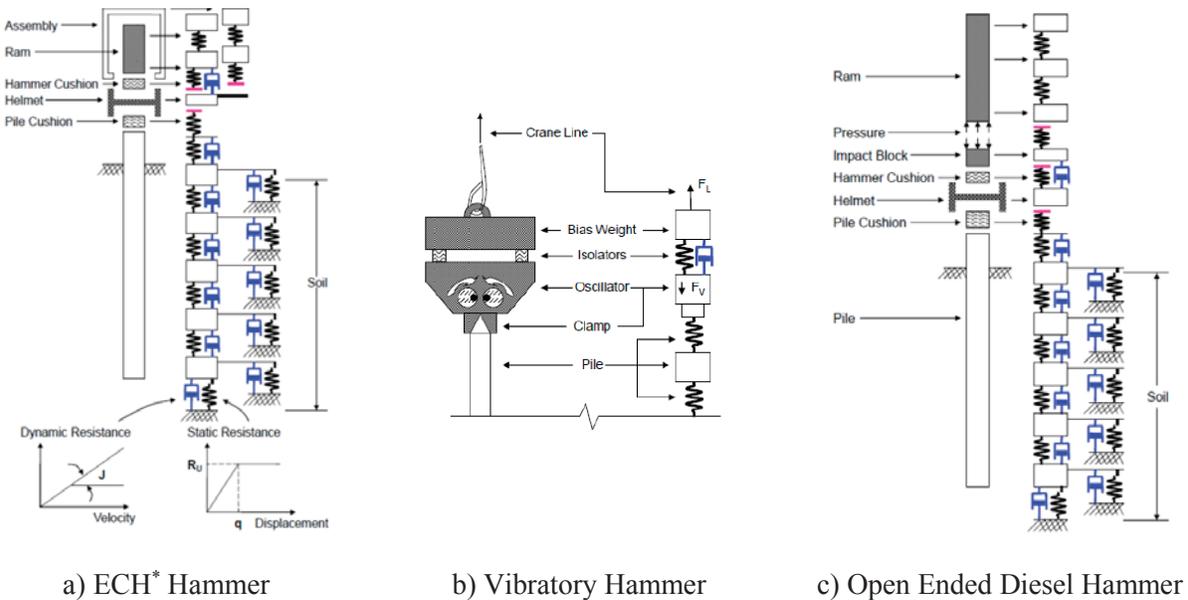
is reached after an infinite number of hammer blows, and  $f_{s-i}$  is the initial long-term unit skin friction resistance computed from the CPT cone resistance,  $q_t$ . The parameter  $k$  is the exponential function's shape factor determined from equation 1b, and  $\sigma'_0$  is the effective vertical stress at the CPT depth.

**Table 1.** Expressions derived for  $f_{s-i}$  and  $f_{s-res}$  (Alm & Hamre 2001)

Soil Type	$f_{s-i}$	$f_{s-res}$
CLAY	Recorded CPT Sleeve Friction ( $q_{sf}$ )	$0.004q_t(1 - 0.0025 \frac{q_t}{\sigma'_0})$
SAND	$0.0132q_t(\frac{\sigma'_0}{P_a})^{0.13} \tan(\delta)$	$0.20f_{s-i}$

### Wave Equation Analysis Program

The original, non-proprietary Wave Equation Analysis Program, WEAP, simulates the conditions in the hammer, pile, and soil element during and immediately after the ram impact. The analysis is completed based on modeling the components of the system (i.e. hammer, pile, and soil) with masses, springs and dashpots. Displacement and velocities of the masses, and the forces in the springs are calculated. Pile movement and stresses along the pile elements are determined from an exact solution of the wave analysis differential equation. Figure 3 illustrates the modelling and components of the system used in WEAP. Considering the wide use of the WEAP program and its offshore feature which allows to model offshore pile driving process, all analyses and modeling presented in this paper has been performed using the WEAP-based, proprietary Offshore Wave version of GRLWEAP-2010. It is important to mention that to the knowledge of the authors the A&H model have not been used yet for driveability analyses completed for a vibratory hammer.



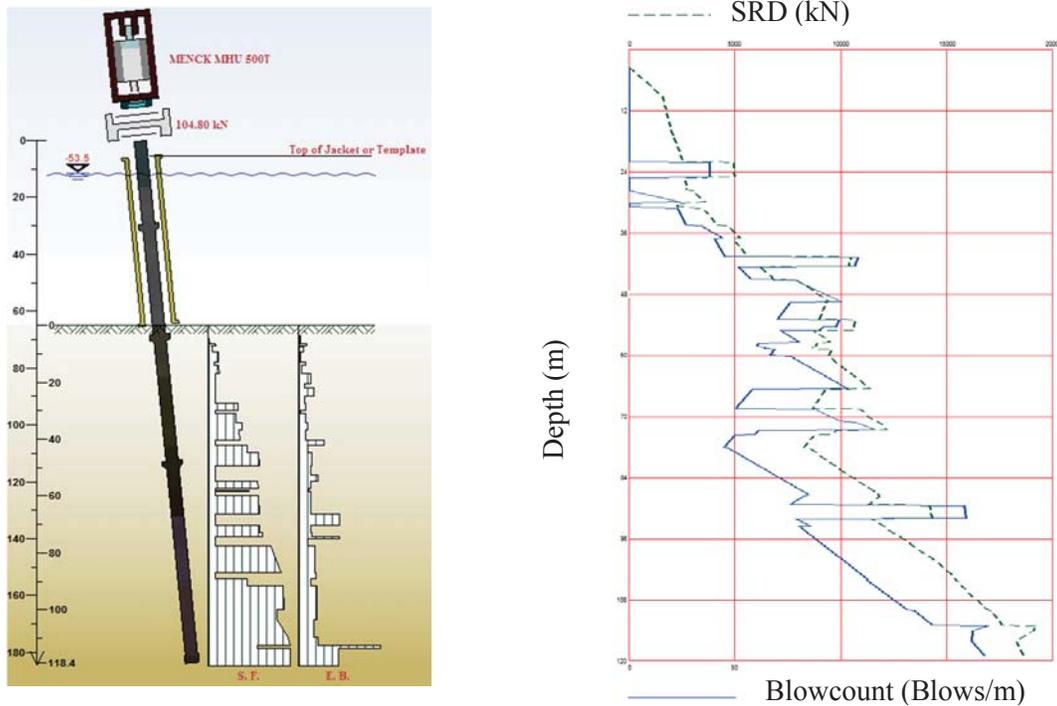
**Figure 3.** Model Components and schematics for three typical hammers (GRLWEAP, 2010)  
\*External Combustion Hammer

## Driveability Analysis

To evaluate the expected Static Resistance to Driving (SRD), and to further predict blowcounts associated with the pile driving process, driveability analyses are performed using the above-mentioned computer program. Driving hammers used in the pile driving operations have variable energies which makes the selection of appropriate hammer energy setting the primary concern of the driveability analysis.

To perform a driveability analyses, input data representing the soil and pile properties as well as hammer and driving system are required. These parameters include pile length, final depth, location of splices, pile profile and inclination, driving system parameters, hammer stroke (energy level) and hammer efficiency. The following input requirements for each soil layer are important in the context of this paper: unit shaft resistance,  $f_{s-i}$ , shape factor,  $k$ , the ratio  $f_{s-res}/f_{si}$  (called setup factor), unit base resistance, the toe resistance area, quake and damping values. In addition, this program version allows for the input of data considering stabbing guides, add-on sections, jacket or template details for the consideration of static pile bending stresses. Once all input data has been entered, the resistance distribution, including shaft resistance and end bearing, along with the schematics of the modeled pile, are displayed as shown in Figure 4a.

A graph showing the SRD, based on the initial shaft resistance,  $f_{s-i}$ , toe area and unit toe resistance, and blowcount vs. depth is one of the important output plots obtained from a driveability analysis, Figure 4b. The primary objective of such plot is to illustrate the blowcounts required to drive the pile through the various soil layers with corresponding ultimate resistance. This type of plot aids to properly select a hammer to be used for the driving process. Other important parameters such as compressive stress, and combined compressive and tensile stresses are also obtained from a driveability analysis.



a) GRLWEAP input schematics  
S.F. Skin Friction- E.B. End Bearing

b) Static Resistance to Driving, SRD, and  
Blowcount vs. Depth

**Figure 4.** Schematic input and output data for driveability analysis using GRLWEAP

## Case Study

The following section presents details of a pile driving project where a driveability analysis has been completed with and without consideration of the friction fatigue concept. Calculated blowcount vs. depth obtained from the traditional setup-factor approach and the friction fatigue approach are compared with the driving records obtained during pile driving monitoring. Note that GRLWEAP's friction fatigue algorithms allow for the A&H resistance distribution calculation as discussed earlier and further presented below.

The project selected is an oil platform which is supported by a series of open-ended pipe piles installed in rows. A representative pipe pile (i.e. the foundation with largest diameter and longest length) has been selected for the analysis. The platform foundation system also included piles with other dimensions as well as skirt piles. However, for purposes of the analyses presented in this paper, only the foundation described above has been analyzed and discussed. It is also important to mention that due to client confidentiality, the authors have abstained from providing further details regarding project location and properties of the superstructure.

### Pile Properties

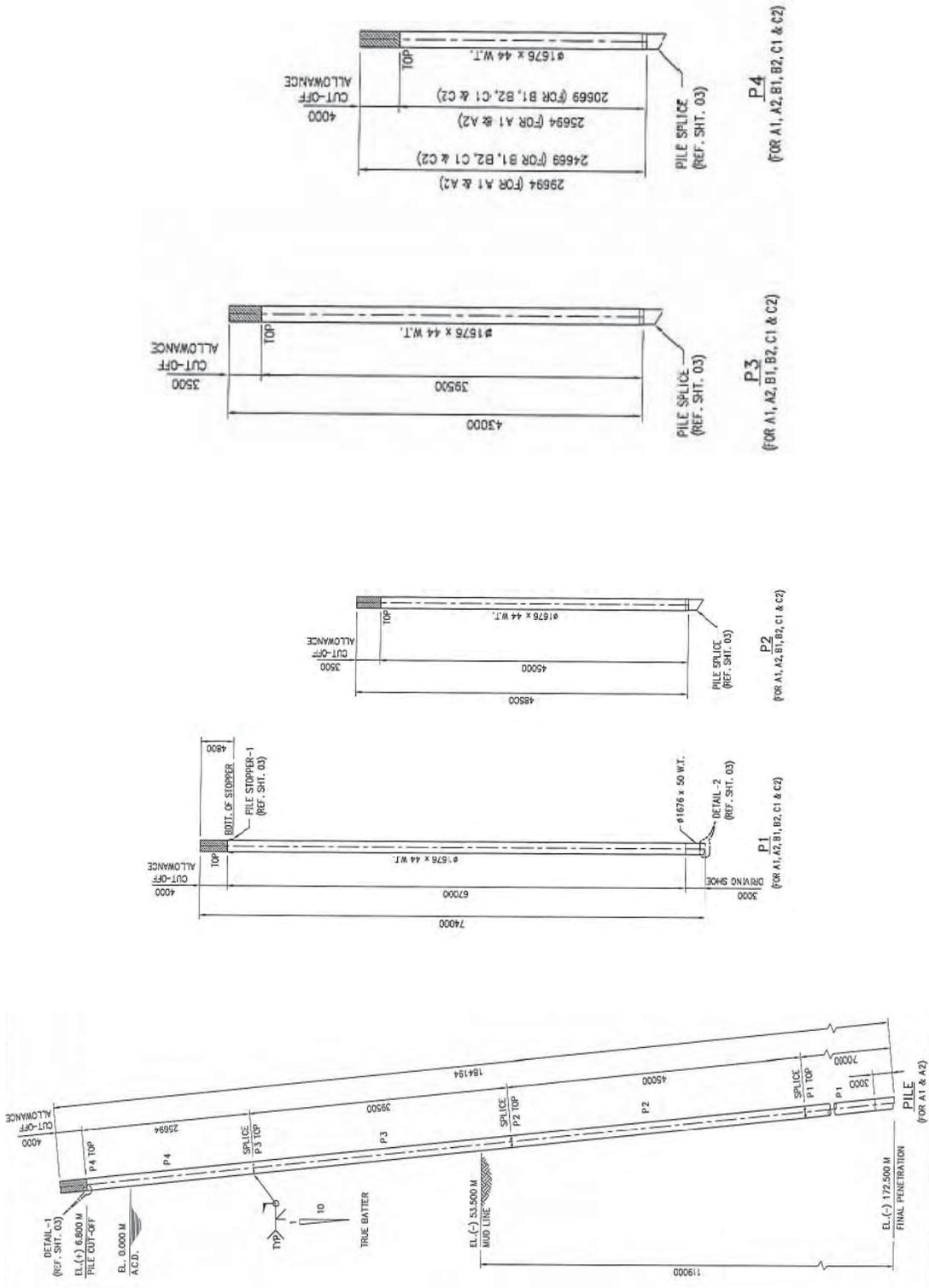
The foundation pile presented herein, consisted of 1676 mm (66-in) O.D. steel pipe piles with wall thickness varying from 44-mm (1.75-in) to 50-mm (2-in) along the pile length. The piles were planned to be driven on a 1:10 batter and in four sections with the first section (P1) being 74.0-m (243-ft) in length which included a 4-m (13-ft) cutoff allowance. The second section (P2) had a length of 48.5-m (159-ft), and the third section (P3) had a length of 43.0-m (141-ft). Both P2 and P3 sections had a cutoff allowance of 3.5-m (11.5-ft). Finally, the fourth section (P4) had a length of 29.7-m (98-ft) and a cutoff allowance of 4.0-m (13-ft), Figure 5.

### Soil Properties

Boring logs associated with this project indicated that the predominant subsurface conditions consisted of interbedded layers of siliceous carbonate medium to coarse sands, and soft to stiff carbonate clays. Between the depths of 13.0-m (43-ft) and 27.5-m (90-ft) two silt layers with 1.0-m and 10.0-m thickness were encountered. Sand layers varied in thickness ranging from 1.0-m (3.3-ft) to 7.1-m (23.3-ft) with an average thickness of 3.2-m (10.5-ft). The thickness corresponding to the clay layers varied between 0.7-m (2.3-ft) and 12.0-m (39.4-ft) with an average thickness of 5.0-m (16.5-ft). In addition to the borings, one CPT was completed at the project site to a maximum depth of 120-m (394-ft) below the seabed, Figure 6. The CPT profile showed an average tip resistance of 10.4 MPa (217-ksf) and 7.2 MPa (150-ksf) for the sand and clay layers, respectively. Similarly, the average sleeve friction determined from the CPT profile was 0.30-MPa (6.3-ksf).

### Hammer and Driving System Details

The proposed driving systems to install the main foundation steel pipe piles to the desired pile penetration depth consisted of a Menck MHU 500T which is a double acting hydraulic hammer with a ram weight of approximately 294-kN (66-kips). The maximum equivalent stroke is approximately 1.87-m (6.15-ft) which results in a maximum manufacturer's rated energy of 550-kJ (405-ft-lbs). However, the hammer energy may be controlled by the hammer operator for multiple energy settings. This Menck hammer does not use a hammer cushion, resulting in steel-on-steel impact, and the helmet weight was assumed to be 104.8-kN (24-kips). According to the manufacturer, the total weight of the hammer is approximately 828-kN (186-kips).

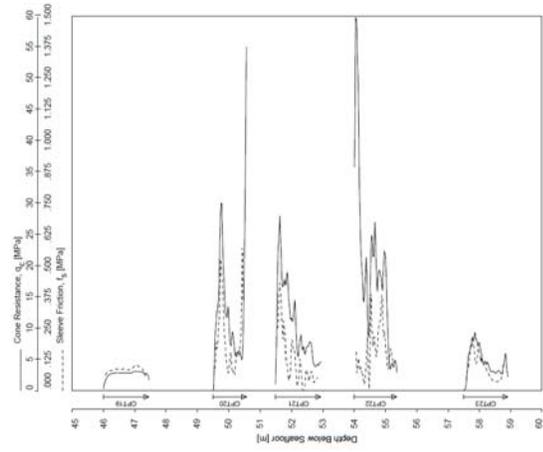


c) Sections P3 and P4

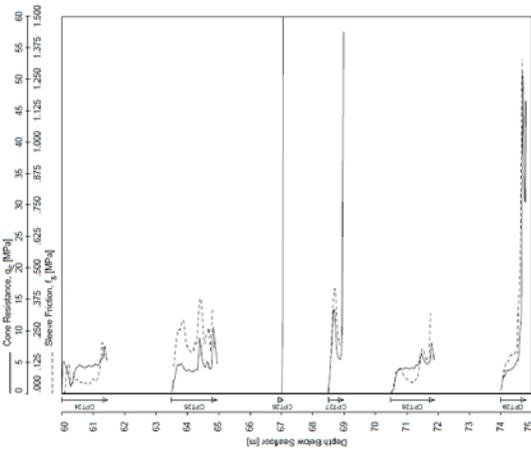
b) Sections P1 and P2

a) Schematics of the Pile A1

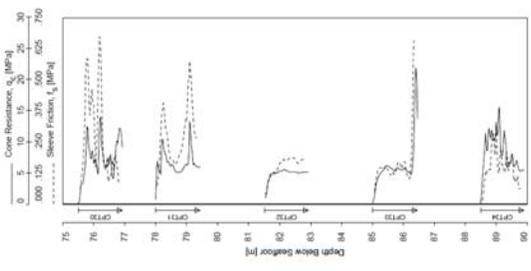
Figure 5. Open-ended pipe pile schematics



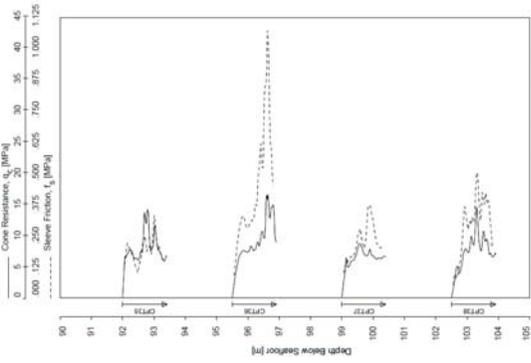
a) Profile 0 to 15-m



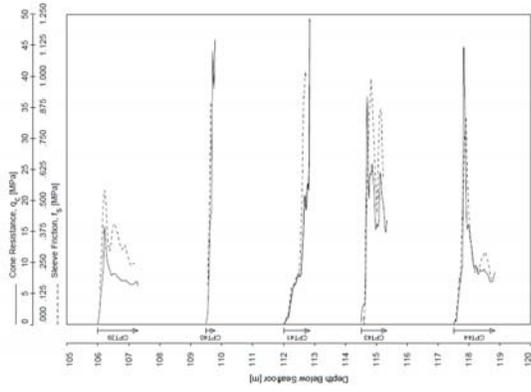
b) Profile 15 to 30-m



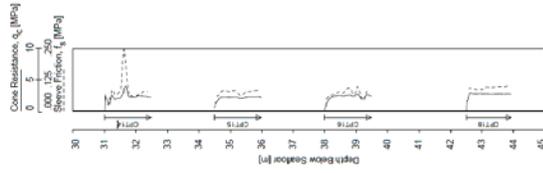
c) Profile 30 to 45-m



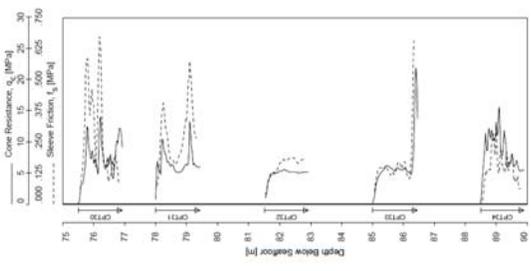
d) Profile 45 to 60-m



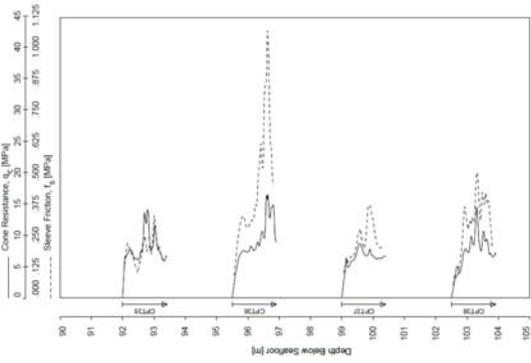
e) Profile 60 to 75-m



f) Profile 75 to 90-m



g) Profile 90-105-m



h) Profile 105-120-m

Figure 6. CPT profiles corresponding to the project site

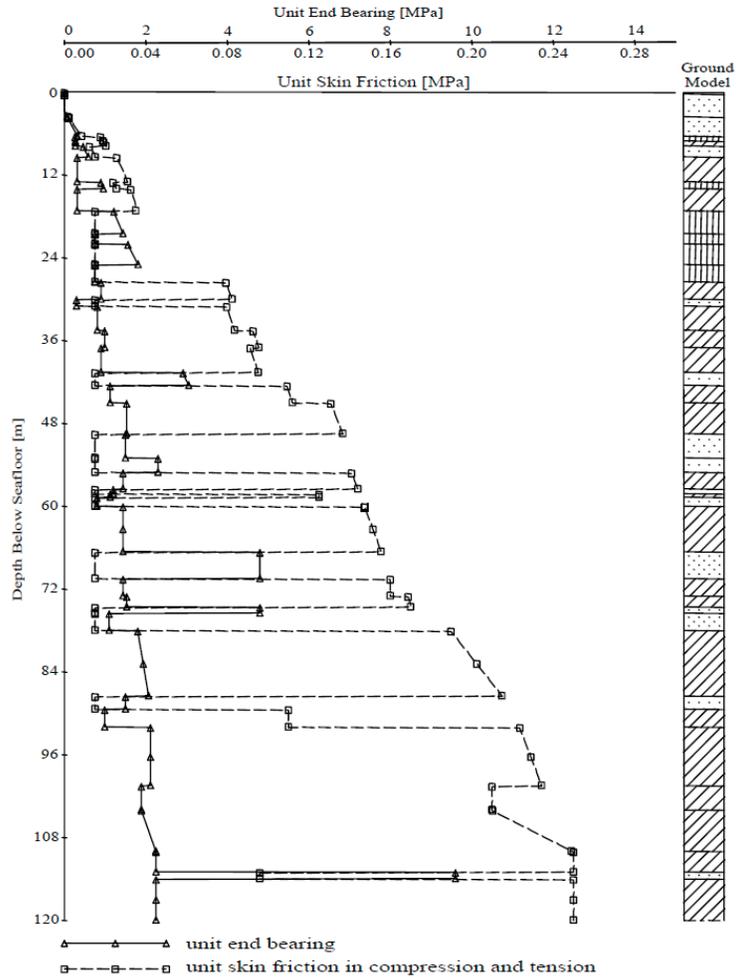
## Wave Equation Analysis

For comparison purposes, two separate series of analyses have been completed for the project presented in this paper to observe driveability predictions performed with and without considering the friction fatigue concept. For both sets of analyses a detail review of available geotechnical engineering information corresponding to the pile installation process yielded relevant data to prepare appropriate input parameters for the driveability analysis.

For the first analysis where the friction fatigue was not considered, the SRD values were determined using standard shaft setup factors of 2 for clay and 1 for sand. The base resistance was analyzed with its Long-Term Static Resistance (LTSR) value and considering the base area as the steel annulus. It is important to mention that these setup factors are based on results obtained from a large variety of land construction sites and are not based on specific offshore experience values. The unit skin friction and unit end bearing resistance values were determined based on API (2000) shown in Figure 7.

For shaft quake, the GRLWEAP recommended value of 2.5-mm (0.1-in) was selected, whereas, toe quakes selected for the analyses were based on the pile diameter and the expected soil conditions. A toe quake of 28.0-mm (1.1-in) was selected for the clay deposits, while a reduced toe quake of 14.0-mm (0.55-in) and 21.0-mm (0.83-in) were selected for the sand and silt layers, respectively. The driveability analyses were performed using Smith damping factors of 0.16, 0.41 and 0.65 s/m (0.05, 0.125 and 0.2 s/ft) for the pile shaft in the sand, silt and clay deposits, respectively. Furthermore, a Smith toe damping of 0.50 s/m (0.15 s/ft) was selected for all layers as per the software recommendations for the given soil profiles and to maintain a slightly conservative approach. These input parameters, as well as the LTSR were the same for both analysis completed for the open-ended pipe pile presented herein.

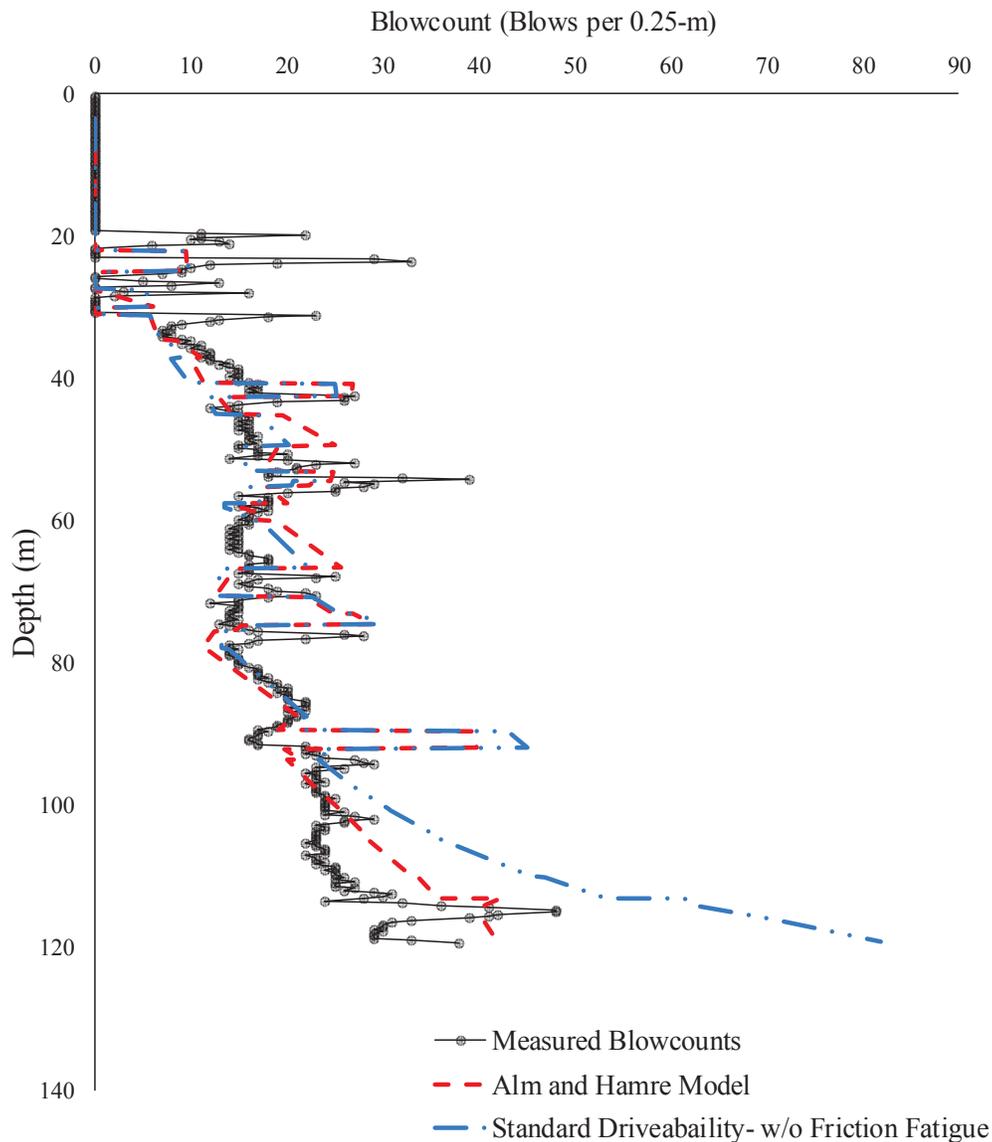
The second analysis utilized the A&H friction fatigue option of the GRLWEAP program. It is important to clarify that the  $f_{s-i}$  and  $f_s$  in the Alm and Hamer (2001) model are equivalent to the LTSR and SRD in the GRLWEAP model, respectively. As previously mentioned, for the A&H model the SRD was determined using Equations (1a) and (1b), and those presented in Table 1. Also, no internal friction and no plug resistance were considered. From the CPT profile, and corresponding laboratory testing, the residual values of tip resistance, sleeve friction, and effective vertical stress were determined. Depending on the type of soil material, the appropriate equation was selected from Table 1, and the values of unit skin friction during driving ( $f_{s-res}$ ), and the initial long-term unit skin friction resistance ( $f_{s-i}$ ) were calculated. The friction fatigue setup factors, required as input in GRLWEAP, were determined from the ratio of  $f_{s-i}$  to  $f_{s-res}$ , typically were near 5 while the land experience based setup factors of the comparison analysis were only between 1 and 2.



**Figure 7.** Unit skin friction and base resistance

### Results of Wave Equation Analysis

For comparison purposes, the calculated blowcount results from both driveability analyses were plotted in Figure 8 together with the measured blowcounts. It is observed that despite the increasing trend of unit skin resistance shown in Figure 7, the measured blowcounts do not behave in the same fashion. Normally it would have been assumed that as the resistance increases with depth the measured blowcounts would do likewise. However, results from the analysis showed that predicted values based on a traditional approach with relatively low setup factors overpredict the blowcounts near the end of driving. In fact, it appears to increase like an exponential function with depth, and it is more noticeable within the last 30-m (98.4-ft) of the pile driving. In contrast, when the effect of friction fatigue is considered using the A&H model, the predicted blowcounts are in much better agreement with the measured values. One important trend to note is that as the pile is driven to greater depths, the effect of friction fatigue is more noticeable. In fact, for depths between 0.0 and 30.0-m (98-ft) both models calculate somewhat lower blow counts than those observed. Between depths of 30.0-m (98-ft) and 95-m (312-ft) the models follow the measured blow counts closely with an overprediction observed at approximately 95-m (312-ft). Below 95-m (312-ft) the friction fatigue model compares well with the measured values whereas the traditional model begins to deviate more and more severely. In this particular case, a higher setup factor for the lower layers should have provided a better agreement.



**Figure 8.** Driveability Analysis Results

### Summary and Conclusions

This paper presented a brief history and background of the friction fatigue concept including a fitted model presented by Alm and Hamre (2001) which accounts for the friction fatigue concept in open-ended pipe piles. As a case study, details associated with a project where a large diameter open-ended pipe pile was driven through multilayered soils were presented. For this pile two different analyses were completed using the GRLWEAP program, one employed the traditional setup factor approach; the other one followed the A&H recommendations. In both cases the LTSR was based on the API recommendations, no internal friction and no plugging plus standard damping and quake values. The outcome of both analyses was compared to measured values determined from the pile driving monitoring.

Results of the analyses show good agreement for both approaches as long as blow counts are below 30 blows/0.25m at a depth of roughly 90 m. For higher blow counts at greater depths, the traditional model calculated increasing overpredictions while the A&H approach followed the observed blow count trend to a much greater degree.

Considering the wide use of driveability analyses for equipment selection, and the cost of offshore pile driving equipment and operations it is recommended to consider friction fatigue models such as A&H when performing wave equation analyses for piles with deep penetrations. In all cases, as also recommended by A&H, both lower bound and upper bound analyses should be performed for conservatism.

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