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Research article

Numerical evaluation of long term monopile head behavior for ocean energy converters under sustained low amplitude lateral loading

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ABSTRACT

The study presented in this paper is motivated from the increased interest in recent years to explore use of Ocean Energy Converters (OEC's) to generate electricity from the ocean. Typically OEC's generate electricity from tidal action, wave action, or marine current. A key challenge for OEC's is the need to decrease the initial cost of OEC's where their foundation systems can represent up to about 35% of the initial installation cost. Common OEC foundation systems are monopiles, however they may experience gradual accumulation of pile head deformations under the ocean induced cyclic loading. Under some conditions monopile head deformations could exceed OEC serviceability limits. This design consideration is important since OEC foundation systems are often subjected to more than 10^8 low amplitude dynamic load cycles during a normal 30 year design life. Experimental research on single model piles installed in sand have shown important gradual accumulation of pile head deformations for some piles subjected to over 10^4 low amplitude lateral load cycles. This gradual development of pile head deformations is largely related to progressive accumulation of plastic strains in soil zones in the vicinity of the monopile. Analytical methodologies based on conventional p-y curves typically cannot predict the observed accumulation of pile head rotations and displacements. Even 3D dynamic finite element analyses (FEA) may not capture this response for some conventionally used soil constitutive models. This manuscript presents predictions of monopile head deflections under sustained cyclic loading using p-y based methods as well as 3D dynamic FEA. The different numerical predictions are compared to available experimental data. Results from this study show that API p-y curves used for offshore piles do not adequately predict the gradual pile head displacements observed experimentally. Modified p-y curves, developed for pseudo-static cyclic loading, do a better job than the API p-y curves, but still greatly under-predict deformations. In contrast, the 3D FEA were found to capture reasonably well the general observed trends of gradual accumulation of pile head rotation and lateral deformation with increasing constant amplitude lateral load cycles.

Keywords: Sustained cyclic laterally Loaded Piles, Ocean Energy Converters Monopiles.

1. Introduction

Ocean Energy Converters (OEC's) are being considered as an alternative source of renewable energy. These devices typically consist of a turbine that generates electricity from the ocean current which can be tidal (i.e., with current direction reversals) or stream (i.e., with a predominant marine current flow direction). For projects involving sea water depths of less than 30 meters, monopiles are typically considered a feasible foundation system. A key challenge for offshore energy projects is to generate enough electricity, which relates to the efficiency of the energy converter and actual marine environmental conditions, in a cost effective fashion so that it is competitive with respect to traditional energy sources. Related to cost, offshore energy projects have important cost components such as initial installation cost and operation and maintenance costs during its service life which typically are high due to the harsh engine operation environment and material durability challenges. In terms of initial costs, Bryne and Houlsby (2003) have reported that the foundation system of an offshore wind turbine can account for about 35% of the total installation cost. Monopile foundations are estimated to represent a similar percentage of the initial installation cost of an OEC. Therefore it is important to ensure these foundation systems are being designed in an optimum fashion. However due to the challenges and uncertainties of the marine environment, in terms of complexity of loading, difficulties and uncertainty in the seabed geotechnical characterization, and scarcity of historic precedence or full scale performance data (from experiments or actual projects), we are likely to see foundation designs of initial OEC projects with some embedded margin of conservatism. It is expected that this extra margin of conservatism will decrease with time as case histories become available thus helping improve our understanding of the behavior of these complex marine foundations.

The foundation systems for offshore energy converters depend largely on the water depth and current conditions. Doherty et al. (2011) report various foundation systems commonly being considered for offshore wind installations. These foundation systems also apply to OEC installations. As shown in this figure, gravity structures (Figure 1a) are commonly considered the most economical alternative in shallow waters of less than about 15 meters. Use of monopile foundations (Figure 1b) have been reported as the preferred system in European projects with ocean depths of less than about 30 meters. In the U.S., monopiles are currently being considered for several offshore wind projects including in North Carolina where a recent study by UNC Chapel Hill (2009) suggested wind turbines could be supported on large diameter monopiles (about 5 meters) with embedment depths of about 30 to 35 meters to be installed in state coastal waters not exceeding 30 meters in depth. For locations with great water depths, above 50 meters, conventional jacket structures (Figure 1c) or floating devices with mooring foundation systems (Figure 1d) are often considered.

The main focus of this paper is on monopiles for ocean stream OEC's. A distinctive feature of this type of deep foundation is that they are subjected to a very large number of lateral load cycles which can be characterized as a force time history oscillating around a mean with relatively moderate load amplitudes and a complex frequency content. As discussed later, most experimental research of piles subjected to cyclic loading have involved piles subjected only to moderate number of lateral load cycles (typically less than 500) and usually involving load cycles applied at a relatively low frequency and cycles characterized with loading to a peak load and unloading to zero. In the following section we describe the typical loading conditions of an ocean stream OEC monopile, which is quite different to published experimental studies of single piles subjected to cyclic loading.

2. Overview of loading conditions of marine current OEC monopiles

The loading conditions for OEC devices are complex and difficult to predict. Lateral loading acting on the turbine is a function of the marine environmental conditions which comprise factors such as geographic location, depth, time of the year or season, and temporal ocean current/stream velocity conditions. The loading demand will also be a function of the turbine design characteristics and its geometry (e.g., rotor diameter, number of blades and geometry, etc). An additional source of lateral loading will be associated with drag forces acting on the turbine support column.

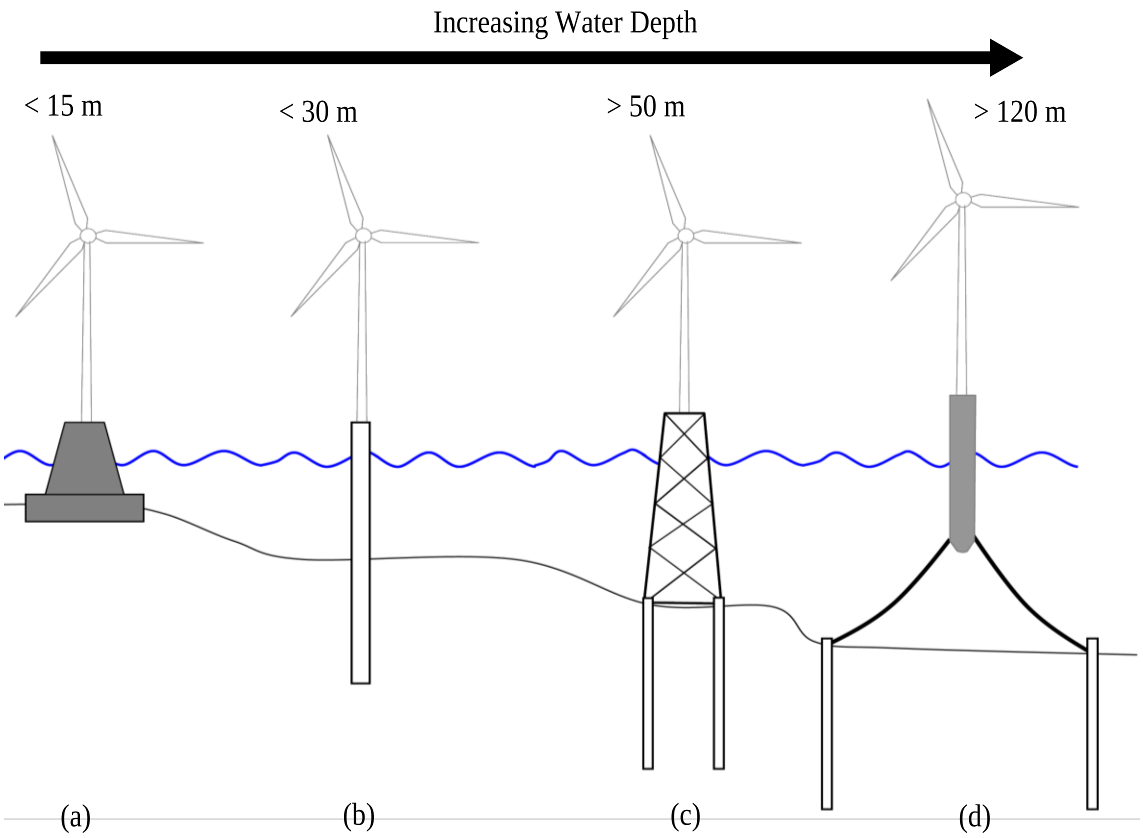

Figure 1: Common types of offshore foundation systems (adapted from Doherty et al. 2011)

As mentioned before, if the OEC is tidal the loading will have reversals of direction, whereas marine current OEC turbines are typically exposed to a marine current with a predominant flow direction but a complex velocity time history similar to the one shown schematically in Figure 2(a). As shown in this figure, the velocity varies in magnitude as a function of time without sign reversal or dropping to zero. For a given depth, there will be temporal fluctuations in the magnitude and direction of the resultant velocity vector. However, even for a given reference azimuth, the component of marine current in this reference direction will have a positive mean offset as shown in Figures 2(a) and 3. This schematic representation illustrates the temporal fluctuations in magnitude and the complex frequency content that marine currents can have. The velocity time history has an average velocity above zero and fluctuates around it with a varying amplitude and frequency. As mentioned earlier, the focus of this paper is on OEC turbines for marine current environments, thus no velocity reversals are considered. To study the induced lateral force time history, it is common to represent this complex marine current velocity time history with a simple sinusoidal velocity time history with a positive offset, oscillating at the predominant period of the marine current. The horizontal forces acting on the OEC foundation can be estimated using computational fluid dynamics or with a more simplistic approach using an average drag coefficient as follows:

$$D = \frac{1}{2} C_d \rho U^2 A \qquad (1)$$

Where D is the average drag force acting at the center of gravity of the OEC turbine for a marine current speed of U. Equation (1) involves the use of a drag coefficient, C_d, which depends on the turbine characteristics and performance.

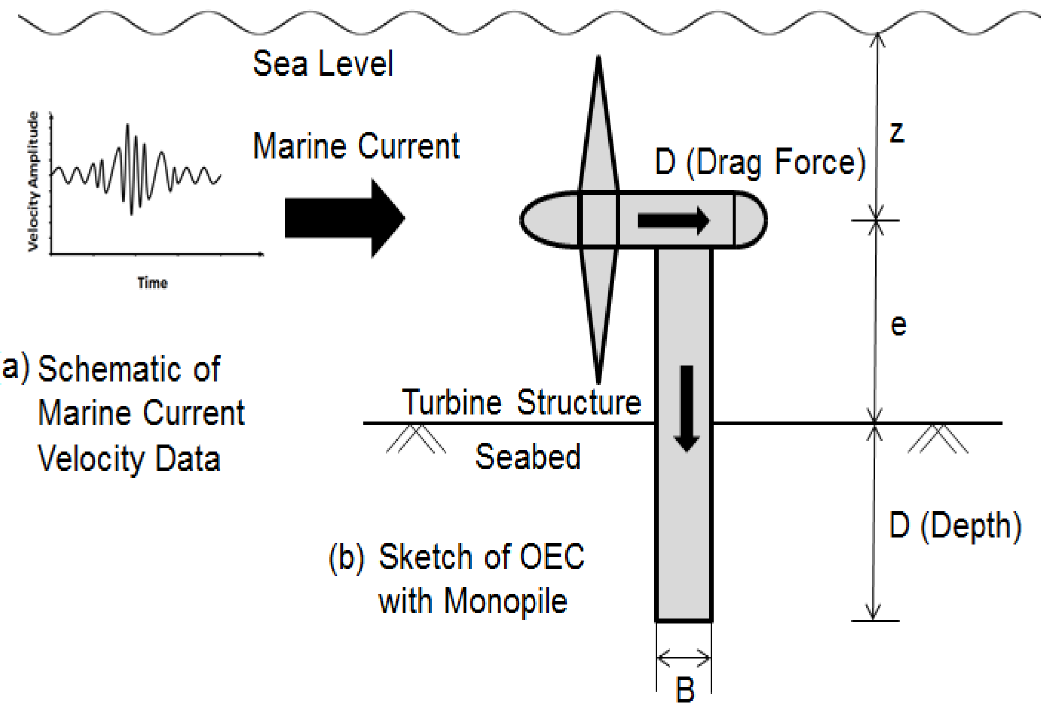

Figure 2: Schematic of marine current velocity and the associated loading on OEC Monopile.

The other terms in this equation involve ρ the density of seawater, and A the rotor swept area calculated as $A=\pi r^2$ where r is the radius of the turbine rotor. Besides force D, from Equation (1), the OEC monopile will also be subjected to a lateral load associated to the drag forces from current acting on the OEC support column.

Fraenkel (2002) reports that current marine OEC converters are usually considered economically feasible, in terms of power output, if the mean marine current velocity is between 2 to 2.5 m/s. Additionally, based on information gathered from ongoing marine OEC research projects, the predominant frequency of the marine current at the turbine elevation can be expected to range between 0.05 to 0.3 Hz. The average stream velocity amplitude can be estimated to range between 10 to 40% of the mean current velocity value. Based on these parameters, the use of Equation (1), and the harmonic time history approximation, one could estimate the lateral force time history acting on an OEC monopile. For example, Figure 3 shows a lateral force time history corresponding to an OEC with a 16.5 meter diameter rotor and a mean speed velocity of about 2.4 m/s (using Eq. 1, and including a drag force along the support column, a mean lateral force of about 600 kN is estimated). The force amplitude shown in this figure corresponds to a mean velocity amplitude equal to 25% of the mean value (which results in a maximum and minimum lateral forces of 750 and 450 kN, respectively), and a predominant frequency of 0.1 Hz (i.e., period T = 10 seconds).

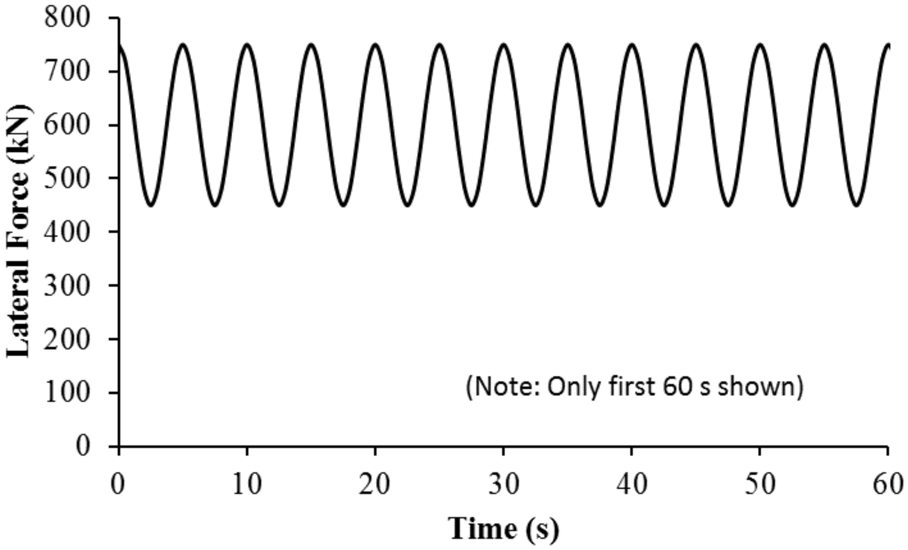

Figure 3: Example of lateral force time history for a marine current OEC (16.5 m rotor).

The schematic lateral force time history, although simplified, helps illustrate important differences with respect to published literature related to single piles under cyclic lateral loading. Figure 3 shows a load ratio R, defined as the ratio of the applied minimum and maximum lateral forces acting on the single pile (monopile), equal to 0.6 (R = 450 kN/750 kN). As shown later in this paper, most of the existing experimental data involving cyclic lateral load tests on single piles has involved load ratios, R, equal to 0. In other words lateral load cycles involving loading to a maximum load value and then unloading to zero. However, for marine current OEC devices load ratio values, R, are above zero and often involve predominant frequencies much higher than those investigated experimentally to date. More details related to published experimental data is presented in a subsequent section of this paper. However, prior to this it is important to also highlight why this unique lateral loading time history can result in a gradual accumulation of pile head displacements when the monopile is subjected to sustained lateral load cycles of small amplitude.

3. Experimental evidence of accumulation of head displacements of OEC monopile

Studying the effect of sustained cyclic loading on monopiles is important to ensure adequate short- and long-term performance of the OEC. This section summarizes experimental studies which provide evidence of gradual accumulation of pile head deformations for monopiles subjected to large number of lateral load cycles. The main mechanism for this gradual accumulation of lateral pile head deformation is related to induced plastic strains in certain regions of the soil surrounding the monopile when subjected to sustained cyclic lateral loading. Several researchers have shown evidence of plastic strains accumulation during sustained cyclic or repetitive loading (e.g., Andersen 2004; Peng et al. 2006; and Leblanc et al. 2009). In particular, the studies by Peng et al. (2006) and Leblanc et al. (2009) have reported experimental data that show how cyclic loading can lead to accumulation of pile head displacements and rotations and have highlighted the influence of important variables such as cyclic load amplitude and frequency.

The experimental study performed by Peng et al. (2006) involved tests on small scale monopiles installed in a dry sand tank. Their experimental setup had the capability of applying a large number of uniform load cycles to the monopile in a harmonic fashion. Other experimental factors studied by the authors included amplitude of loading, and frequency. Model tests included, pile subjected to one-way cyclic loading at three different frequencies with a constant force amplitude, one-way loading with three different force amplitudes at a constant frequency of loading, and tests with the monopile subjected to two way balanced and unbalanced loading. In general, the results from this study showed that the magnitude and rate of pile head displacement accumulation increased with increasing lateral force amplitude and with increasing frequency of the loading. Figure 7, discussed later in this paper, presents one of the sets of experimental data from this study corresponding to a monopile subjected to harmonic lateral load cycles with a frequency of 0.45 Hz, and a load ratio R=0. The data in this figure shows a significant accumulation of pile head lateral displacement as a function of applied load cycle. This figure corresponds to tests using a medium dense sand and a monopile with a diameter B, equal to 4.45 cm and an embedment depth D, equal to 40 cm. As shown, the monopile initially displaces laterally about 1.35 mm but after 10^4 lateral load cycles the pile head deforms laterally about 10 mm.

Leblanc et al. (2009) also performed an extensive experimental program involving small scale laterally loaded monopiles. Their test setup was specifically designed to gather insight on the behavior of monopiles for offshore wind turbines. The experimental setup had similar capabilities to the one by Peng et al. (2006) in terms of flexibility to apply large number of uniform lateral load cycles, modes of loading, and variation in amplitude of loading. However their setup had a constant frequency of lateral loading of 0.106 Hz. This study included tests for single monopiles subjected to up to 10^4 load cycles tested using two different soil relative density conditions. Their tests included application of different lateral loading amplitudes to monopiles under both one way and two way loading conditions. The Leblanc et al. (2009) study provided valuable evidence of the strong dependency of accumulated lateral pile head deformations to factors such as loading mode and loading direction history.

4. Numerical methods commonly used for single piles under cyclic lateral loading

Assessment of pile head deformations of single monopiles under cyclic lateral loading is often carried out by using p-y based analyses (e.g., Reese et al. 1974) or by means of finite element analyses (e.g., Achmus et al. 2009). A brief overview of these two methods is presented below.

4.1. Cyclic lateral load analyses using P-Y curves

P-Y based analyses of laterally loaded piles are routinely used in design practice, particularly for static loading conditions. The methodology is based on representing the soil reactions acting along the pile as a series of discrete non-linear springs. The non-linear behavior of the springs is specified by the assigned p-y curves. At a given depth, the p-y curve relates the soil reaction per unit pile length (P) to the corresponding pile lateral deflection (Y). Details on the P-Y methodology for analysis of laterally loaded piles can be found in Reese et al. (1974). Pile head displacements of a pile under cyclic lateral loading can be estimated using the different p-y formulations summarized below.

4.1.1. P-Y Curves based on API (2000)

API (2000) is presented herein because it pertains to design standards for offshore fixed platforms. This reference recommends using the p-y curves developed by Reese et al. (1974) for piles installed in sandy soils. The details can be found in this reference, but the basic expression for this p-y curve is as follows:

$$P = A \times p_u \times tanh\left[\frac{k \times H}{A \times p_u} \times y\right] \qquad (2)$$

Where P is the soil reaction per unit pile length (in units of force divided by length) for the corresponding pile lateral deflection Y, both computed at a certain depth H. In this equation, p_u is the ultimate soil resistance at the same depth H, k is the initial modulus of subgrade reaction, and A is a factor to consider whether the applied lateral loading is cyclic or monotonic. The factor 'A' is equal to unity for static lateral loading and equal to 0.9 for cyclic loading. Thus, this particular p-y curve formulation considers a 10% degradation of the p-y curve when the applied lateral loading is cyclic. It should be pointed out that the authors developed this p-y curve formulation based on experiments conducted on piles with a diameter of 0.60 m, subjected to no more than 100 pseudo-static lateral load cycles with a load ratio R of zero (i.e., loading to the peak load and then unloading to zero). Therefore this p-y formulation may not be applicable to piles subjected to different loading conditions, such as much larger number of lateral load cycles, or load cycles with a different load ratio R. As mentioned earlier, marine OEC monopiles typically involve 10^8 lateral load cycles, loading ratios always above zero, loading frequencies beyond pseudo-static conditions, and pile diameters that are usually 1 meter or higher. Additionally, the API p-y formulation (Reese et al., 1974) provides pile head displacements that are independent of the number of load cycles applied, thus pile head displacements as a function of the applied load cycle N cannot be computed.

4.1.2. Cyclic P-Y curves by Little and Briaud (1988)

Little and Briaud (1988) carried out a multi-phase experimental program which resulted in cyclic p-y curves. These cyclic curves are developed by modifying the p-y curves proposed by Reese et al. (1974). The study was performed at three different phases comprising in-situ pressuremeter tests, full scale cyclic lateral loading tests of piles installed in sandy soils, and a final phase integrating both sets of experiments with numerical analyses of the piles. The full scale experiments included piles subjected to up to 20 unload-reload cycles to two different lateral load levels. For the first 10 cycles, the load was unloaded to almost zero (load ratio, R ≈ 0) and the remaining 10 cycles the load was unloaded to half the applied peak load (load ratio, R = 0.5). Based on this study, the authors proposed modifying the static pile lateral deflection y, as a function of the number of applied load cycles, N, as follows:

$$y_N = y_1 . N^a \qquad (3)$$

Where y_N is the lateral pile deflection corresponding to the soil resistance, (P_N), at the N^{th} load cycle; y_1 is the pile lateral deflection for the static or monotonic loading condition and 'a' is a degradation parameter developed from the results of cyclic pressuremeter tests. In this cyclic p-y curve formulation, the ultimate soil resistance remains constant throughout the lateral load cycles.

Cyclic p-y curves using the Little and Briaud (1998) formulation are presented in Figure 4 for the OEC monopile geometry shown in Figure 8. This monopile consists of a 2 meter diameter concrete filled steel tube installed in dense sand with an embedment depth of 16 m. Figure 4 shows the Little and Briaud (1988) p-y curves for load cycles N = 1, 10, 10^2 and 10^3.

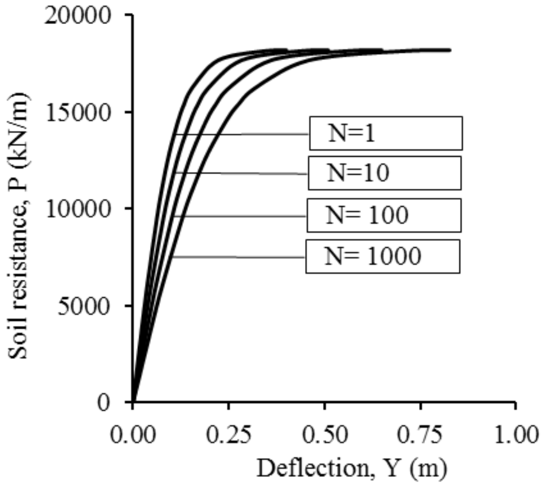

Figure 4: Cyclic P-Y curves based on Little and Briaud (1988) for OEC monopile shown in Figure 8.

This cyclic p-y curve formulation was developed for pseudo-static cyclic loading conditions where the loading rate (or frequency) is low enough to neglect dynamic effects such as inertia or soil and pile damping.

4.1.3. Cyclic P-Y Curves by Long and Vanneste (1994)

Long and Vanneste (1994) proposed cyclic p-y curves based on 34 experimental studies, involving full scale lateral load tests on different types of piles installed in both sandy and clayey soils. The experiments involved lateral load cycles with different loading ratios (R ≈ -1, -0.25, 0, 0.5, 1) and most of the tests applied less than 100 lateral load cycles (although a few experiments involved up to 500 lateral load cycles). The loading rate or frequency was reported to be slow enough to neglect effects of inertia or effects due to excess pore water pressures generated in the soil.

Long and Vanneste (1994) proposed modifying both the soil reaction (P) and the corresponding pile lateral deflection (y) of the non-linear p-y curves by Reese et al. (1974), as follows:

$$P_N = P_1 . N^{-0.4t} \qquad (4)$$

$$y_N = y_1 . N^{0.6t} \qquad (5)$$

Where P_N is the soil reaction for the N^{th} cycle, P_1 is the soil reaction for the first load cycle, and y_N and y_1 are the lateral deflections for the p-y curves corresponding to the N^{th} and 1^{st} load cycle, respectively. The exponent *'t'*, in both these equations, corresponds to a degradation parameter and is a function of load ratio R, installation effects, and soil density.

Figure 5, shows the cyclic p-y curves according to Long and Vanneste (1994) for the same OEC monopile geometry mentioned in the previous section (e.g., Figure 8). Figure 5 shows p-y curves for load cycles N, equal to 1, 10, 10^2 and 10^3. An important difference between this cyclic p-y curve formulation and the one by Little and Briaud (1988) is that Long and Vanneste (1994) degrade both P and Y as a function of increasing load cycle number, N. The Long and Vanneste (1994) formulation is for pseudo-static lateral loading.

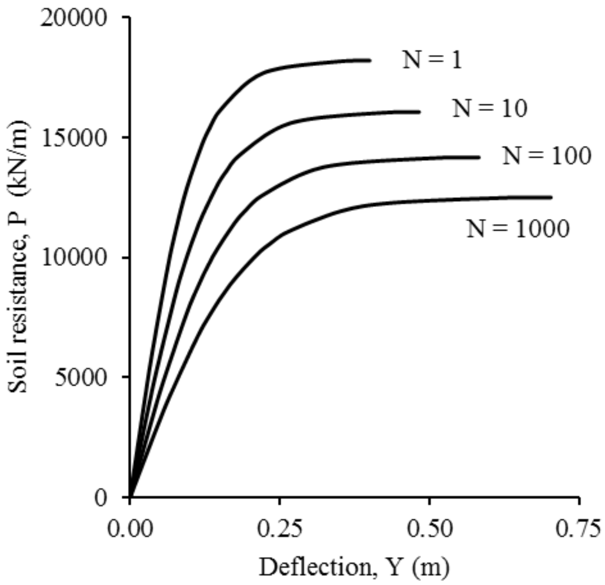

Figure 5: Cyclic P-Y curves based on Long and Vanneste (1994) for OEC monopile shown in Figure 8.

4.2. Analyses of Cyclic Lateral Loaded Monopiles using 3D Finite Element Analyses

In routine engineering practice, finite element analyses (FEA) have often been the less preferred approach for analysis of this soil structure interaction (SSI) problem. This has been primarily due to the required computational effort and challenges to select adequate constitutive soil models to capture the complex soil behavior when subjected to a large number of loading cycles. However a few studies involving FEA of monopiles under cyclic lateral loading have been reported in the literature. The work by Achmus and collaborators (Achmus et al., 2005 and 2009) is summarized below.

Achmus et al. (2005) conducted three dimensional finite element analyses to predict behavior of large diameter monopiles for offshore wind installations requiring to resist high horizontal loads due to wind and wave action. The objective of their study was to identify the difference in predicted monopile behavior when analyzed using conventional p-y based software versus advanced FEA. Specifically, these authors considered a 7.5 meter diameter monopile installed in a sandy foundation with an embedment length of 30 meters. The sandy foundation soil was modeled as an elasto-plastic material with Mohr-Coulomb failure criterion. The authors used 3D FEA and the software ABAQUS (ABAQUS, 1994). Their numerical study showed that the monopile lateral deflections predicted using p-y analyses (using p-y curves as per API, 2000) were significantly lower than the pile head lateral deflections obtained from their 3D FEA.

Achmus et al. (2009) reported results from additional 3D FEA where they considered an improved soil model calibrated using results from drained cyclic triaxial tests. From the results of the cyclic triaxial tests, a relationship between plastic strains and stiffness of the soil was used to update the soil properties in the model as a function of applied load cycle. Using this approach the stiffness of the soil was updated as a degraded stiffness in the FEA model. The numerical results were then integrated in order to obtain the estimated pile head behavior of a monopile subjected to up to 10^4 lateral load cycles.

5. Numerical Predictions of Head Deflections of OEC Monopiles under Cyclic Loading

5.1. P-Y Based Predictions of Experiments by Peng et al. (2006)

This section presents p-y analyses, using the three p-y formulations described in Section 4.1, carried out to predict pile head displacements of one of the monopiles tested by Peng et al. (2006). The geometry and lateral load time function used in this test are shown schematically in Figure 6. This test involved a model monopile consisting of a steel pipe with a diameter B, equal to 44.5 mm, a wall thickness t, equal to 2.15 mm, and an embedment depth D, equal to 400 mm. The monopile was installed in a dry uniform quartz sand placed at a relative density of 71.7% which was reported by Peng et al. (2006) as having a dry unit weight of 16.5 kN/m^3 and an effective internal friction angle of 35.2 degrees. A harmonic lateral load was applied with a peak load of 50 N, a frequency equal to 0.45 Hz, and a load ratio, R equal to 0. The lateral pile head displacements, measured at the point of lateral load application, are shown in Figure 7 as a function of applied load cycle.

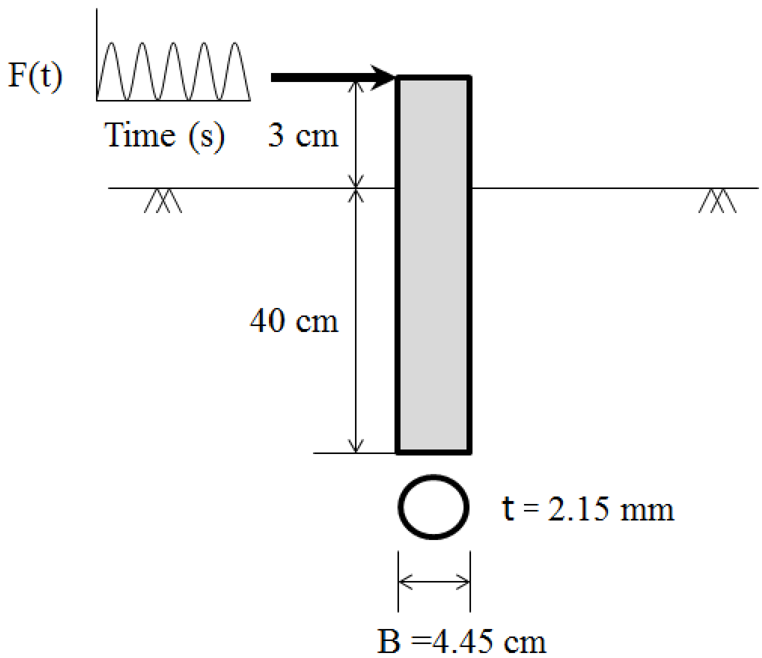

Figure 6: Geometry and Loading of monopile used in an experiment by Peng et al. (2006).

This same figure shows predictions of pile head deflections from p-y analyses using the p-y curves proposed by Reese et al. (1976) (API, 2000), Little and Briaud (1988), and Long and

Vanneste (1994). The predictions using API (2000) show a horizontal line, which as mentioned earlier reflects the use of a one-time degradation factor of 0.9, thus resulting in pile head displacement predictions that are independent of the applied load cycle, N. Figure 7 shows pile head displacements gradually increasing with applied load cycle (N) for analyses that used the cyclic p-y curves by Little and Briaud (1988) and by Long and Vanneste (1994). However both of these predictions significantly under-predict the experimental values reported by Peng et al. (2006).

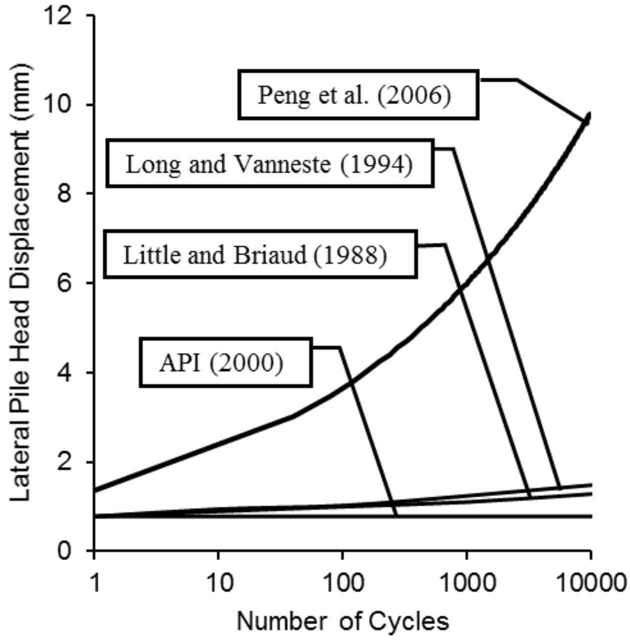

Figure 7: Comparison of Pile head displacements from numerical predictions and experiments by Peng et al. (2006).

From Figure 7 it appears that, at least for the OEC example chosen, that all three p-y curve formulations considered, significantly underestimate the long term pile head lateral displacements measured in the experiments involving a monopile installed in dense sand under harmonic lateral load cycles. The measured pile head displacements at 10^4 load cycles were almost 10 times larger than displacements predicted by any of the p-y analyses. Furthermore, all p-y based predictions used formulations that do not consider dynamic effects such as inertia or pile or soil damping. If soil damping effects were to be included the computed pile head displacements would be even lower than the ones reported in Figure 7. Thus clearly current p-y formulations under-predict long term OEC monopile head deformations due to cyclic loading.

5.2. Comparison of Monopile Head Displacements Predictions using 3D Dynamic FEA and P-Y Formulations

To further assess the similarities and differences in pile head predictions using both FEA and P-Y analyses, this section presents a comparison of predictions carried out for the OEC monopile shown in Figure 8. The predictions involved dynamic 3D finite element analyses (FEA) carried out using Plaxis 3D Dynamics (Plaxis, 2011) and the same p-y curves discussed in the preceding section.

For this comparison exercise, the lateral load was considered harmonic with a load frequency of 0.2 Hz and a maximum lateral force of 750 kN. This maximum force, obtained using Equation 1, corresponds to an OEC with a rotor diameter of 16.5 meters and a maximum current speed of 2.7 m/s. The load cycles were assumed with different loading ratios, R, but for the sake of brevity only results for the loading ratio R equal to zero are presented and discussed.

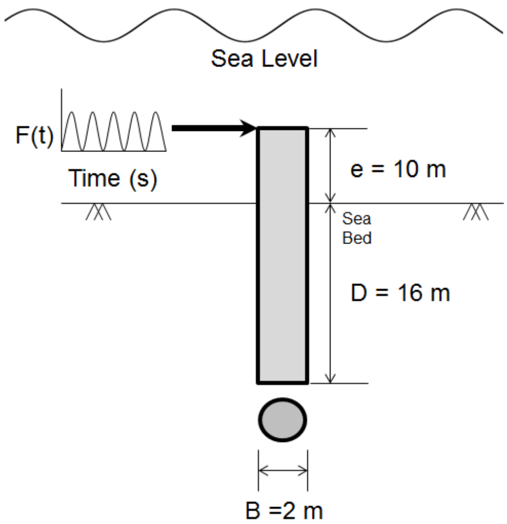

Figure 8: Geometry of the OEC monopile used for the FEA and P-Y Comparison.

The FE model used for this study is shown in Figure 9. The FE mesh used 10-node tetrahedral elements for both the pile and the soil elements. The final FE model used consisted of approximately 20,400 elements and 28,400 nodes. The model involved using interface elements between the pile and the surrounding soil. The FE mesh had three zones: (i) the zone closest to the pile which undergoes highest plastic strains had the finest mesh; (ii) the intermediate zone; and (iii) the coarser mesh corresponding to the zone farthest away from the pile. The nodes located along the outer vertical boundaries of the mesh were restricted to move only along the vertical boundary plane. Movements for the nodes along the base plane of the model were restricted in all directions. Pile and soil damping effects were included in the model. Non- reflective boundaries were also included in the FE model along the outer boundaries to minimize boundary effects due to reflecting waves.

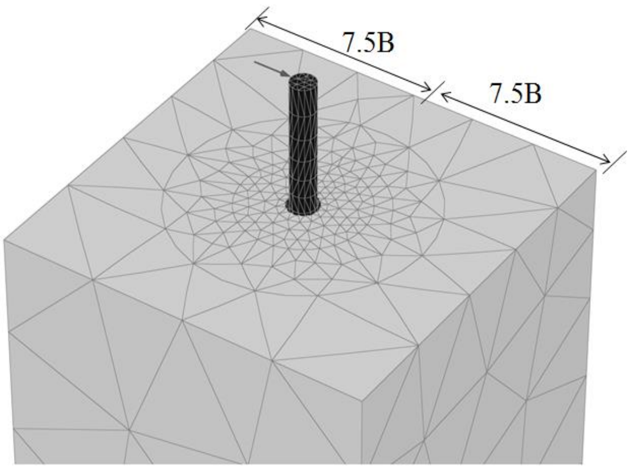

Figure 9: FE mesh used for the comparison study of OEC monopile shown in Figure 8.

The pile was modeled as linear elastic with properties selected to match the flexural stiffness of the CFT pile of Figure 8. The soil model used was the Hardening Soil (HS) model as described in Plaxis (2011). A summary of the main soil parameters used in the comparison exercise is presented in Table 1. A detailed description of the FE model can be found in Pappusetty (2013).

Table 1. Soil parameters used in the FEA

Parameters	Dense Soil condition
γ' (kN/m^3)	11
c′ (kN/m^2)	0
ϕ′ (Degrees)	37.5
E_{50}^{ref} (MN/m^2)	60
E_{oed}^{ref} (MN/m^2)	60
P^{ref} (kN/m^2)	100
E_{ur}^{ref} (MN/m^2)	180

The predicted pile head lateral deflections, for the OEC monopile in Figure 8, computed using both the dynamic 3D FEA and the three p-y formulations discussed earlier are shown in Figure 10. All prediction types resulted in similar lateral pile head deformations for the first load cycle. However, the API p-y formulation (Reese et al., 1974) fails to predict a gradual accumulation of lateral deformations of the pile head with increasing load cycles. The p-y based predictions made using the cyclic p-y curves by Little and Briaud (1988) and by Long and Vanneste (1994) compare reasonably well with the pile head displacements from the 3D Dynamic FEA for approximately the first 30 lateral load cycles. However beyond about 50 lateral load cycles the lateral pile head displacements predicted using both cyclic p-y formulations significantly under-predict the displacements predicted from the 3D Dynamic FEA.

The predicted pile head displacements, after 10^3 lateral load cycles, were 0.10, 0.06, and 0.05 meters for the FE analyses, and the Long and Vanneste (1994) and Little and Briaud (1988) cyclic p-y curves, respectively. Compared to an initial pile head displacement of about 0.04 meters, for the first cycle, these computed values after 10^3 lateral load cycles correspond to an increase in pile head displacement of 250%, 150%, and 125% for the 3D FEA, and the Long and Vanneste (1994) and Little and Briaud (1988) cyclic p-y curves, respectively.

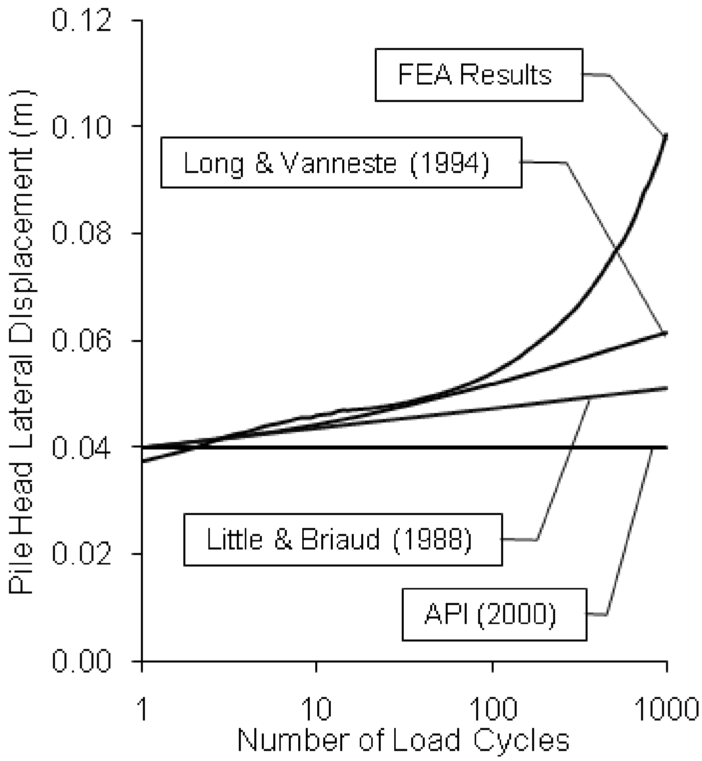

Figure 10: Comparision of monopile head deflections computed using 3D dynamic FEA and three types of P-Y analyses.

5.3 Summary and conclusions

The paper describes the general loading conditions of marine OEC monopiles to highlight how these conditions are significantly different to the loading conditions used in most of the experimental studies of single piles under cyclic loading. The paper also presents a brief summary of published experimental data (e.g., Peng et al., 2006; and Leblanc et al., 2009) that show how sustained cyclic lateral loading on monopiles can result in considerable gradual accumulation of pile head lateral displacements and rotations after very large number of lateral load cycles. This is particularly relevant for monopiles of proposed OEC projects where the marine environment and a 30 year design life can result in 10^8 lateral load cycles or more for these foundation systems.

An overview of different cyclic p-y formulations was presented and used to make predictions of experimental results by Peng et al. (2006). The p-y based predictions were found to greatly under-predict the pile head displacements reported from this study. Furthermore the evaluated p-y formulations do not consider dynamic effects such as soil damping which would further under-predict pile head deformations. In contrast, the predictions obtained using 3D dynamic FEA were found to predict reasonably well the lateral head displacements reported by Peng et al. (2006). A comparison of numerical predictions, of pile head lateral deflections, for a representative OEC monopile was described and presented. Predictions involved 3D dynamic FEA and three p-y formulations. The comparison shows that 3D dynamic FE analyses appear to best predict the observed gradual accumulation of pile head displacements compared to the predictions made using cyclic p-y curves by Long and Vanneste (1994) and Little and Briaud (1988).

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