New method for determining p-y curves on rigid piles - a theoretical and numerical investigation of the interaction of soil with large scale piles

Nouvelle méthode pour la détermination des courbes p-y sur pieux rigides - étude théorique et numérique sur l'interaction entre du sol et des pieux de grand diamètre

António Fonseca, António Viana da Fonseca, Pedro Costta
CONSTRUCT-GEO, Faculty of Engineering (FEUP), University of Porto, Portugal

Ole Hededal
Marine & Foundation Engineering, COWI A/S, Kongens Lyngby, Denmark, Technical Director, olhe@cowi.com

ABSTRACT: With the increase of energy consumption demanded by nowadays society and its necessity to look for new energy sources, engineering faces new challenges to guarantee that sustainable means and resources accompany the objectives. Being the wind energy one of the most clean and cost-effective renewable energy, large investments in this field have been made in the last years, mainly offshore where the efficiency is very high. Monopiles are the most commonly types of foundation used for offshore wind turbines with diameters ranging usually from 2.5 to 6 meters. P-y curves used in current models, aiming to characterize the lateral load-displacement and the soil-structure interaction, were obtained from few full-scale lateral load tests on slender piles. This means that the available laws were attained for very high length/diameter ratios' piles, being of foremost importance to adapt these curves to these increasing diameter rigid piles in offshore. The aim of this paper is to present new p-y curves more adapted to very rigid monopiles with large diameters driven into the seabed on clayey horizons. The study involves a numerical investigation of the soil-pile interaction response with special emphasis to the ultimate bearing capacity and the initial stiffness of the soil.

RÉSUMÉ : En raison de l'incrément de la consommation d'énergie exigée par les sociétés d'aujourd'hui et la nécessité de rechercher des nouvelles sources d'énergie, l'ingénierie est confrontée chaque jour à des nouveaux défis pour que les objectifs soient accompagnés des moyens et des ressources nécessaires. L'énergie éolienne est l'une des plus propres et rentables sources d'énergie et c'est pourquoi des importants investissements ont été réalisés tout au long des dernières années, surtout offshore où l'efficacité est très élevée. Aujourd'hui, les monopieux sont le type de fondation plus courante utilisé pour les éoliennes offshore avec grands diamètres de 2.5 à 6 mètres. Les méthodes actuellement disponibles, qui visent à caractériser la relation charge-déplacement latéral et l'interaction sol-structure, utilisent courbes p-y obtenues à partir des essais de charge statique, sur échelle réelle, en pieux souples. Cela signifie que les lois disponibles pour les pieux avec des très grands rapports longueur/diamètre doivent être adaptées pour être utilisées aux cas de plus en plus fréquents d'utilisation de pieux rigides avec des grands diamètres, tel que les pieux utilisés offshore. L'objective de cet article est de présenter des nouvelles courbes p-y adaptées aux monopieux très rigides avec grands diamètres encastrés dans les fonds marins argileuses. Le travail implique une étude numérique de l'interaction sol-structure, plus particulièrement la capacité portante du sol et la raideur initiale du sol.

KEYWORDS: Monopiles; p-y curves; lateral loading; soil-pile interaction; rigid piles; offshore; foundations.

1 INTRODUCTION

Most of non-renewable energy resources have consequences upon the environment. The large emissions of carbon dioxide and other pollutant gases created what is usually defined as the increase of the greenhouse effect that is leading to a global warming. As these problems began to have a big impact on the living conditions of our planet people and the governments started to take action and try to prevent a catastrophe. The solution is renewable energies. Wind is a renewable and a source of clean, non-polluting, energy that is becoming very popular in the last years. The offshore wind speed average is, more or less, 90% greater than onshore. As the market of offshore wind energy is increasing, many companies seek more accurate and reliable methods for the design of the foundations of the wind turbines. When it comes to the lateral-load design, the current methods are based on experiments made on flexible piles, while offshore foundations have a more rigid behaviour. This is leading to a lot of investigation by many experts on the field in order to find a more accurate way of describing the lateral load-response behaviour for the soil-pile interaction design. The common way of characterizing this load-response behaviour is through the usually called p-y curves.

2 API CLAY MODEL

Offshore wind turbines are subjected to very significant lateral loads. Therefore, the foundations of these structures are likely to suffer horizontal displacements. A precise prediction of these rigid foundations displacements is being investigated by many researchers since the second half of the 20th century. It is common to use a discrete model to predict these displacements, where the pile is divided in sectors, corresponding to soil layers with prospectively distinct soil-structure interaction response. Each layer will be associated to a spring representing the soil interacting with the pile and the soil and independent of all the others. The p-y curves will, therefore, represent the nonlinear relation between the soil reaction, p, and the pile deflection, y.
For static lateral loads the ultimate bearing capacity, p_u, of stiff and soft clay would vary between $8S_u$ and $12S_u$ except at shallow depths where failure occurs in a different mode due to low values of overburden pressure. Due to rapid deterioration under cyclic loadings, the ultimate lateral bearing capacity will reduce to considerably lower capacities. The ultimate soil resistance is the smaller of the values given by Eq. 1 and Eq. 2:

$$p_u^{shallow} = 3S_u + \square' z + J\frac{S_u z}{D} \quad (1)$$

$$p_u^{deep} = 9S_u \tag{2}$$

These equations differentiate a wedge failure mechanism at shallow depths and a flow mechanism of the soil around the pile in the horizontal plane for deep depths, being z_{cr} the depth at which the two equations intersect and there is a change of failure mechanisms. The p-y curves for the short-term static load case may be generated from Eq. 3 (y_{50} is also usually denoted as y_c).

$$\frac{p}{p_u} = 0.5\left(\frac{y}{y_{50}}\right)^{\frac{1}{3}} \tag{3}$$

3 DEFINITION OF THE NUMERICAL MODEL

3 .1 *Geometry*

For this problem, only half of the pile and the surrounding soil were modelled (more details in Fonseca, A.) due to the symmetric conditions of the problem, allowing a large reduction of the computational effort. To facilitate the construction of a model for different piles, all the lengths in the different directions are expressed by a proportional number of the pile diameter.

3 .2 *Soil*

This work is focused in a clay type soil. This option was made for two main reasons: first, there are few case-studies regarding cohesive soils when compared to granular soils; and, secondly, because both the North Sea and the Baltic Sea, located close to the UK, Scandinavia and Germany, have a seabed composed predominantly by cohesive soils. For this reason, there was a big interest in studying these particular conditions.

A Zomergem Clay was considered to best suit the purpose of this work. It is classified as a high plasticity clay according to BSCS (Biological Sciences Curriculum Study) and its characteristic stiffness parameters are presented in Table 1.

Table 1. Characteristic parameters for a Zomergem Clay according to the BSCS and input parameters for a Hardening-Soil model in PLAXIS.

Parameter	*Value*	*Unit*
Geotechnical Identification	Zomergem clay	-
Unit Weight (Υ_{sat})	19.0	kN/m3
Secant Modulus (E_{50}^{ref})	10.0	MPa
Oedometer Modulus (E_{oed}^{ref})	4.0	MPa
Unload-Reload Modulus (E_{ur}^{ref})	30.0	MPa
Undrained Shear Strength (S_u^{ref})	100.0	kPa
Unload-Reload Poisson Ratio (ν'_{ur})	0.20	-

The constitutive model used for the soil was the Hardening Soil Model (HSM) available in Plaxis®. When subjected to primary deviatoric stress ($\sigma_1 - \sigma_3$), the soil shows a decreasing stiffness and simultaneously irreversible plastic strains development, which very well represent the inelastic behaviour of the soil.

3 .3 *Monopile*

Being the monopile a steel hollow cylindrical tube, the best way to model it in PLAXIS 3D was a plate element. This plate is composed by steel with Unit Weight, Υ, of 78.5 kN/m^3 and a Young's Modulus, E, of 210 GPa. The length of the pile was normalized by its diameter, as it happened with the size of the model, so it should always be 5 times the diameter.

4 INTEGRATION OF THE STRESSES AROUND THE PILE

As the p-y curves relate the lateral deflection of the soil and the induced stresses, several calculations were carried out in order to find the best way to estimate the distribution of the stresses around the pile. This study was conducted using Matlab to process the data exported from PLAXIS 3D (more details in Fonseca, A.).

The stresses around the pile were integrated for different applied displacements, resulting on several relations of deflection and soil reaction at each depth, as shown in Figure 1.

In order to normalize the results and identify the critical parameters, it was necessary to find an analytical solution that best fitted the obtained data. The following hypotheses were tested: Matlock's p-y curve, which is the one suggested by the America Petroleum Institute (Matlock, 1970; API, 2002), with Eq. 4, where the ultimate bearing capacity, p_u, and the deflection at 50% of the ultimate bearing capacity, y_{50}, are the unknown variables; and Eq. 5 (Georgiadis et al. 1992), where the ultimate bearing capacity, p_u, and the initial stiffness of the p-y curve, k_s, are the unknown variables.

To finalize, the hyperbola from Eq. 5 was chosen as the one fitting best the obtained results, since Matlock's method for the definition of the p-y curves largely underestimated the capacity of the soil.

$$p = 0.5 * p_u\left(\frac{y}{y_{50}}\right)^{\frac{1}{3}} \tag{4}$$

$$p = \frac{y}{\frac{1}{k_s}+\frac{y}{p_u}} \tag{5}$$

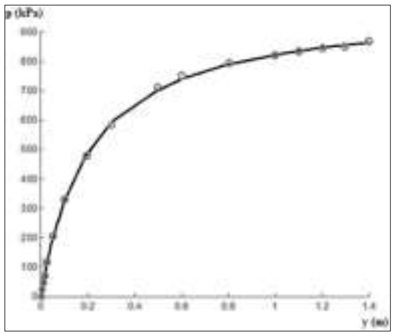

Figure 1. Fitting of the p-y curve proposed by Georgiadis et al. (1992).

5 PROPOSED METHOD FOR DEFINITION OF P-Y CURVES IN LARGE DIAMETER PILES IN CLAYS

5 .1 *Overview*

Having adopted the Eq. 5 to define the p-y curves, it is now necessary to propose a method for the characterization of the variables of the equation, that is, the ultimate bearing capacity, p_u, and the initial stiffness of the p-y curve, k_s.

By calculating both these parameters for the different p-y curves over the length of the pile, it is possible to obtain their evolution in depth. Creating graphs representing the evolution of these parameters it is possible to infer these critical parameters mathematically, as it is already used in the method suggested by the API.

For this, it is necessary to perform sensitivity analyses under that model in order to find out which aspects have an impact on the critical parameters of the equation. The sensitivity studies performed in this work were the undrained shear strength, S_u, the diameter of the pile, D, and the Young's Modulus (Secant Modulus, E_{50}^{ref}, in the Hardening Soil model of PLAXIS 3D).

Firstly, an analysis of the results of the ultimate bearing capacity of the soil will be performed and then the same will be done for the initial stiffness of the p-y curves.

5 .2 *Ultimate Bearing Capacity, p_u*

Knowing that the undrained shear strength would be the most influent parameter of the soil on its ultimate lateral bearing capacity for an undrained loading case, several tests were run using different values for this parameter.
With a constant S_u in depth, three values were tested: 50kPa, 100 kPa and 200 kPa.
It is important to notice that by imposing a constant value of undrained shear strength over the depth of the model some unrealistic and inaccurate results will appear at the shallow depths of the soil. This happens because, on one hand, the OCR is imposed as 1 (normally consolidated), while, on the other hand, in order to have high values of undrained shear strength, the over-consolidation ratio needs to be higher than 1 (maybe higher than 5 for the case of 200 kPa). Additionally, at the tip of the pile, the behaviour of the soil is not very representative of a laterally loaded pile, leading to some unreliable results at these depths of the soil.
For the case of an increasing undrained shear strength in depth, two different cases were tested: one with an increase of 3 kPa of the undrained shear strength in depth and another with an increase of 4 kPa. These values of 3 and 4 kPa for the evolution of the S_u over the depth is based on a constant ratio of S_u and σ'_{v0} of around 0.3 and 0.4.
To test whether the diameter of the pile has any influence on the p-y curves, three different models, each one with a different diameter, were run and analysed. The diameters used on the three models were of 6, 4 and 2 meters.
The Hardening Soil model of PLAXIS 3D characterizes the deformation of the soil by introducing a reference value for the Secant Young Modulus (E_{50}^{ref}), being in these parametric studies adopted the values of 10 MPa, 20 MPa and 50 MPa (always with a S_u of 100 kPa). It was concluded that the soil Young's Modulus has no relevant impact on the lateral p_u of the soil.
Three main conclusions can be deduced from the obtained results concerning the ultimate bearing capacity of the soil:

- The value for the ultimate bearing capacity of the soil at the surface is of $3S_u$;
- The constant value for the ultimate bearing capacity of the soil at high depths is $9S_u$;
- The depth at which there is a change of failure mechanisms is typically at 1.5 pile's diameters.

That being said, the method proposed for the definition of the p_u of the soil consists on using Eq. 6 and Eq. 7:

$$p_u^{shallow} = 3S_u + \frac{4S_u}{D} z \quad (6)$$

$$p_u^{deep} = 9S_u \quad (7)$$

The application of the equations is the same as in the method suggested by API, with the following specificity: the ultimate soil resistance at a certain depth, z, is the smaller of the two previous equations. Again, Eq. 6 corresponds to a wedge failure mechanism at shallow depths – with the ultimate bearing capacity increasing with depth – and Eq. 7 to a flow failure mechanism of the soil around the pile in the horizontal plane for deep depths – constant in depth.
In terms of p_u, there is one big difference between the method proposed in this work and the one suggested by the API: the flow failure mechanism of the soil of the API occurs at very deep depths compared to the depth of 1.5 diameters hereby suggested. This leads to a big underestimation of the ultimate bearing capacity of the soil by the API. The reason of this might be the fact that API method is based on tests on slender piles where the failure of soil is difficult to identify, since the failure is mostly conditioned by structural resistance of cross section of the pile, which is mobilized a priori.

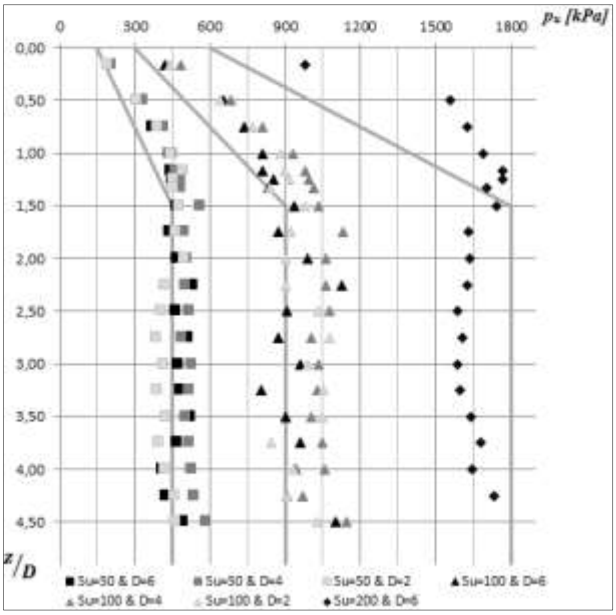

Figure 2. Results for the p_u depending on the D and constant S_u.

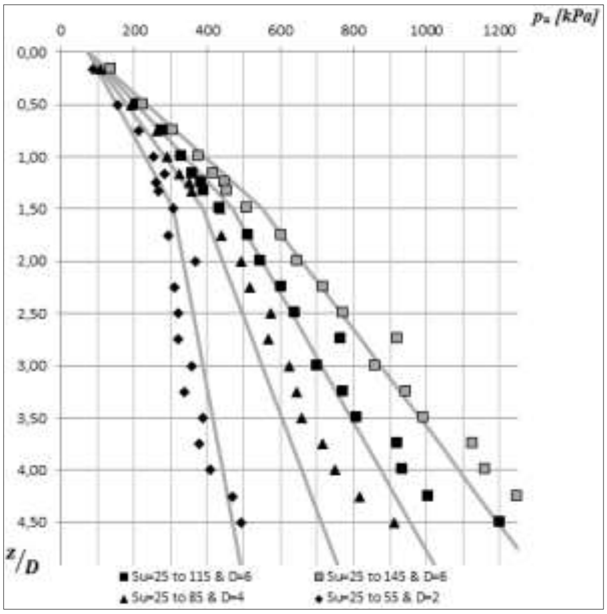

Figure 3. Results for the p_u depending on an increasing S_u over depth.

5 .3 *Initial Stiffness of the p-y Curve, k_s*

Obtained from the same models used for the estimation of ultimate lateral bearing capacity of the soil, p_u, Figures 4 and 5 present the results varying the initial stiffness of the p-y curves, k_s, over the length of the pile.
On the contrary of what happened with the p_u, there was no impact on the k_s for different values of undrained shear strength (both constant and increasing in depth). On the other hand, the diameter of the pile and the Young's Modulus had a significant influence on the initial stiffness of the soil.
Similarly to the pattern observed in the ultimate lateral bearing capacity, the initial stiffness of the p-y curves has one equation for shallow depths concerning a wedge failure mechanism and another for deep depths, being this associated to a flow failure mechanism of the soil. However, at a certain depth, the higher value for k_s obtained from the two equations should be assumed, in contrast with what happened with the ultimate bearing capacity.

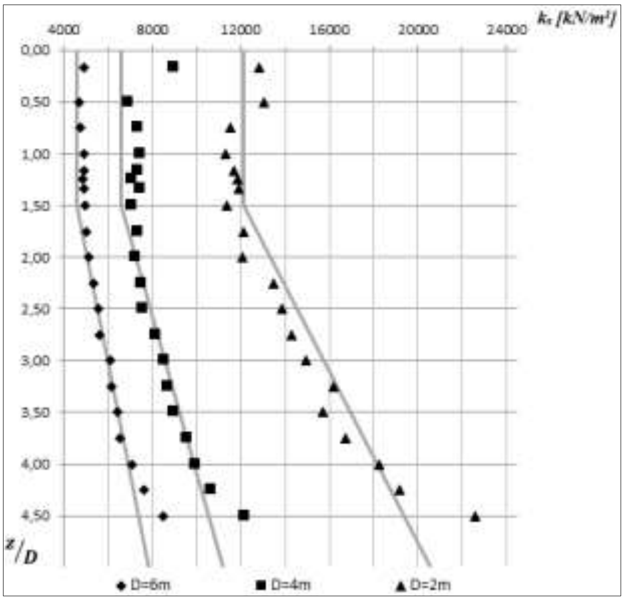

Figure 4. Results for the k_s depending on the D.

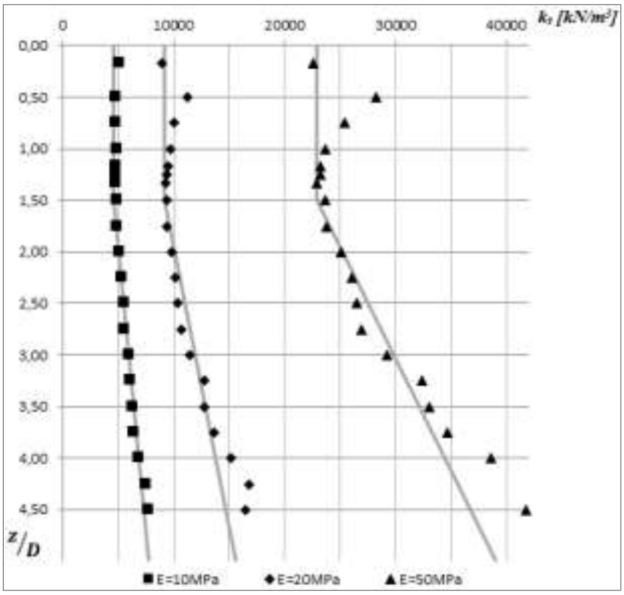

Figure 5. Results for the k_s depending on the E_{50}.

By observing the results of Figures 4 and 5, Eqs. 8 and 9 were deducted and presented as the solution for the evolution over the depth of initial stiffness of the p-y curves, k_s.

$$k_s^{shallow} = 3 \frac{E_{50}}{D^{\left(1+\frac{1}{D^{1.7}}\right)}} \tag{8}$$

$$k_s^{deep} = 0.6\left(\frac{z}{D} + 3.5\right)\frac{E_{50}}{D^{\left(1+\frac{1}{D^{1.7}}\right)}} \tag{9}$$

6 CONCLUSIONS

A new method is proposed for determining p-y curves on rigid piles, by recurring to a theoretical and numerical investigation of the interaction of soil with large scale piles (large diameters, D). The results are compared with the p-y curves obtained from the API method.

In the API method, the only parameter that varies over the depth is the ultimate lateral bearing capacity, p_u, of the soil. On the other hand, with the proposed method, not only the p_u of the soil varies in depth differently from the API method, but also the variation of the stiffness of the p-y curves in depth has also to be taken into account.

Figures 6 and 7 show the effect of the diameter of the pile and the undrained shear strength of the soil on p-y curves obtained in both methods. The variation of the Young's Modulus will not be presented, as the API method does not take into consideration this parameter.

For the case of the variation of D, with the API method both the k_s and the p_u increase as the diameter of the pile decreases. As for the proposed method, p_u is mostly constant (as it was concluded that the dimeter, D, of the pile had no impact on the p_u of the soil) and the k_s increases as the D decreases, just like in the API method. Notice that the curves are always for the same relative depth (z/D). Additionally, the soil lateral bearing capacity, p_u, is strongly underestimated by the API method.

As for the parametric studies, considering different values of S_u, it is also possible to verify that the API method highly underestimates the resistance of the soil.

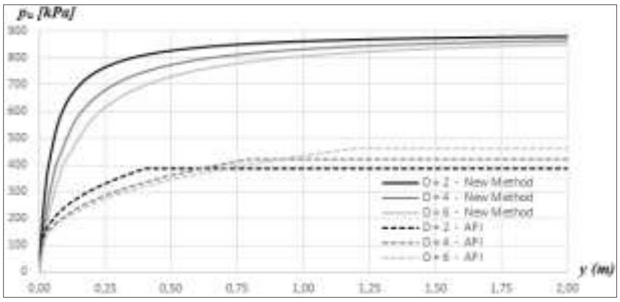

Figure 6. Effect of the D of the pile on the p-y curves of both methods.

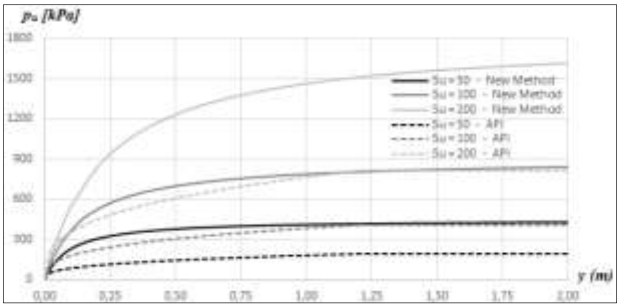

Figure 7. Effect of the S_u of the soil on the p-y curves of both methods.

To summarize, it is probable that the lateral loading tests on slender piles, in which the API based the estimation of the relation between load and lateral displacement, are not adequate to rigid piles. Therefore, it tends to highly underestimate the resistance of the pile, leading to an oversizing of these piles. It is important to investigate and define a more precise way to predict the lateral displacements of these structures as this might have a large impact on the cost of these foundations.

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