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A parametric study of different analytical design methods to determine the axial bearing capacity of monopiles

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HIGHLIGHTS

- A sensitivity analysis is carried out to show the influence of different parameters.
- The sensitivity analysis shows a variation between the capacities of 1.7 to 16.4.
- A comparison with five different field tests shows the performance of the methods.
- For some methods, there is good agreement between predicted and measured capacities.
- Other methods show a strong deviation to the measured capacity.

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ABSTRACT

In Europe many offshore wind power parks have already been realized and more are planned. Often monopiles are used as foundation for wind power plants. The determination of the axial pile capacity of monopiles is among the important issues for offshore energy projects. Despite progress made so far in this field, there are still big challenges faced by researchers. Among them is to provide guidance to assist engineers in the selection of an appropriate design method for the soil condition and pile configuration of interest. First, different state of the art methods (API, Fugro-05, ICP-05, NGI-05 and UWA-05) together with two new methods (HKU-12 and a German approach) to determine the axial bearing capacity based on the cone resistance of the soil are presented. Afterwards there is a summary of different approaches to determine the average cone resistance value. Furthermore a sensitivity analysis is carried out to show the influence of the pile diameter and the cone resistance on the predicted axial bearing capacity of the different design methods. In the last part, published field tests are used to compare the presented design methods and to identify their potential for reliable predictions for engineering practice. In addition to existing publications, these comparisons contain the two new design methods to determine the axial bearing capacity.

1. Introduction

Monopiles (open steel pipe piles in general) are becoming increasingly important in constructing offshore structures, especially as foundation for offshore wind power plants. In order to replace fossil and nuclear energy with renewable energy sources, more and more wind power parks are being constructed. The determination of the axial pile capacity of monopiles is one of the important issues of offshore energy projects. Despite the progress made so far in this field, researchers are still faced with many challenges. Among them is the provision of guidance to assist engineers in the selection of an appropriate design method based on the soil condition and pile configuration of interest. Hence, this paper discusses an important issue related to geomechanics in energy and environment.

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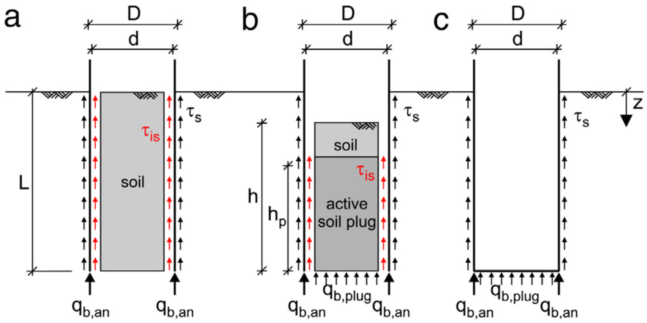

Fig. 1. Axial bearing behaviour of an open steel pipe pile: (a) fully coring, (b) partially plugged, (c) fully plugged.

The axial bearing capacity of open steel pipe piles in granular soils depends, among others, on the installation method, the pile diameter, the embedment length of the pile, the interface friction angle between the pile and the soil, and the relative density of the soil. During the installation, a plug may be formed inside the pile. A plug can be visualized as a spatial bracing of soil between the inner surface of the pile, cf. Lüking.[1] Such a plug influences the axial bearing capacity significantly.

In Fig. 1, the principle axial bearing behaviour of an open steel pipe pile is shown. In the case of a pile with no plugging effect, the axial bearing capacity is achieved by an internal and external frictional resistance and a resistance mobilized by the tip pressure of the annulus (a). In the case of a partially plugged pile (b), there is an additional resistance mobilized by the plug inside the pile, though the internal frictional resistance is lowered compared to the pile without a plug. In the case of a fully plugged pile (c), an open pile behaves like a closed pile, with a high resistance mobilized by the plug and no internal frictional resistance. Observations by Jardine et al.[2] show, that an open steel pipe pile is likely to form a plug when its diameter is 1.5 m and below. This means that in the case of large diameter open steel pipe piles, no plugging effect is expected and the bearing behaviour presented in Fig. 1(a) can be anticipated.

A parameter to define the degree of plugging is the Incremental Filling Ratio (IFR) introduced by Brucy et al.[3] It is defined as follows

$$\mathrm{IFR} = \frac{\Delta h}{\Delta L}. \tag{1}$$

In real applications, for example in the installation of monopiles, it is hard to determine the IFR because the height of the plug as well as the penetration depth of the pile need to be continuously monitored. For this reason Paik et al.,[4] introduced the Plug Length Ratio (PLR). Its definition is similar to the IFR except that the PLR is not an incremental value and is only measured once at the end of the installation process.

$$\mathrm{PLR} = \frac{h}{L}. \tag{2}$$

In scientific papers, different analytical approaches exist to determine the axial bearing capacity, e.g. Randolph et al.[5,6] and Paik et al.[4] Nowadays the API[7] and the DIN EN ISO 19902:2014-1[8] operate as technical standards for the design of monopiles. Both are referring to CPT based design methods. These CPT based methods should lead to a more realistic and economical axial design of the piles because the axial bearing capacity is directly linked to the cone resistance of a CPT. The referred methods are the Fugro-05,[9] ICP-05,[2] NGI-05[10] and UWA-05.[11] More recent methods to determine the axial bearing capacity are the HKU-12 method[12,13] and an approach recommended by EA-Pfähle.[14] What all these methods have in common is that they are only valid for impact-driven piles. Lammertz[15] proposed a method to determine the axial bearing capacity of vibratory-driven piles.

The objective of this paper is to perform a comparison among the different analytical axial design methods for monopiles. A sensitivity analysis with regard to the pile diameter and the cone resistance shows the quality of the methods in a parametric study. A comparison with the results from different field tests shows the quality of the methods under real conditions. The result of this paper could serve as a guide to help the engineer select a method that suits his individual case.

2. Analytical design methods

All the respectively predicted capacities and resistances are ultimate values assuming a settlement of the pile of 10% of the diameter, i.e. $\frac{s}{D} = 0.1$. To calculate the total axial bearing capacity, Q_{tot}, of open steel pipe piles, the following general equation is used for almost all of the presented methods

$$Q_{tot} = Q_b + Q_s = 0.25\,\pi D^2\, q_b + \pi D \int \tau_s\,(z)\,dz. \tag{3}$$

Fig. 2(a) and (b) can be used to determine the qualitative distribution of Q_b and Q_s before the relative settlement of the pile reached $0.1D$. A summary of the design equations to determine q_b and τ_s of the CPT based design methods can be found in Tables 3 and 4.

2.1. API

The API 2A-WSD[7] is a technical standard that provides guidance in the design of offshore structures. Among other things, a recommendation on the determination of the axial bearing capacity is given. This recommendation can also be found in DIN EN ISO 19902:2014-01.[8] The values of

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