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# Centrifuge modelling of the impact of the installation method on the lateral response of the pile

## Modélisation en centrifuge de l'impact de la méthode l'installation d'un pieu sur sa réponse en latérale

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**ABSTRACT:** Two methods of pile installation were reproduced in the centrifuge on reduced models of close-ended piles. In one case, the pile is installed at 1×g to model the behaviour of a wished-in-place pile. In the second case, the pile is installed in flight to generate the stresses obtained during the installation of a displacement pile. Then, these piles are loaded laterally without stopping the centrifuge. The piles are instrumented with strain gages from it inside, the bending moment profiles along the piles can be compared. From these profiles, the experimental P-y curves are calculated by double derivation and double integration. These P-y curves are compared to those obtained from the DNVGL considered as reference for the offshore wind turbines.

**RÉSUMÉ:** Deux méthodes d'installation de pieux ont été reproduites en centrifugeuse sur des modèles réduits de pieux fermés en pointe. Dans un cas, le pieu est installé par fonçage à 1×g afin de modéliser le comportement d'un pieu foré. Dans le second cas, le pieu est mis en place sous macrogravité afin de générer les contraintes obtenues lors de l'installation d'un pieu de déplacement. Par la suite, ces pieux sont chargés latéralement sans relâcher l'état de contraintes. Les pieux étant instrumentés de jauges de déformations à l'intérieur du fût, les profils des moments le long du fût peuvent être comparés. A partir de ces profils, les courbes P-y expérimentales sont calculés par double dérivation et double intégration. Ces courbes P-y sont confrontées à celles obtenues à partir du DNVGL faisant référence dans l'éolien en mer.

**Keywords:** Piles; lateral loading; centrifuge modelling; p-y curves.

## 1 INTRODUCTION

The high efficiency of the offshore wind turbines makes the demands on this source of renewable energy increase drastically especially in developed country searching to increase their green energy production. Different types of structures are used nowadays in the construction of the offshores wind turbines. Gravity bases and large monopiles are considered the most economies and suitable for wind turbines installed in relatively shallow water. The new demands for offshore wind energy lead to the use of wind turbines in deeper water supported by jacked structures. On the other side the piles of these types of structures are exposed to severe laterals loads originated from the waves and wind. In order to design piles under such types of severe lateral loads DNVGL-ST-0126 (DNVGL, 2016) method is used which is based on the load-transfer approach known also as the p-y method. This method models the pile as a beam and the soil as a series of nonlinear springs (Figure 1). The springs are described by the p-y curves which define the load displacement relationship for the interaction between soil and pile.

In the literature, despite the existence of a few in-situ studies (Baguelin and Jézéquel 1972, Bigot et al. 1982), centrifuge modelling is predominantly used to investigate the lateral behaviour of piles (Mezazigh et al. (1994), Mezazigh (1995), Rosquoet et al. (2007), Dyson and Randolph (2001)). Kong and Zang (2007) cited that Scott (1981) was among the first to model laterally loaded piles in centrifuge. In his tests, a smaller model pile was installed at 1g and another larger pile was installed by raining the sand around it. He stated that neither method of installation represented the prototype conditions. Jacking (or driving) model piles in flight better simulates prototype conditions, particularly the lateral stress distribution following installation. Other studies on the effect of installation methods on the lateral behaviour of piles are presented in the work of Kim and al. (2004) and Dyson and Randolph (2001) where an important effect of the installation methods of piles on the stiffness of the load transfer curve was proved to exist. Although the important effect of the installation method on the lateral behaviour of piles found in the literature DNVGL methods do not account for this important factor.

The aim of the work presented here is to study in details the effect of the installation method on the lateral behaviour of piles. An extensive experimental campaign where different installation methods are used followed by lateral loadings of piles and full analyses and comparison of the experimental p-y curves is realized. The experimental work is followed by a full comparison between the experimental p-y curves of the various installations methods used and the p-y curves given by the DNVGL method in order to test the performance of these DNVGL curves toward experimental results.

## 2 METHODOLOGY

### *2.1* Centifuge modelling

Centrifuge modelling is based on the observation of small scale models placed in a high gravity field to allow for the replication of the stress state in the full scale prototype. The use of the 5.5-m radius swing arm centrifuge to study deep foundations is essential to obtain a negligible gradient of g between the top and the bottom of the model pile.

The tests described here are carried out at an acceleration level of 100 times the earth gravity (100×g) on 1:100 scale model piles.

### *2.2* Model soil

The model soil is a poorly graded NE34 Fontainebleau sand (Table 1). The rectangular strongbox has a relative soil density (58% ± 0.5 %) achieved by filling the strongboxes with sand using the air pluviation technique. The unit dry weight of this strongbox is 1.59 g/cm$^3$.

### *2.3* Model pile

The model pile is 1.5 mm thick aluminium close-ended pile with 200 mm of embedded depth, i.e., a thickness of 0.15 m and a depth of 20 m for prototype scale. The pile was instru-

*Table 1. Characteristics of Fontainbleau NE34 sand*

| **Sand** | **$U_C=d_{60}/d_{10}$** | **$d_{50}$ (µm)** | **$\rho_{d\min}$ (g/cm$^3$)** | **$\rho_{d\max}$ (g/cm$^3$)** |
|---|---|---|---|---|
| Fontainebleau NE34 | 1.53 | 210 | 1.46 | 1.71 |

$U_c$ is the coefficient of uniformity (Silva 2014).
$d_x$ is the grain size, at which x% of particles by weight are smaller (Silva 2014).
$\rho_{d\min}$, $\rho_{d\max}$ are minimum and maximum dry unit weight according to NF P 94-059.

mented from inside with a 16 levels of quarter-bridge strain gages diametrically opposed for bending moments measurement. The instrumentation of the pile from inside was essential in this work and gives the present study an important advantage and opportunity to jack the pile even in flight without damaging the strain gages. The model pile presents an equivalent prototype pile with bending stiffness of 19.74 GN.m$^2$ at 100×g.

The ratio between the pile diameter B and the Fontainebleau sand $d_{50}$ is 18/0.21 = 85 which is larger than the minimum limit of 45 given by Garnier et al. (2007) needed to eliminate any grain size effects.

### 2.4 Pile installation and experimental campaign

Extensive work has been undertaken to develop an innovative experimental campaign (Figure 1). Thanks to this earlier work it becomes possible to carry out the specific steps required for both installation and loading of the piles studied. The experimental set-up contains a hydraulic jack in order to jack the pile and an electric jack used for the lateral loading of the piles. A 25-kN ± 0.25 kN load sensor (FN3070 from *FGP*) located between the pile head and the hydraulic jack measures the total bearing capacity of the pile. The pile displacement is determined using a magnetostrictive displacement sensor (1/300350S010–1E01 from *TWK*), which controls the displacement of the hydraulic jack. In the other hand the lateral loading was measured by a 2.5-kN ± 0.025 kN load sensor (F521-06TC from *TME*) located at the end of the electric jack. The displacement of this jack is given by an integrated sensor inside the jack manufactured by *Exlar*. In addition, a lateral laser is placed in the frond of the installed pile to meas-

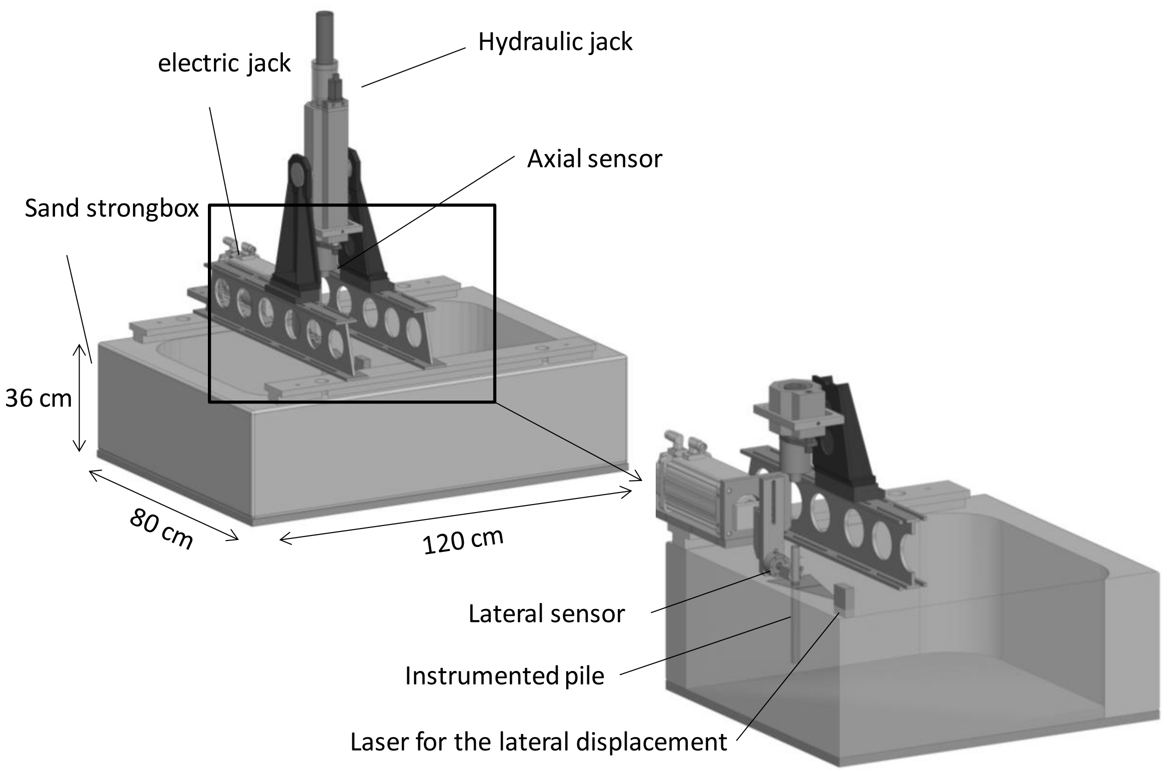


*Figure 1. Experimental set up (inside dimensions)*

ure the lateral displacement of the pile at the high of 12 mm from the sand surface.

Two installation methods are tested in the present study. First, the pile is jacked at 1×g used to model wished-in-place pile installation then the centrifuge is putted in-flight and the lateral loading is realized. The second one, jacking the pile in-flight at a speed of 0.1 mm/s to simulate installation effects and soil displacement that takes place during the installation of displacement piles followed by the lateral loading of the pile without stopping the centrifuge. In the both cases the lateral loading is realized in force controlled mode at a constant speed of 0.1 daN/s up to the desired lateral force of 50 daN. Such limit is chosen in order to stay in the elastic limit of the pile and to prevent any worries of plastification.

## *2.5* Results analysis and p-y curves constitutions

The first step in the results analysis and as a consequence of the use of quarter-bridges strain gages is to calculate mathematically the difference between the results of the two gages on the same level. The answer will then be multiplied by the bending calibration coefficient to obtain the bending moment at each level. Once the bending moment of all level is obtained it is necessary to fit these moments by a function in order to give a mathematic expression to the moment profile. Rosquoet et al. (2010) have cited that king (1994) has demonstrated that a single polynomial function is not satisfactory. In the present study a cubic spline is indeed been used to fit the moments profiles. The moment fitting is an essential step in the results analysis because it make possible to apply mathematic procedure to the moment profile like integration

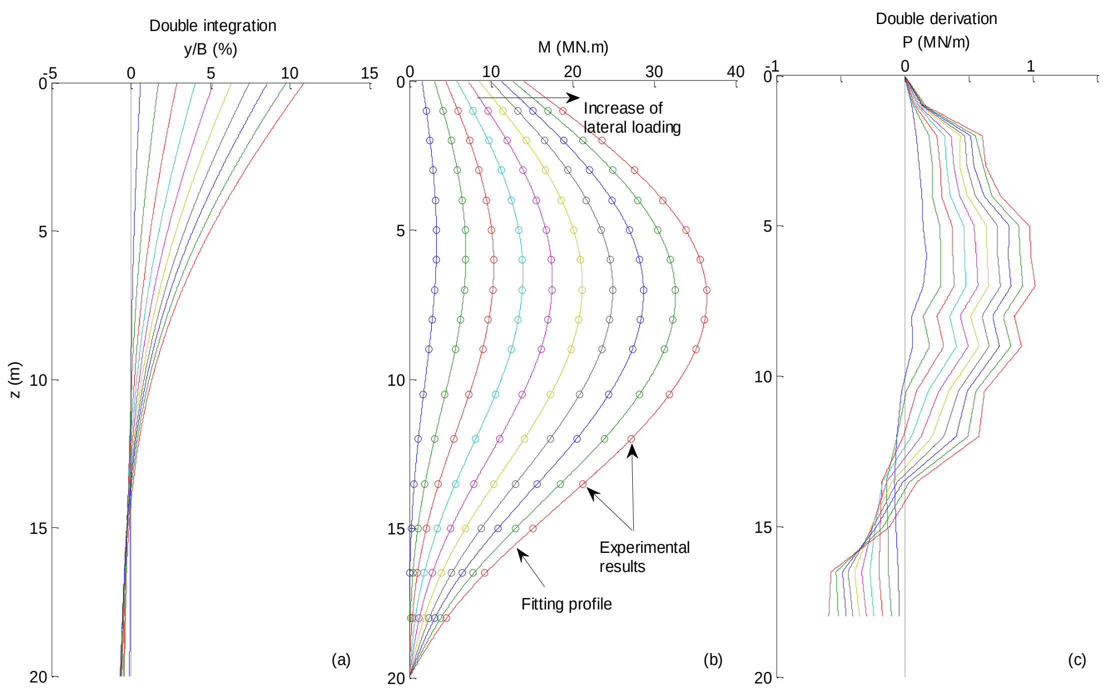


*Figure 2. Pile installed at 1×g (a) pile deflection (b) moment profile (c) soil reaction*

and derivation. In fact it is known that in order to obtain the experimental p-y curves, a double differentiating of the bending moment profile to obtain the force per unit length *P* and a double integrating of the curvature *M/EI* to obtain the lateral displacement y is necessary. The constant needed in the double integration are extracted from the pile displacement at the Laser level and the rotation of the pile around the level where P equal to zero (i.e. y=0 at this level). Figure 2(b) present the experimental moments points in plus of the fitting profiles. From these profiles the soil reaction (figure 2(c)) and lateral displacement (figure 2(a)) is extracted. P-y curves can finally be obtained from the both profiles of soil reaction and lateral displacement.

# 3 TEST ANALYSIS

## *3.1* Moment and surface displacement comparison

The method of pile installation can affect the pile response for both model and prototypes tests (Craig 1980). In order to study the effect of the installation method on the axial capacity of piles a first comparison was done between the moments profiles of the both piles installed at 1×g and 100×g (Figure 3). Figure 3 shows the moment profiles for both piles at different stage of lateral charging going from 0.5 MN up to 5 MN at the end of the tests. It is clear that a difference exist between the moment profiles of both piles from early stage of charging. Two distinctions between the profiles can be clearly identified: (1) the maximum moment of the pile jacked at 100×g is always smaller than the maximum moment of the pile jacked at 1×g and the difference between the two maximum increases with the increase of the charge, (2) the maximum moment of the pile jacked in flight is shallower than that of the pile jacked at 1×g. These differences exist for any stage of loading.

The decrease of the maximum moment and the fact that this maximum is shallower when the pile is jacked in flight can be associated to a densification and augmentation of the resistance of the soil around the pile on the upper few di-

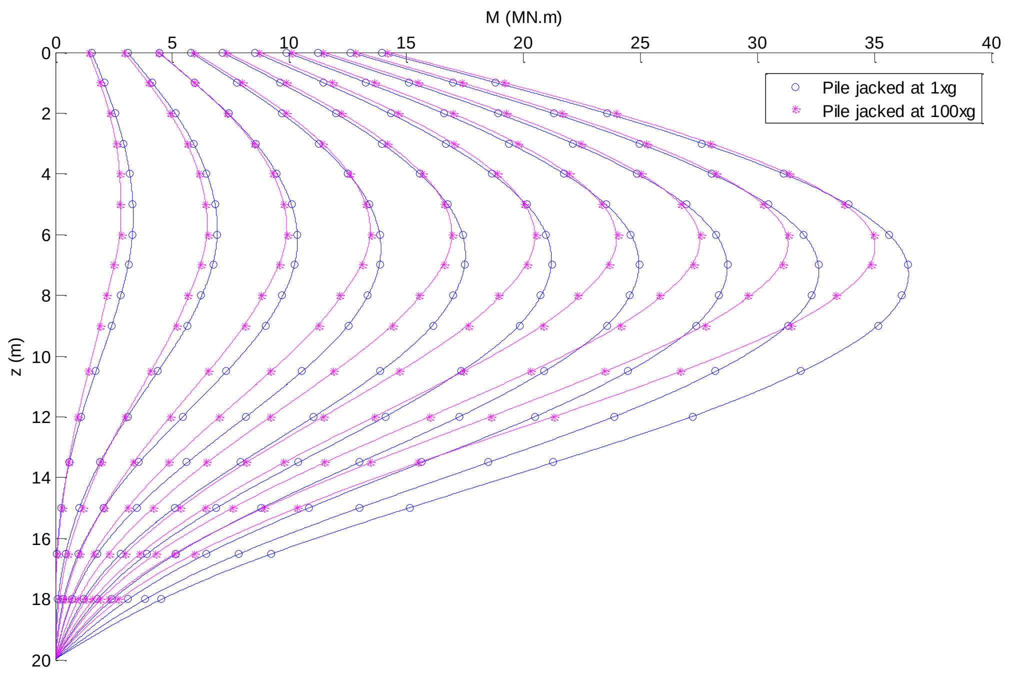


*Figure 3. Moment profiles*

ameters. A decrease of the maximum is clearly a consequence of that the soil had the ability to more resist the lateral load when the pile is jacked in flight in comparison with the pile jacked at 1×g. This densification can be due to that jacking the pile in flight is a displacement installation method which induces a high displacement of the sand around and under the pile as the pile progressively had been jacked. Contrary to jacking the pile at 1×g where much less sand is displaced when the pile is jacked.

Figure 4 shows the displacement of pile at the sand surface for the tested piles. The displacement of the pile jacked at 1×g is always higher than the displacement of the in-flight pile. Moreover the increase of the displacement of the first pile with the lateral loading is sharper than the displacement of in-flight pile which leads to that the difference between the displacements of the two piles increase with the loading. At the end of the tests the displacement of the pile jacked at 1×g already exceeds 11% of B and that of the in-flight pile is about 8% of B. The smaller displacement of in-flight pile can also be attributed as in the case of the moment to the densification of the surrounding soil which prevented the pile from experiencing high lateral displacements.

### *3.2* Experimental p-y curves and comparison with DNVGL p-y curves

The design of the pile under lateral load is nowadays based on the use of the load-transfer method which uses different p-y curves with the level of the soil.

Figure 5 shows the p-y of the installed piles until the depth of 5 pile diameters which considered sufficient to understand the behaviour of the upper sand layer above the rotation point. The p-y curves of the 100×g pile show a stiffer initial response at all the studied depths. Moreover, at depths of 1B and 2B where the p-y curves begin to converge, the 100×g pile gives a higher final limit than the pile installed at 1×g. This improvement in the behaviour of the in-flight pile is undoubtedly related to the densification of the surrounding soil and the augmentation of the horizontal stresses.

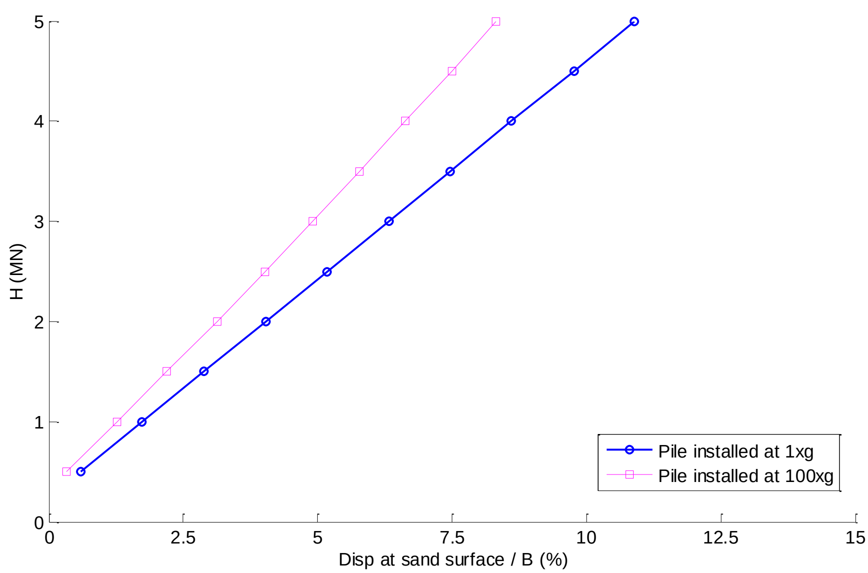


*Figure 4. Piles displacement at sand surface*

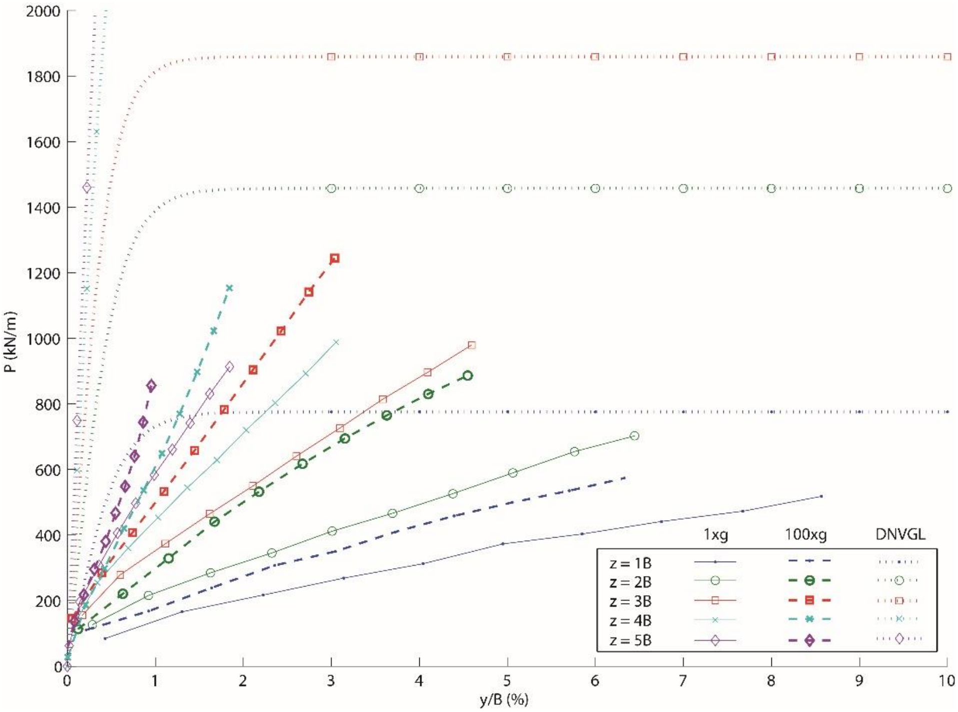


*Figure 5. P-y curves*

The p-y curves obtained using the DNVGL design code are also plotted in Figure 5. The DNVGL p-y curves give an initial stiffness reaction much higher than the experimental results. Pile in flight installation appears to reduce the difference between DNVGL and experimental initial stiffness, the DNVGL initial stiffness remaining, however, significantly higher.

These results seem in good accordance with the work of Kim et al. (2004) where the soil-pile reactions of driven piles showed to be larger and stiffer than the preinstalled piles. Kim et al. (2004) also has related this phenomenon to the densification of the ground around the pile and the increase of the effective horizontal soil stress with pile driving. The work of Dyson and Randolph 2001 where they studied a pre-installed, jacked at 1×g, jacked at 160×g and driven pile at 160×g showed also similar results.

## 4 CONCLUSIONS

The effect of the installation method on the lateral response of the pile installed in Fontainebleau NE34 sand was studied using centrifuge modelling tests. A new experimental device has been developed to be able to jack the pile and then load it laterally without stopping the centrifuge. The model pile is instrumented with strain gages inside its wall. Thus the profile of the moments along the pile can be calculated during loading. By double derivation of this profile, the reaction of the soil is obtained and by double integration, the lateral displacement of the pile is found. The experimental P-y curves can then be plotted at different levels in the massif.

The pile installed at 100 × g has a more curved moment profile and generates less displacement than the pile set up at 1 × g in the pile. Also the experimental P-y curves of the pile jacked in flight are more rigid. This is a consequence of the densification of the soil and the increase of the lateral pressures around the pile during it jacking in flight. On the other hand, the experimental P-y curves are much less rigid than those obtained by the DNVGL considered as reference for the offshore wind turbines.

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