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Probabilistic structural assessment of conical grouted joint using numerical modelling

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A B S T R A C T

Conical grouted joints have been proposed as a solution for the relative settlement observed between the sleeve and the pile on monopiles for wind turbines. In this paper, the influence of the design parameters such as steel wall thicknesses and conical angle on the failure modes associated to continual loadings are assessed based on finite element analysis. It is found that both the sleeve's and pile's wall thicknesses have a significant impact on the grouted joint health. Namely, the larger are the wall thicknesses, the more vulnerable the grout is with respect to fatigue and material degradation but the more limited the progressive settlement is, and inversely. This implies that the appropriate wall thicknesses should be chosen by designers having in mind that neither extreme is conservative. Based on statistical modeling, the grout length is found to be the most influential parameter of the settlement caused by extreme loadings: longer grout significantly contributes to the reduction of extreme settlement. To ensure that the inevitable settlement does not jeopardize the joint's structural integrity, a probability-based method has been developed to estimate the minimal gap between the pile top and the brackets required to achieve a targeted annual reliability index (of 3.3).

1. Introduction

In order to support the wind turbines placed at seas, monopile substructures are the most frequently employed types in commercial wind farms (Kallehave et al., 2015). Relying on experience from the Oil and Gas industry, the connections between the transition piece and the monopile for wind turbine support structures are made by the means of grouted joints. Classically, the grouted joints for monopile substructures are built from the overlap of two cylindrical tubes: a transition piece and a pile, and the resulting annular gap is filled with a high strength concrete. The grouted joints are efficient as they are easily constructible and they serve to correct the pile misalignment due to driving errors (Schaumann et al., 2013) as presented in Fig. 1.

A typical construction process follows few steps: (1) the transition piece is jacked up at the pile top edge using jacking brackets; (2) the concrete is poured in the annulus and left for curing; and (3) after the concrete has hardened, the jack-ups are removed and the transition piece holds due to the passive friction resistance at the contact faces between the layers. The passive friction resistance is made of two contributions, which are the chemical adhesive bond between the concrete and the steel and the mechanical interlock between the rough concrete surface and the undulations on the steel surfaces. An additional contribution, Coulomb friction, is generated during the loading operations by the normal-to-the-interface components of the loads transferred from the transition piece to the pile.

After few cycles, gaps open between the grout and the steel walls at the connection top and bottom; the adhesive bond deteriorates and cannot recover. Furthermore, the friction abrades the geometrical imperfections at the adjacent surfaces over the whole connection length. At very early age of the structure, the two initial contributions depreciate and only the coulomb friction persists, which is only effective when the normal pressure is present. In case of insignificant normal pressure, the shear resistance may not support the weight of the structure anymore and the transition piece will progressively slide downwards until the jacking brackets touch the pile top edge: the connection fails.

This failure mode has been observed in some commercial wind farms (Dallyn et al., 2015). In order to constantly keep the shear resistance, two principal solutions were proposed (DNVGL, 2016a), (DNVGL, 2016b): the conical grouted joint and the shear-keyed grouted joints. Fig. 2 illustrates both proposed solutions.

The conical grouted joint is derived from the convention grouted joint by imposing a small conical angle (1°–3°) to the overlapping tubes. With

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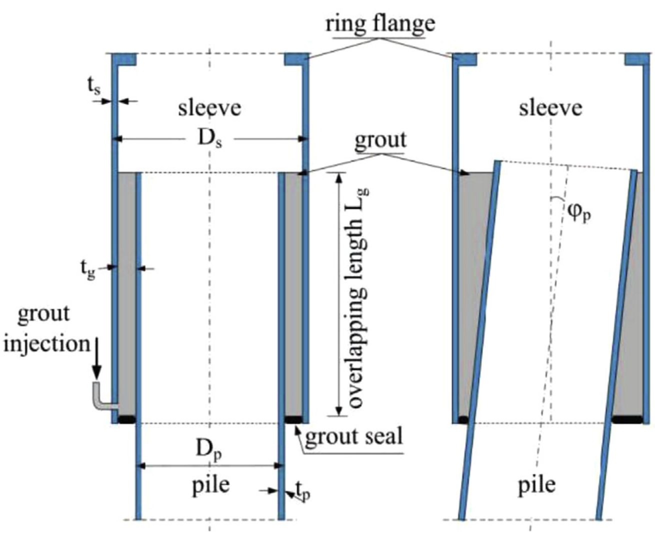

Fig. 1. Grouted joint with plain cylindrical tubes (Schaumann et al., 2013).

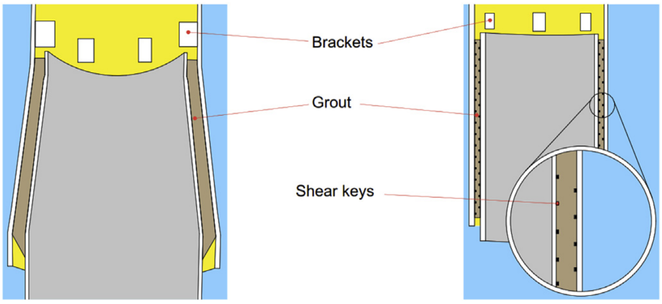

Fig. 2. Conical grouted joint (left) and shear-keyed cylindrical grouted joint.

the conical angle, the effect of the structure weight on the connection decomposes into a shear component along the contact faces and a normal component to the contact faces. The latter component generates a permanent coulomb friction resistance, which prevents the failure described above. The alternative solution adds shear keys to the inner faces of the steel walls close to the connection middle in order to enhance the mechanical interlock: the resulting friction resistance is said active. It is not advisable to put shear keys close to the connection edges as the gap openings will nullify their effect. In either solution, as the passive mechanical interlock and the adhesive bond are ephemeral, it is realistic to carry out analysis without accounting for their respective contributions (Nielsen, 2007). As many studies devoted attention to the shear-keyed grouted joints, e.g. (Schaumann et al., 2013), (Dallyn et al., 2015), (Lotsberg, 2013), (Lotsberg et al., 2012), (Schaumann and Raba, 2015), (Schaumann et al., 2014), this work will focus on the conical solution, which is also addressed in (Lotsberg et al., 2012), (Lee et al., 2014) for example. Whereas Lotsberg et al. (2012) (Lotsberg et al., 2012) have introduced the concept of conical grouted joints as a solution to limit settlements, Lee et al. (2014) (Lee et al., 2014) have presented a reliability-based design optimization method for conical grouted joints. They have considered various limit states except the grout degradation and the progressive settlement, which has been proven crucial for grouted joints.

This article aims at investigating the behavior under continual loadings of the conical grouted joint based on detailed finite element analysis. Over years, in addition to fatigue, the grout material will progressively lose its elastic modulus (Nielsen, 2007), (The International Federation for Structural Concrete, 2010), which might impact the support structure stiffness. The influence of the design parameter such as pile's wall thickness, transition piece's wall thickness, and conical angle on the grouted joint performance under continual loadings will be assessed.

Although the conical shape of grouted joints will reduce the progressive settlement of the transition piece, its vertical displacement cannot completely be precluded as materials have finite elastic moduli. Even if appropriate designs lead to acceptable progressive settlement at the end of their lifetime under normal conditions, higher vertical displacement can be expected after extreme events. Therefore, provisions should be given such that extreme settlements do not close the gap between the brackets and the pile top. Otherwise, loads will not follow the same path or be transferred anymore as intended. Hence, a procedure to estimate the minimum gap between the brackets and the pile top required to achieve a targeted annual reliability index (of 3.3) is established. This problem formulation is preferred to counterpart that consists in designing the grouted joint in such way that the vertical settlement lies below a certain threshold. In fact, as long as the settlement is not excessive, the size of the gap will not strongly influence the remaining design features.

2. Site conditions, structure, and design constraints

2.1. Metocean conditions

The selected site is located in the North Sea at 53°13′04.0” N and 3°13′13.0” E and its metocean conditions are given by (Von Borstel, 2013). The operational wind range goes from 4 m/s to 25 m/s and is binned into 11 intervals whose centres are 2 m/s apart. Each mean wind speed bin is associated with a turbulence level as presented in Table 1. The expected values of the sea states are conditional on each mean wind speed. Pierson-Moskowitz or JONSWAP spectra are used to model the wave height in case of normal operations or extreme cases, respectively. The mean sea level (msl) is 26.0 m above the seabed. The verification of the grouted joint structure is done under loading cases corresponding to the wind turbine operations. For the continual loadings, the design load case DLC 1.2 (The international Electrotechnical Commission, 2005) is considered and for the extreme loading (design load case that drives the ultimate limit state), DLC 1.3 (The international Electrotechnical Commission, 2005) is used as it has been shown by (Njomo Wandji et al., 2017) to be critical at the grouted joint level. DLC 1.2 is characterized by the wind normal turbulence and DLC 1.3 by the wind extreme turbulence.

The wind direction distribution is depicted by Fig. 3 as indicated by Ref (de Vries, 2011).

From the metocean conditions of the selected site, a statistical model describing the extreme loading case is prepared as tabulated in Table 2. A probabilistic study is carried out only for the ultimate limit state whereas

Table 1

Metocean conditions (Von Borstel, 2013). The expected annual frequency only applies to the normal conditions.

Mean wind speed [m/s]	Normal turbulence intensity [%]	Extreme turbulence intensity [%]	Significant wave height, Hs [m]	Peak period, Tp [s]	Expected annual frequency [hrs/yr.]
5	18.95	43.85	1.140	5.820	933.75
7	16.75	33.30	1.245	5.715	1087.30
9	15.60	27.43	1.395	5.705	1129.05
11	14.90	23.70	1.590	5.810	1106.75
13	14.40	21.12	1.805	5.975	1006.40
15	14.05	19.23	2.050	6.220	820.15
17	13.75	17.78	2.330	6.540	633.00
19	13.50	16.63	2.615	6.850	418.65
21	13.35	15.71	2.925	7.195	312.70
23	13.20	14.94	3.255	7.600	209.90
25	13.00	14.30	3.600	7.950	148.96