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Assessment of grouted samples from monopile wind turbine foundations using combined non-destructive techniques

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HIGHLIGHTS

- The NDT assessment of grouted samples from monopile offshore wind turbines is presented.
- The combined use of the UPV and X-ray techniques is discussed for the assessment.
- Clear correlations between pulse velocity and attenuation and porosity with compressive strength are revealed.
- A reliable, fast and relative low cost monitoring scheme is presented with great potential for in situ application.

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ABSTRACT

The vast majority of offshore wind farms uses wind turbines on monopile foundations for cost effective designs. These foundations are complex structures consisting of steel and a high strength cementitious grout that fills the annulus between the two concentric steel pipes known as monopile and transition piece. The grouted connection is potentially prone to structural failures when subjected to harsh offshore conditions due to combinations of extreme wind and wave excitations. Already grouting failures related to slippage of the transition piece relative to the monopile due to weakening of the adhesion between the grout and the steel have been observed at several windfarms during the construction phase. Therefore, a thorough investigation of the grouted connection is of utmost importance. In this study, a large population of cementitious cores were sampled from as many as four offshore wind turbines. The samples were subjected to Ultrasonic Pulse velocity (UPV) non-destructive testing (NDT) and compression testing while a smaller set of samples was subjected to X-ray analysis as well. This paper presents the results of the combined use of the UPV and X-ray techniques as well as correlations with compressive strength results and critically discusses the possibility of using the techniques for in situ application. To the authors' knowledge it is the first time that these techniques are applied for assessment of the grouted connection of offshore wind turbines on monopile foundations.

1. Introduction

The abundance of wind resource potential in swallow and deep-water seas is of worldwide growing interest and continuously forms a high motivation for increasing installations of new offshore wind farms. Until the end of 2014, a total of 2488 wind turbines had been installed and connected to the electricity grid in 74 offshore wind farms in 11 countries across Europe reaching a cumulative total installed capacity of 8 GW [1]. Most of these large-scale offshore wind farm projects use monopile foundation to obtain a cost effective design. More precise, 78.8% of the total number of installed substructures are monopiles [1]. These foundations contain pile–sleeve connections that basically consist of two concentric steel pipes cast together by means of grout (Fig. 1). This grout has significantly high design strength that can reach above 100 MPa. Despite the high initial quality of the material, its durability cannot be taken for granted because of the dynamic operational loads. Indeed, the primary loads related to this type of offshore wind turbines are the wind and wave induced vibrations and consequently overturning bending moments (Fig. 2). Therefore, the loads are transferred as a force couple in the top and the bottom of the grouted region. Due to this alternating moment loading, there is a serious possibility of wear on the sliding surfaces and hence a reduction in the axial load bearing capacity (Fig. 2). Moreover, at several windfarms, during the construction phase it

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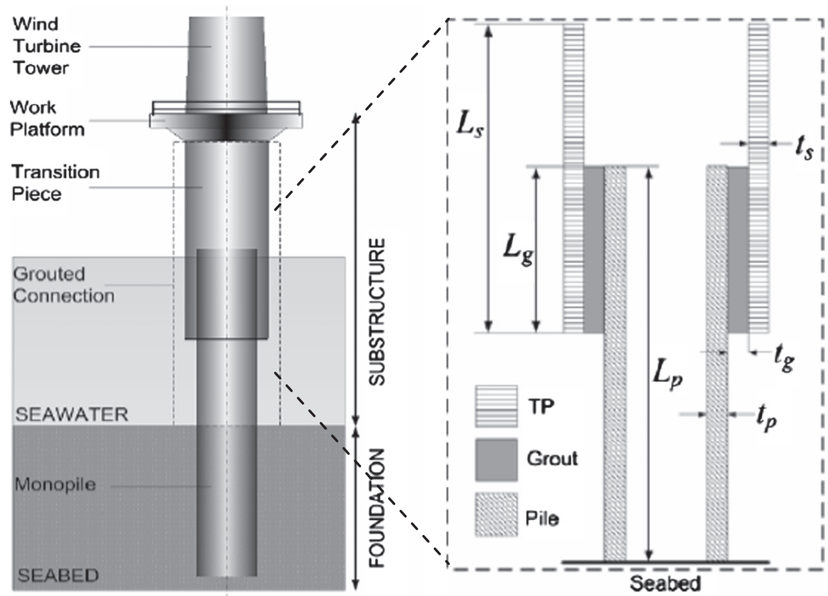

Fig. 1. Lower part of the tower-foundation system of a wind turbine on a monopile foundation (left) and detailed view of the MP/TP interface (right).

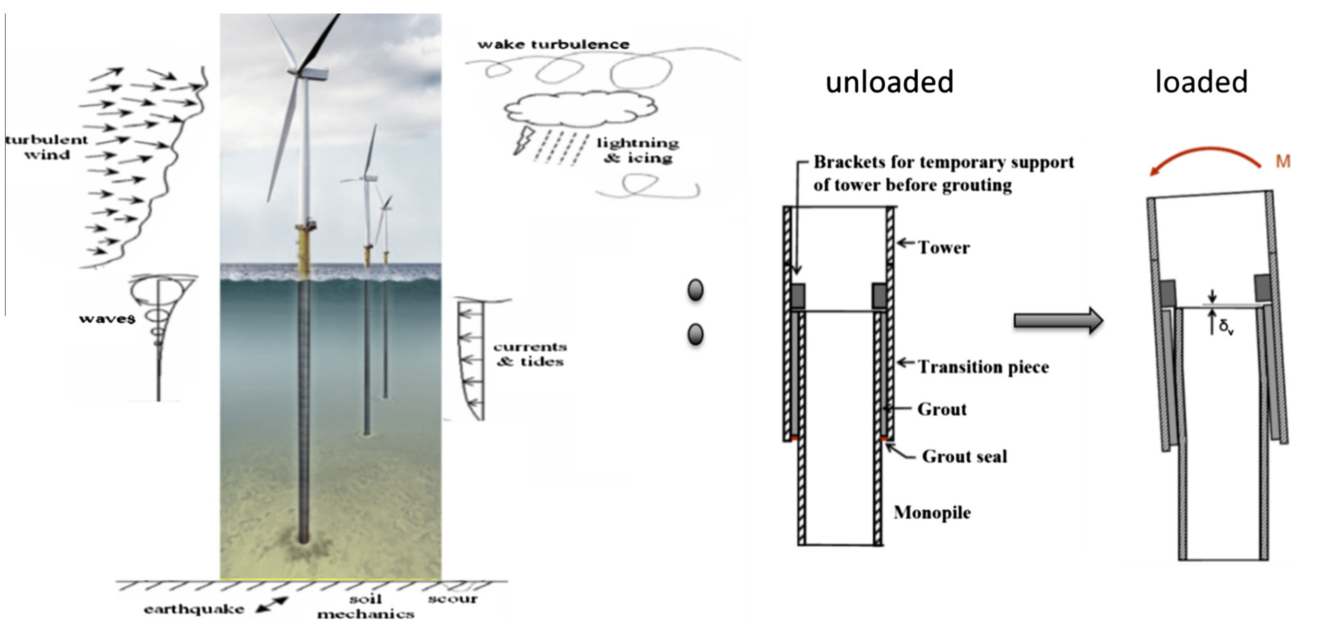

Fig. 2. Loading conditions of an offshore wind turbine on monopile foundation.

is noticed that the transition piece (Fig. 1) is slipping downwards. One of reasons for the slippage is the so called "ovalization", which is the change of the circular cross section to ellipsoid, according to various Root Cause Analyses undertaken amongst others by DNV et al. [2].

Two reasons are mainly responsible for this ovalization. The first is related to the unintentional tapering of the grout annulus due to possible misalignment of the transition piece and the monopile. The second is related to a reduction of stiffness of the members as the structures are increasing in size (length) in order to capture more energy at higher levels. This "upscaling" of the offshore wind turbines increases their susceptibility to load induced deformation causing this change in cross section shape.

As a result of weakening of the adhesion between the grout and the steel, the slippage that is occurring can cause possible further damage to the grout during extreme operational conditions requiring mitigation to avoid further degradation. For offshore wind, the costs for Operation and Maintenance are estimated in the order of 30–35% of the Costs of Electricity. Roughly 25–35% is related to preventive maintenance and 65–75% to corrective maintenance [3,4]. One of the approaches to reduce the cost for corrective maintenance is the application of condition monitoring for early failure detection and accumulative fatigue damage estimations [5]. Acquiring an early indication of structural or mechanical problems allows operators to better plan for maintenance, possible operate the machine in a de-rated condition rather than take the turbine off-line, or in the case of an emergency, shut the machine down to avoid more severe damage. In such a way, the repair costs are less than the costs of replacing components after total failure. In order to eliminate the ambiguities and assess the strength of the