Engineering Structures 113 (2016) 89–102

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental investigation on the development of wear in grouted connections for offshore wind turbine generators

Paul Dallyn [a,*], Ashraf El-Hamalawi [a], Alessandro Palmeri [a], Robert Knight [b]

[a] School of Civil and Building Engineering, Loughborough University, Leicestershire, England, United Kingdom
[b] Civil Engineering, E.ON Technologies (Ratcliffe) Limited, Nottingham, England, United Kingdom

ARTICLE INFO

Article history:
Received 10 October 2014
Revised 9 November 2015
Accepted 16 November 2015

Keywords:
Grouted connection
Integrity assessment
Offshore structures
Wear development
Wind turbines

ABSTRACT

Relative displacements between grout and steel have been observed in grouted connections used for offshore wind turbine substructures, which appear to be linked to the unexpected settlements that have occurred in some offshore wind farms. A literature review has highlighted a lack of understanding of the implications that this relative movement has on the grout wear. Experimentation has therefore been undertaken to determine the influence of various factors on the wear development, including compressive stress, displacement amplitude, surface roughness and the presence of water, looking at conditions typically experienced by offshore grouted connections. These experiments have indicated that wear of the steel and grout surfaces occur, even at low magnitude compressive stresses. The presence of water has the most significant impact on wear rate, being up to 18 times higher than for the equivalent dry condition. The presence of water can also significantly reduce the coefficient of friction to values lower than typically recommended for evaluation of grouted connections. These findings demonstrate that wear of the grouted connection is likely to occur over the life of this type of offshore structures and should therefore be considered when evaluating their integrity and assessing their behaviour.

1. Introduction

Grouted connections have extensively been used in the oil and gas industry for decades, but in recent years their use has proliferated in the offshore wind industry as an efficient method of joining the monopile (MP), embedded in the sea bed, to the transition piece (TP), which connects to the wind turbine generator (WTG) tower. In comparison to grouted connections used in the oil and gas platforms, offshore WTG connections have considerably lower radial stiffness with pile diameter to thickness ratios greater than 85, compared to 45 typically for oil and gas. However, lower length to diameter ratios exist with WTG connections, having generally 1.5 times pile diameter overlap compared to oil and gas connections with up to six times overlap, and a higher ratio of moment to axial loads with WTG grouted connection typically experiencing twice the moment to axial force compared to a quarter in oil and gas connections. They consist of a larger diameter circular section placed with overlap, of typically greater than 1.5 diameters, over a smaller diameter circular section, with the resultant annulus between the two sections filled with high strength grout. A typical offshore wind turbine foundation example is depicted in Fig. 1.

The concept of a straight-sided sleeved grouted connection without shear keys had been used for over 650 installed monopiles for several commercial offshore European wind farms, representing around 60% of all installations in Europe [1] up until 2011, when the last of the pre-2010 designed foundations were installed. Following the announcement in 2009 of unexpected settlements of the TP relative to the MP in many offshore wind farms, existing grouted connections have required extensive monitoring assessments and remedial works. This has resulted in a shift away from straight-sided grouted connections without shear keys as the primary load transfer mechanism for offshore wind turbine structures.

Site inspections have shown unexpected settlements resulting in hard contact and load transfer between verticality jacking brackets and the top of the MP, which indicate that the connection has an insufficient axial capacity. The capacity initially develops mainly as a shear resistance due to the surface irregularities mobilising friction, but partially due to adhesion between the grout and the steel. As a result of the overturning moment at the base of the tower, however, an increased shear stress as well as compressive stress is created between the grout and the steel and, if the shear stress at that position exceeds the grout–steel friction resistance,

* Corresponding author.
E-mail addresses: P.A.Dallyn@lboro.ac.uk (P. Dallyn), A.El-hamalawi@lboro.ac.uk (A. El-Hamalawi), A.Palmeri@lboro.ac.uk (A. Palmeri), Bob.Knight@eon.com (R. Knight).

http://dx.doi.org/10.1016/j.engstruct.2015.11.028
0141-0296/

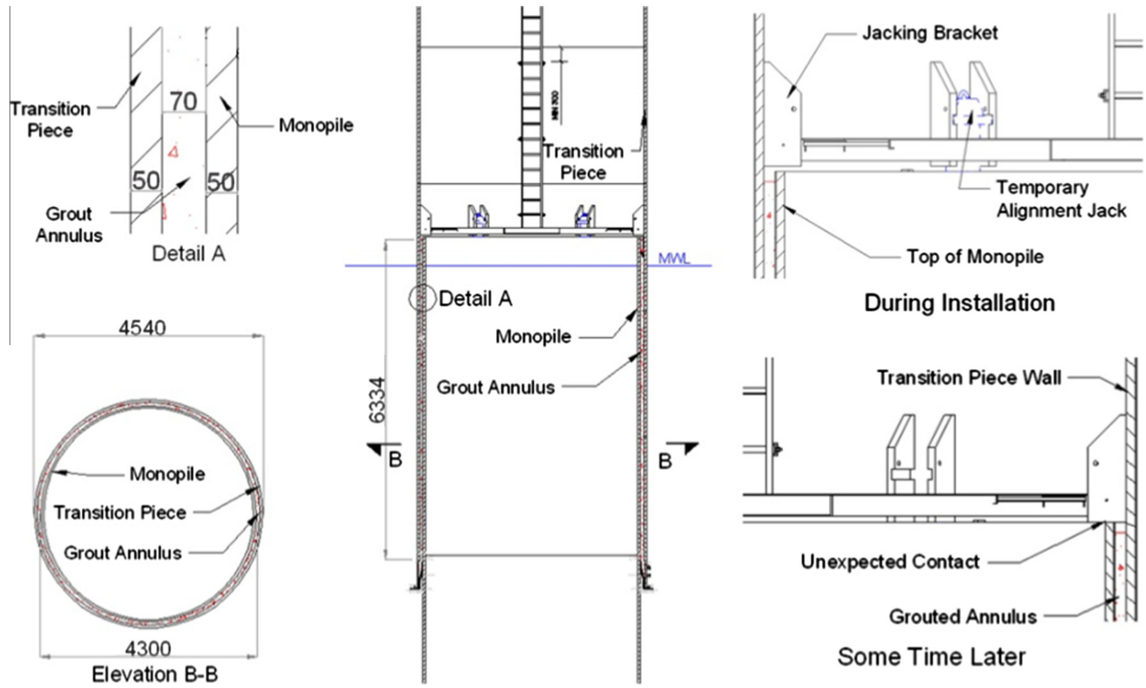

Fig. 1. Typical grouted connection general arrangement.

a relative displacement between the steel and grout occurs. These relative displacements between the MP and the TP are often in excess of 1 mm. They have been observed by subsequent structural condition monitoring, and appear to occur during changes in overturning moment caused by turbine cut-in and cut-off as well as variations in the wind direction and wind speed. The load transfer mechanism is illustrated in Fig. 2.

For full axial capacity of the connection to be mobilised, a relative movement between the steel and grout is required and so small relative displacements should be expected. However, due to the cyclic nature of the loading experienced by the grouted connections, this repeated relative movement has led to degradation of the axial capacity, with a global downward movement in the TP relative to the MP. Importantly, this combination of potentially high compressive stress and relatively large displacements could result in wear at the grout–steel interaction surfaces.

The remedial solutions that have been proposed so far to address this problem typically consist of additional steel brackets and elastomeric bearings installed between the TP and MP. However, the connection still relies on the grout to transfer the bending moments from the TP to the MP and therefore its integrity over the design lifespan of the foundation remains crucial.

Further, the potential for wear, and insufficient axial capacity in non-shear-keyed grouted connections is potentially worsened by water ingress that has been reported at some sites, although not considered in the original design.[1] A literature review undertaken by the authors [2] has revealed that there is a lack of detailed knowledge of the behaviour of the grouted connections, not only for the scale and size of actual structures, but also under the loading and environmental conditions of operation, particularly because the design principles in the existing standards up to 2011 were based on small-scale experimental testing from the oil and gas industry [3–6]. High-strength grout had also only been tested for compressive strength and single axis fatigue by manufacturers and limited testing had been undertaken for some of the conditions relevant for offshore wind turbine foundations [7–10].

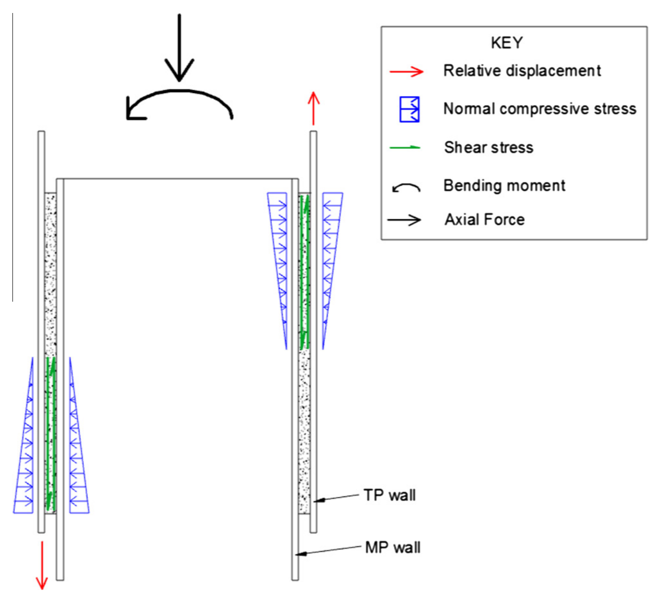

Fig. 2. Load transfer mechanism.

Overall, the behaviour of the grout–steel interface over long-term service operation is not fully understood within industry and scientific community. Testing has been recently carried out [11–15], but some areas of concern, such as grout wear and environmental conditions, had not been investigated. As a result of the JIP on grouted connections DNV amended DNV-OS-J101 standard [16] to ensure wear failure mode is considered during design. In particular, if wear is occurring and the water ingress provides transportation for the grout material worn down; gaps are likely to form between the grout and outer face of the monopile. This may lead to a lack of fit and some significant dynamic effects on

[1] Due to commercial sensitivity the sites cannot be named.