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Evaluation of full scale shear performance of tension anchor foundations: Load displacement curves and failure criteria

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A B S T R A C T

One of the biggest challenges faced by the offshore wave and tidal energy industry is the high cost of constructing and installing offshore foundations. Foundations based on post tensioned pile anchors can be effectively proposed to tackle this issue. A series of full-scale direct shear tests were performed on-shore to evaluate the shear resistance of post-tensioned pile anchor foundations designed for securing tidal turbine devices to a rock seabed. We focused, in particular, on the primary shear resistance mechanism of post-tensioned anchors, by applying a vertical force which mobilizes, a frictional force able to resist horizontal thrusts. Different load paths, involving monotonic or cyclic loading, were applied; several configurations for the footing of the foundation were tested. The footing stress-displacement behavior and the stress conditions at sliding failure from a number of different testing configurations were compared and analyzed. A marked consistency with the shear performance of natural rock joints was identified. This allows the behavior of tension pile foundations subjected to substantial horizontal loads to be modeled using relationships developed for rock joints, widely available in the literature. Additionally, the results obtained from different tests were also collated considering the various configurations adopted for the foundation-rock system and the applied load paths, to identify the factors that affect the shear resistance of the foundation.

1. Introduction

Among the most promising sources of renewable energy, the harvesting of electrical power from wind turbines or wave/tidal power generators, is a key resource in the area of the British Isles, because of the vast potential of offshore energy reserves (UK Government, 2003; DETINI, 2009; Renewable UK, 2013; EMEC, 2016). In this context, a critical problem currently encountered by civil engineering is the realization of adequate foundation systems for wind/wave/stream offshore turbine devices. These foundations must be capable of connecting these structures to the seabed and of transferring the loads applied to the turbines safely to the ground (e.g. Adhikari and Bhattacharya, 2011; Bhattacharya et al., 2012; Abhinav and Saha, 2015). These demanding engineering tasks significantly affect the installation costs of such turbines and may constitute up to 35% of the installed cost (Byrne and Houlsby, 2003). This influences negatively the cost competitiveness per megawatt when compared to energy from fossil fuels (DETINI, 2009).

Over recent years, several foundation solutions for tidal power generators have been developed and implemented. The most common solutions, that have been used for a range of different environments (e.g. water depth, nature of seabed), are: gravity foundations (e.g. McLaughlin and Harvey, 2016), piled foundations (e.g. Whittaker et al., 2007; Spagnoli et al., 2013), moored foundation solutions (Jeffcoate et al., 2015; Scotrenewables, 2016;), tripods with buckets and suction buckets. The advantages and disadvantages of each of these systems have previously been established (IEA – RETD, 2012). Considering the need to meet challenging engineering requirements and to reduce construction and deployment costs, the offshore foundation industry is continuously evolving, with new or hybrid solutions being developed. Recently, the use of foundations for tidal turbines based on post-tensioned anchors has been proposed, jointly with a system for their efficient installation in offshore environments (Callan et al., 2012). This foundation type aims to provide the tidal turbine

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Nomenclature

A	area
α	asperity angle
c_O	cohesion intercept
d_h	shear, horizontal displacement
d_v	normal, vertical displacement
d_{vj}	vertical displacement related to the closure of the rock joint and failure of asperities (net deformation or closure)
d_{vr}	portion of vertical displacement due to solid rock compression
d_{vt}	total vertical displacement
f_h	shear, horizontal force
f_{ha}	horizontal asymptotic load of the f_h–d_h curve
f_v	normal, vertical force
φ_b	basic friction angle
K_j	stiffness number
K_{nji}	initial normal stiffness for rock joint closure or failure
K_{nri}	initial normal stiffness of solid rock compression
k_{si}	initial shear stiffness referred to the f_h–d_h curve
K_{si}	initial shear stiffness referred to the τ–d_h curve
n_j	stiffness exponent
R_f	failure ratio
σ_n	normal, vertical stress
σ_{na}	horizontal asymptote of the σ_n–d_{vr} curve
τ	shear stress
τ_a	horizontal asymptotic of the τ–d_h curve
τ_{max}	shear stress at failure
V_m	maximum achievable closure for a rock joint

with sufficient bearing resistance, whilst at the same time reducing the overall size of the foundation when compared to gravity based foundations (thereby reducing concrete requirements). This system consists of small-diameter hollow bars drilled in the rocky seabed and secured to the underlying rock volume by means of grout bond. When tensioned using hydraulic jacks, they apply a vertical force on the underwater structure that replicates the self-weight of a ballasted structure to ensure its stability (Fig. 1). The technology of post tensioned anchors (hereafter referred to as "tension anchors") is readily available and widely used for a range of onshore applications (e.g. as micropiles for foundations and anchorages, soil nails for reinforcing soil, slopes or tunnels; see for instance standards BS EN 14490, 2010, and BS EN 14199, 2015, within Eurocode 7, 1997). Conversely, the use of tension anchors in underwater applications is less common, because of the difficulties in tensioning the anchors in the subsea environment, where access and operating conditions might be extremely difficult; hence these topics are currently the subject of industry research and development (Callan et al., 2012; Meggitt et al., 2013; Tiwari et al., 2014). Additionally, underwater structures may be subjected to substantial horizontal loads, e.g. generated by tidal currents (de Jesus Henriques et al., 2014) or induced by wave action, that the foundations are required to resist. Studies found in the literature that discuss the performance of piles or anchors embedded in rock mainly focus on the evaluation of their shaft resistance (see for instance Gu and Haberfield, 2004; Serrano and Olalla, 2004, 2006) rather than on their behavior when subjected to significant shear forces.

To assess the potential of tension anchor foundations to resist significant horizontal loads, as typically found in a tidal environment, a set of full scale, direct shear tests were conducted. These tests were performed onshore, on a particular foundation primarily designed to fix tidal stream turbines to a rock seabed (Callan et al., 2012), constituted by a circular footing connected to the bedrock by means of a post-tensioned anchor. These trials are part of a wider experimental phase aimed at testing the performance of this foundation system prior to offshore installation in its planned working environment (i.e. a shallow sea, with a depth of few tens of meters, with substantial tidal currents). In the experiments presented in this paper, the tension anchor foundation supports a specifically designed test rig through which normal and shear loads are applied to the foundation (Figs. 2 and 3). This experimental apparatus was installed in a schist quarry (Ballykinler, Co. Down, Northern Ireland) in order to test the tension anchor system on a weathered, poor quality rock. Additional tests on other imported rock types were also carried out (e.g. sandstone, gritsone or granite rock, concrete). Several configurations for the footing of the foundation were adopted. Different loading scenarios were applied during the tests, including (1) monotonic loading until the peak shear strength was mobilized, and (2) bidirectional cyclic shear loading until failure. The resultant shear and normal displacements were measured at the foundation footing by means of linear variable differential transformer (LVDT) sensors.

In both the experimental and subsequent analysis phases, attention was focused on the primary shear loading resistance mechanism of post-tensioned anchors, by applying a vertical force which mobilizes a frictional force able to resist horizontal thrusts (Fig. 1). Indeed, the anchor itself also opposes horizontal movements; however, this mechanism comes into play at large displacements, when the rock-foundation footing coupling has already failed, and the anchor provides the residual shear resistance. The evaluation of the resistance provided by the anchor is, however, not within the scope of this work. Therefore, testing and analyses was focused on relatively small displacements, and failure was considered to occur when the foundation footing-rock adhesion fails, so that the footing "slides" on the rock surface, save for the constraint later posed by the anchor.

The experimental apparatus and details of the tests are described in "Experimental method" (Sections 2.1 and 2.2). The acquired datasets were studied and interpreted with reference to the scientific literature concerning the shear behavior of natural rock joints (Section 2.3). In this area of study, a wide range of works have focused:

i) on the analysis of load-displacement relations for rock discontinuities prior to failure (e.g. Kuhlawy, 1975; Hungr and Coates, 1978; Kulhawy, 1978; Bandis, 1980; Bandis et al., 1983);
ii) on the definition of criteria representing the state of stress at failure for rock discontinuities (e.g. Patton, 1966; Jaeger, 1971; Barton, 1973; Hoek and Brown, 1980).

For both aspects, the behavior displayed by the foundation footing-

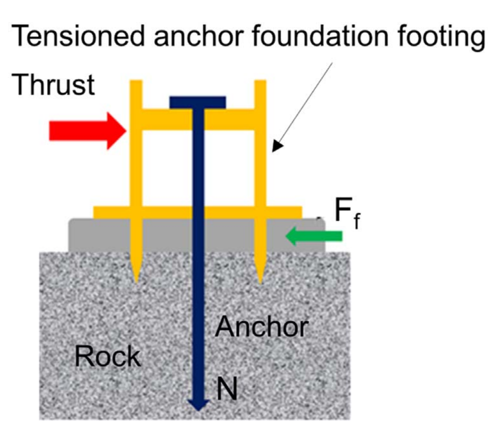

Fig. 1. Sketch of tension anchor foundation system. When the anchor is tensioned, a vertical force N (composed of tension in the anchor and self-weight) is applied to the structure to be secured. Consequently a friction force F_f is mobilized, which enables the structure to resist horizontal thrusts.