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Suitability of helical anchors for mooring a floating wave energy converter

Pertinence des ancres hélicoïdales pour l'amarrage d'un convertisseur d'énergie houlomotrice flottant

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ABSTRACT: Within a joint research project with industry and university partners a new type of floating wave energy converter is currently being developed at prototype scale. One aspect of the geotechnical research part is to investigate the suitability of helical anchors for mooring such a device. In floating offshore installations predominantly cyclic tensile loads of varying direction act on the mooring system, while the static load component is very small. For such load constellations, helical anchors may be an attractive alternative, because the possible tensile capacity can be significantly increased by arranging one or more screw plates along the lower part of the shaft. In this research project 1g laboratory model experiments in saturated sand at a model scale of approximately 1:8 have been carried out. Helical anchors with different geometries have been tested in monotonous pre- and post-cyclic pullout tests as well as in multistage cyclic load tests with or without pre-stressing of the anchors. The multistage tests reveal the importance of a reasonable pre-stressing of the anchors as it leads to a more continous accumulation behavior with stabilization of the displacement rate within the investigated load levels and numbers of cycles. The results of the pre-cyclic pullout tests, however, are only partly in agreement with available results from the literature due to possible effects from the installation process and the water saturation which needs further investigation.

RÉSUMÉ: Dans le contexte d'un projet de recherche conjoint avec des partenaires industriels et universitaires, un nouveau type de convertisseur d'énergie houlomotrice flottant est actuellement en cours de développement à l'échelle de prototype. L'un des aspects de la partie recherche géotechnique consiste à investiguer la pertinence des ancres hélicoïdales pour l'amarrage d'un tel dispositif. Dans les installations flottantes extracôtières, des charges de traction de direction variable, essentiellement cycliques, agissent sur le système d'amarrage, tandis que la composante de charge statique est très faible. Pour de telles constellations de charges, les ancres hélicoïdales peuvent se révéler une alternative intéressante, parce que la possible résistance en traction peut être significativement accrue en prévoyant une ou plusieurs plaques vissées le long de la partie inférieure de l'arbre. Dans ce projet de recherche, des expériences de modélisation en laboratoire 1g ont été menées en sable saturé avec des maquettes à l'échelle d'environ 1/8ème. Des ancres hélicoïdales de géométries différentes ont été testées lors d'essais d'arrachement monotones pré- et post-cycliques, mais aussi lors d'essais de charge cycliques multi-étages avec ou sans précontrainte des ancres. Les essais multi-étages révèlent l'importance de pré-contraindre raisonnablement les ancres puisque, dans le contexte des niveaux de charge et nombres de cycles étudiés, cela permet plus de continuité dans le comportement d'accumulation, avec stabilisation de la vitesse de déplacement. Toutefois, les résultats des essais pré-cycliques d'arrachement ne sont que partiellement d'accord avec les résultats proposés dans les publications scientifiques pour la raison de possibles effets émanant du processus d’installation et de la saturation de l’eau qui nécessite de plus amples investigations.

Keywords: Wave energy; helical anchor; model tests; saturated sand; cyclic loading

1 INTRODUCTION

1.1 The NEMOS system

The research presented in this paper was focused on the NEMOS wave energy converting system which is under development since 2011. As illustrated in Figure 1 the NEMOS converter is an arrangement of an elongated floating body and three ropes controlling the motions of the floater. The working rope directly connects the floater with the tower which houses the generator system. Two guiding ropes indirectly connect the floater with the tower by leading them through pulleys at seabed level. This enables the floater to continuously align itself to the current wave direction. In harsh conditions the floater can be pulled down out of the wave zone to avoid damage to the system (NEMOS 2018).

The technical and economic feasibility of the NEMOS system in full scale was examined in a joint research project with partners from industry and research funded by the German Federal Ministry for Economic Affairs and Energy. As a main result of this project, a prototype converter will be erected off the Belgian coast in 2019.

This research project not only covers the development of the structural layout of the converter, but also addresses adequate foundation solutions for the prototype structure. The main research aspects in this part are identified in the following section.

1.2 Geotechnical research aspects

In floating offshore installations predominantly cyclic tensile loads of varying direction and magnitude act on the mooring system, while the static load component is very small. In contrast to conventional foundations such as gravity based or pile foundations, especially helical anchors can be an interesting alternative, because with a given shaft diameter the tensile capacity can be significantly increased by arranging one or more screw plates (helices) along the the shaft. Helical anchors are further considered to be economical due to an efficient use of materials and a fast installation procedure appropriate ground conditions provided. Added to this, the noise emissions during installation are limited which is a great advantage compared especially to driven piles. Accordingly, e.g. Newgard et al. (2015) suggested their use for offshore wind turbines.

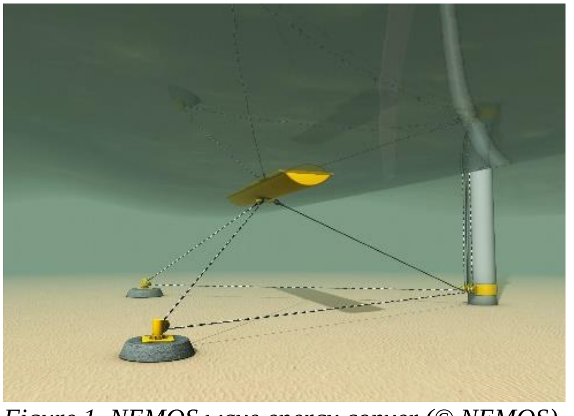

Figure 1. NEMOS wave energy conver (© NEMOS)

However, especially the bearing behavior of helical anchors in saturated sand under cyclic loading of different levels and amplitudes resulting from wave impact has not yet been thoroughly investigated. In (Narasimha Rao & Prasad 2008) small scale model tests in soft marine clay were analysed. Schiavon (2016) conducted ng centrifuge tests in dry sand and

Newgard et al. (2015) performed scale model tests in saturated sand but with different loading conditions. The presented research project therefore investigated the bearing behavior of helical anchors in 1g scale model tests in saturated sand. The experimental setup and results of pre- and post-cyclic pullout tests as well as cyclic multistage tests are discussed in the following.

2 EXPERIMENTAL SETUP

The 1g model tests were conducted in a cylindrical steel tank of 1.90 m in height and a diameter of 1.60 m (Figure 2, left). The test soil was a medium to coarse sand. Its basic properties are provided in Table 1. The sand was filled into the tank by pluviation from a container via a tube with an attached mesh for a uniform sand distribution. By adjusting the pluviation height a pre-determined soil density could be achieved. The density was controlled via cylindrical cans placed in three layers over the soil mass during pluviation. After soil placement the sand was saturated by filling the tank gradually with water from the bottom. All tests were conducted in dense sand with a relative density of approximately 0.89 and an effective angle of internal friction of about 43°.

Four model anchors each with one helix of varying diameter D were used (Figure 3). The anchors were closed-ended with a conical tip and a shaft diameter of 30 mm. They represent a model scale of about 1:8 in comparison to a full-scale anchor for the expected conditions at the NEMOS prototype location. The model scale was derived on the basis of a preliminary design using the design approach of (Ghaly et al. 1991).

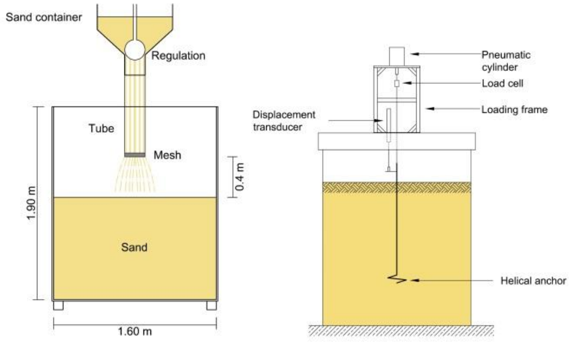

Figure 2. Experimental setup of tank with sand pluviation (left) and loading arrangement (right)

Table 1. Parameters of the test soil

parameter	value
grain density ρ_s	2.64 [g/cm³]
coefficient of uniformity C_u	2.6 [-]
maximum void ratio e_{max}	0.81 [-]
minimum void ratio e_{min}	0.49 [-]
dry density ρ_d	1.69-1.72 [g/cm³]

Table 2 summarizes the main anchor geometry for anchors S4 to S7 and the number of conducted pullout tests. The type of installation process is also given with "p" indicating that the anchor was placed during sand pluviation and "s" meaning that it was screwed in after sand placement. However, the rotational speed was very slow due to limitations in the current test setup and not specifically measured.

Figure 3. Model anchors S4 to S7 (from left to right)

The embedment depth was H = 1.0 m in all tests which means, that the relative embedment depth varied in the tests as indicated in Table 2. Nevertheless, according to (Ghaly & Hanna 1994) all anchors were expected to fail in a shallow failure mode reaching the soil surface which was visually confirmed in the tests.

In the monotonous pullout tests the anchors were pulled displacement-controlled by an indoor crane with a constant rate of 20 mm/s which was the lowest possible value of the crane. For application of the cyclic load, three different pneumatic cylinders were used to cover a load spectrum between 0.2 kN and 28 kN for the tensile force. The applied load was measured by different load cells depending on the load range, the anchor displacement by a displacement transducer mounted on the loading frame as indicated in Figure 2 (right).

Table 2. Summary of conducted pullout tests with measured pre-cyclic pullout capacities Q_u

Type	Test No. - installation method	D [mm]	H/D [-]	Q_u [kN]
S4	1-p	100	10	8,5
	2-s			9,0
	3-s			9,1
	4-s			8,9
	5-p			9,4
	6-p			9,6
	7-s			9,5
	8-s			7,0
	9-s			5,6
S5	1-p	120	8.3	14,9
	2-p			12,3
	3-p			11,8
S6	1-p	150	6.7	19,5
	2-p			16,9
	3-p			17,0
S7	1-p	200	5	25,9
	2-p			23,1
	3-p			20,0

The cyclic load tests were performed on anchor S4 (placed) as multistage tests. This means, in one test with one given test setup the level of cyclic loading was kept constant for a certain number of cycles, after that the cyclic load was increased to the next load level which was applied again for a certain number of load cycles and so on. The level of cyclic loading was determined by the cyclic load ratio CLR which is defined as:

$$CLR = \frac{F_{cyc}}{Q_{u,mean} - F_{min}} \tag{1a}$$

$$F_{cyc} = F_{max} - F_{min} \tag{1b}$$

Where F_{max} (kN) is the maximum load and F_{min} (kN) the minimum load, which is either zero or corresponds to an applied pre-stress. With that, F_{cyc} (kN) is the cyclic load range, whereas $Q_{u,mean}$ (kN) is the mean of the measured pullout capacities. In Equation (1a) the pre-stress F_{min} is subtracted from the available pre-cyclic pullout capacity Q_u as it already mobilizes a part of this capacity. Three pre-stress conditions were considered with F_{min}/Q_u = 0.00/0.05/0.10. The static pre-stress was applied first followed after a certain time lap by the cyclic loading according to the first load level. In each multistage test five load levels of CLR = 0.05/0.10/0.15/0.20/0.25 were applied. Each CLR was maintained for at least N = 10,000 load cycles. The load frequency was 0.1667 Hz.

3 MODEL TEST RESULTS

3.1 Pre-cyclic pullout capacity

The pullout capacity was determined for all anchors by multiple tests per anchor as shown in Table 2. It was defined as the peak of the respective load-displacement curve. Figure 4 shows the load-displacement curves from the tests on anchor S4 in which both installation methods were applied. Obviously due to the very slow installation speed there is no significant difference in the measured capacities from placed and screwed anchors. For further analysis the pullout capacities were expressed in dimensionless form as follows:

$$N_{qu} = \frac{Q_u}{\gamma \cdot H \cdot A_{Helix}} \quad (2)$$

Where N_{qu} (kN) is the dimensionless pullout capacity, H (m) the embedment depth, γ (kN/m³) the relevant unit weight of the soil and A_{Helix} (m²) the helix cross-sectional area. In Figure 5 the dimensionless pullout capacities from the conducted tests are compared to test results from (Ghaly et al. 1991), (Ghaly & Clemence 1998), (Tsuha et al. 2007), (Newgard et al. 2015) and (Schiavon 2016).

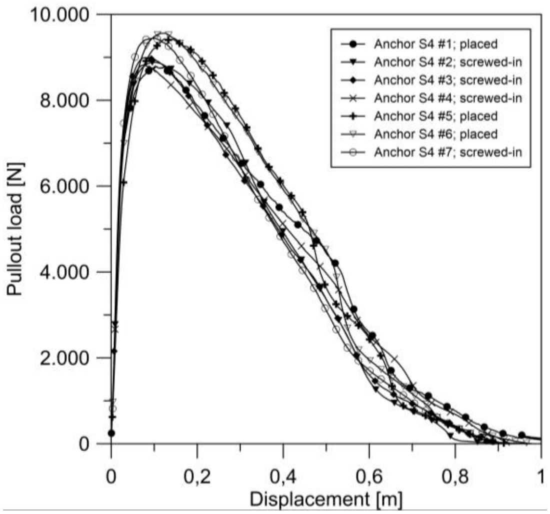

Figure 4. Load-displacement curves from monotonic pullout tests on anchor S4

From Figure 5 it can be stated that the measured capacities are in good agreement with the results from small scale model tests on dry sand presented in (Ghaly et al. 1991) and (Ghaly & Clemence 1998). On contrast to this, the pullout capacities presented in (Tsuha et al. 2012) and (Schiavon 2016), who conducted ng centrifuge tests on dry sand, are significantly smaller. This applies also to the results of (Newgard et al. 2015) for scale model tests on saturated sand. Due to the different test conditions, however, a comparison is difficult. Negative pore water pressure caused by the high pullout speed as well as a possible scale effects are assumed to have an influence on the measured capacities as well as the installation process.

In regard to the latter, two tests on anchor S4 were repeated later (No. 8-s and 9-s in Table 2) with a greater rotational speed during screwing. Indeed, the measured capacities for these tests are significantly smaller than the other test results for this anchor. This confirms that a more thorough study of the aforementioned effects is required which will be part of the future work.

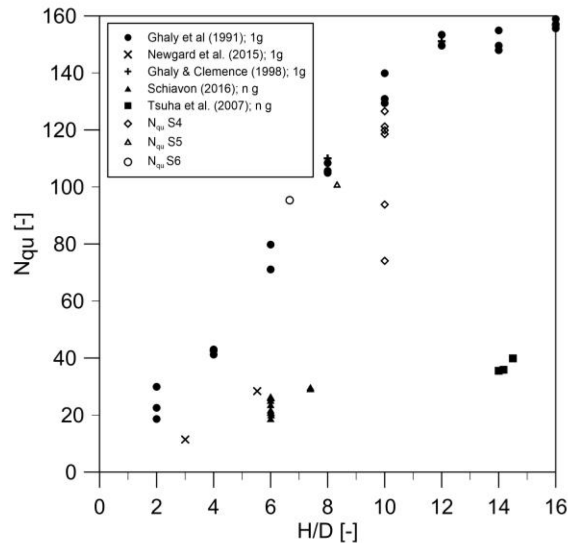

Figure 5. Comparison of measured pullout capacities with available test results

3.2 Anchor behavior under cyclic loading

Figures 6 and 7 show the accumulated deformations from the multistage tests on anchor S4 with a pre-stress of $F_{min}/Q_u = 0.00$ (no pre-stress) and 0.10 under increasing CLR from 0.05 to 0.25 in a semi-logarithmic plot. For each pre-stress three multistage tests were performed. For the determination of $Q_{u,mean}$ in Equation (1a) only tests S4 No. 1 to 7 in Table 2 were used.

Despite of a limited reproducibility of the tests, the accumulation curves in Figures 6 and 7 show a typical foundation behavior under cyclic loading which is similar e.g. to the one presented in

(Schiavon 2016) independently of the aforementioned different test conditions.

Especially in Figure 7 (pre-stressed anchor) a shakedown of the plastic deformations can be identified for very small CLR of 0.05. For larger cyclic load ratios up to CLR = 0.25 at least a stabilization of the deformation rate is observed within the 10,000 load cycles applied for each CLR indicating possible hardening without progressive failure. However, the accumulated displacements over one load level increase with increasing CLR.

Such an accumulation behavior can be expressed by an equation of the general form:

$$\frac{h_N}{D} = \frac{h_1}{D} \cdot a \cdot N^b \qquad (3)$$

Where h_N (mm) is the accumulated displacement (heave) after N cycles, h_1 (mm) is the displacement after the first cycle and D (mm) is the helical diameter. The parameters a and b determine the initial slope and the shape of the accumulation curves and depend on CLR and F_{min}. Such an expression is similar e.g. to the one recommended in (DGGT 2012) for predicting the accumulated head displacements of piles under cyclic lateral loading.

It has to be noticed that Equation (3) only expresses the accumulated displacements for one load level CLR. For varying load levels as in the multistage tests the resultant displacement of the anchor could be derived by superposition of the accumulated displacements for the each load level following the procedure of (Lin & Liao 1999) which is also suggested in (DGGT 2012). However, a thorough derivation requires further analyses on the basis of more tests under varying conditions which has not been done yet.

Considering now the displacements accumulated at the end of one multistage test it can be seen that its magnitude with about 100 mm is significant. The initial embedment depth of 1.0 m was reduced by approximately 10%. Assuming that the displacements shall not exceed 10% of the width or diameter of the construction element, which is 10% of the helical diameter of anchor S4 or 10 mm, this criterion will be exceeded already at load levels CLR between 0.10 and 0.15. This is indeed problematic especially as the number of load cycles is still small compared to real operational conditions. Though the NEMOS wave energy system is able to accommodate large anchor displacements, a more robust anchor layout is desirable which may be reached by use of multi-helix anchors and a greater embedment depth.

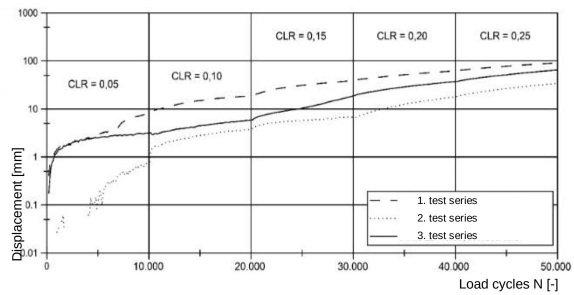

Figure 6. Accumulation of displacements over number of load cycles for different CLR and $F_{min}/Q_u = 0.00$

Overall, when again comparing Figures 6 and 7, especially at small CLR, it can be stated that a pre-stress leads to a more continuous progression of the accumulation curves and therefore improves the anchor behavior. On the other hand, the pre-stress should be limited as the magnitude of the accumulated deformations also increases with increasing pre-stress.

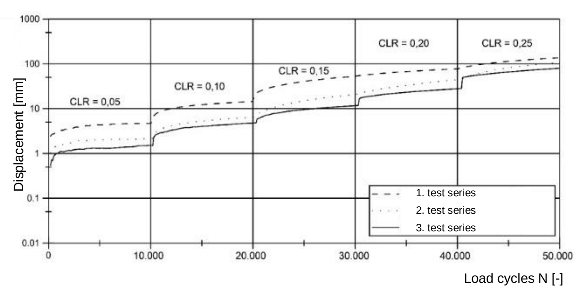

Figure 7. Accumulation of displacements over number of load cycles for different CLR and $F_{min}/Q_u = 0.10$

3.3 *Post-cyclic pullout capacity*

After selected cyclic load tests, the post-cyclic pullout capacity of the tested anchor S4 was determined. Overall, the loss of the pullout capacity was 30% on the average as compared to the pre-cyclic pullout tests.

Figure 8 shows the test results compared to results from (Schiavon 2016) in dimensionless form. Here, the ratio of the post-cyclic pullout capacity $Q_{u,post}$ over the mean value of the pre-cyclic pullout capacity of anchor S4 $Q_{u,mean}$ is shown depending on the maximum cyclic load defined as the ratio of F_{max} related to $Q_{u,mean}$. For the multistage test the largest load range, i.e. for CLR = 0.25, was considered. By doing this, possible scale effects are minimized as it can be assumed that the physical behaviour of the anchors is similar in both kind of tests, 1g small scale model tests and ng centrifuge tests.

Obviously, the results of (Schiavon 2016) indicate either a slight improvement or reduction of the available pullout capacity due to cyclic loading. In contrast to this the measured post-cyclic pullout capacities are significantly reduced for all pre-stresses.

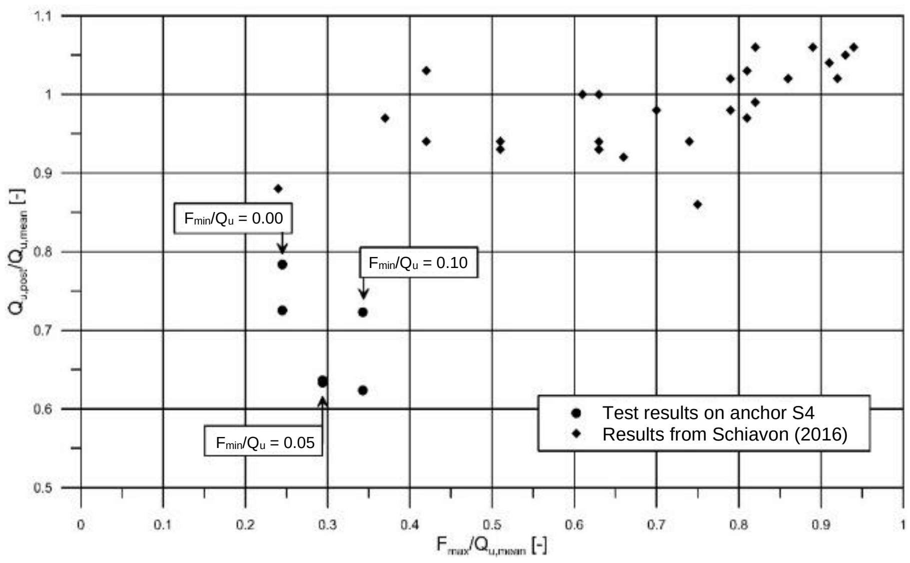

Figure 8. Comparison of the post-cyclic pullout capacity of anchor S4 with literature results

One reason for this may be again the installation process. In the work of (Schiavon 2016) the anchors were installed by screwing which possibly caused disturbance of the soil matrix above the helix. The following cyclic loading then led to a densification which improved the pullout capacity. In the tests presented here, the anchor S4 was placed during sand pluviation. Hence the soil matrix was in a dense state at the beginning of the cyclic multistage tests. Correspondingly, the soil above the helix loosend during cyclic loading which later caused the reduction in the post-cyclic pullout capacity. On the other hand, (Schiavon 2016) mainly performed tests with only one cyclic load level whereas in the multistage tests the soil around the anchor already experienced several cyclic load steps with comparably large numbers of cycles before reaching the maximum load level. This may have induced a much greater disturbance of the soil matrix.

4 CONCLUSIONS

The results of monotonous pre- and post-cyclic pullout tests as well as multistage cyclic load tests on helical anchors of various geometries and related embedment depth were presented.

The cyclic multistage tests showed that the application of a pre-stress leads to a more continuous accumulation behavior. Hence, pre-stressing is advantageous for the anchor behavior but should not be too large as it increases the magnitude of the accumulated displacements.

The results further revealed that shakedown of the plastic deformations can only be expected for very small cyclic load ratios and pre-stresses. At larger load levels of CLR up to 0.25 as investigated in this study, stabilization of the deformation rate can be observed. Overall, the accumulated displacements were relatively large even for a limited number of load cycles which could be critical for the behavior of a helical anchor under real operational conditions.

The investigations overall showed that the installation process plays a decisive role in the bearing behavior of helical anchors. Hence, the influence of installation effects on the pullout capacity and on the behavior under cyclic loading besides the effect of water saturation, relative embedment depth and the possible use of multi-helix anchors for improving the anchor behavior will be the main objectives for future research.

Nevertheless, the presented results help to improve the understanding of the behavior of helical anchors in saturated sand which can be helpful for the use of such anchors not only for wave energy converters but also for other offshore structures.

5 ACKNOWLEDGEMENT

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