

Experimental investigation of the dynamic installation of a slip joint connection between the monopile and tower of an offshore wind turbine

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Abstract. The failure of the traditional grouted connections of offshore wind turbines has led to the investigation of alternatives that provide a connection between the foundation pile and the turbine tower. An alternative to the traditional joint is a steel-to-steel connection also called a slip joint. To ensure a proper fit of the slip joint a dynamic installation of the joint is proposed. In this contribution, the effectiveness of harmonic excitation as an installation procedure is experimentally investigated using a 1:10 scaled model of the joint. During the dynamic installation test the applied static load, settlements and dynamic response of the joint are monitored using respectively load cells, taut wires and strain gauges placed both inside and outside the conical surfaces. The results show that settlement occurs only when applying a harmonic load at specific forcing frequencies. The settlement stabilizes to a certain level for each of the specific frequencies, indicating that a controlled way of installation is possible. The results show that it is essential to vibrate at specific frequencies and that a larger amplitude of the harmonic force does not automatically lead to additional settlement.

1. Introduction

At the end of 2012 more than 70% of the offshore wind turbines (OWT) were standing on a monopile (MP) foundation [1]. Most of these OWT's have a straight grouted connection between the transition piece (TP) and MP. In 2009, a visual inspection on the monopile support structures at the offshore wind farm Egmond aan Zee off the Dutch North Sea coast revealed that the grouted connections of the support structures were settling. A similar subsiding of the TP's with respect to the foundation pile was subsequently observed at most of the other wind farms in the North Sea. This resulted in an Joint industry project led by DNV and an update of the Det Norske Veritas (DNV) offshore standard for the design of OWT structures in 2011 [2]. The DNV standard now suggests to assume that no axial capacity is present in a straight grouted connection. This adjustment to the standard results in the necessity of a alternative transfer of the axial forces trough the joint.

An alternative to a TP with a grouted connection, depicted in figure 1(a), is the slip joint. A slip joint consists of two conical sections, one welded to the top of the foundation pile and the other to the bottom of the TP. The two cones fit closely inside the other in the same way as two inverted cups illustrated in figure 1(b). The load transfer mechanism is based on friction and the geometry automatically allows the transfer of axial loads. This joint has been applied



onshore in the Dutch Windmaster turbines in the early nineties and the connection did not show any signs of deterioration or progressive settlement over the years [3]. Up to this date no slip joints are installed offshore but this might change due to the renewed attention for alternatives for the grouted connection such as the slip joint.

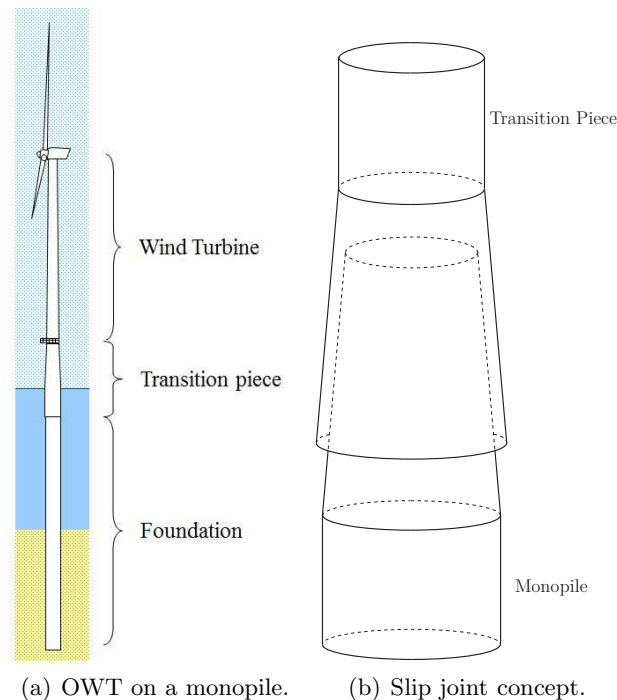


Figure 1. Explanatory figures of an OWT and slip joint

In Segeren & Lourens [4], it was shown that the installation of a slip joint under self-weight of the transition piece alone was not sufficient to ensure the desired overlap length. In that study, it was assumed that the cone angle of the top piece is slightly smaller than that of the bottom piece, to ensure a more durable fit. To install such a joint offshore, after the monopile has been installed, an additional forcing mechanism is therefore needed. In this contribution, the effectiveness of harmonic excitation as an installation procedure is experimentally investigated using a 1:10 scaled model of the joint. It is expected that with harmonic excitation around the natural/resonance frequencies of the system the desired settlement can be achieved. The goals of the test are to provide data for validation of future numerical models and prove that a controlled installation of a slip joint connection under self weight is possible provided that an additional harmonic load is applied at the top of the TP. Please note that the slip joint is part of the transition piece and that with self weight, the weight of the transition piece is meant.

2. Case study and scaling effects

2.1. Dimensions of the case study

The dimensions of the slip joint are based on the MP design of the OC3 project [5]. A MP of 6m in diameter with a wall thickness of 60mm is used as basis for the design of the slip joint. The desired overlap length, L_{overlap} , is defined as for classic grouted connections, i.e. $1.5 D_{\text{MP}}$, where D_{MP} is the diameter of the monopile. The cone angle of the TP, β , is smaller than angle of the conical part of the MP, α , as mentioned before. The dimensions of the TP are dependent on the cone angles and can be calculated using equations 1 and 2. These equation are set up

assuming that the cones are in full contact when the TP settles over a certain distance L_{slip} , see figure 2. In table 1 the full scale dimensions are given.

$$L_{slip} = L_{overlap} - \frac{L_{overlap} \sin(\beta)}{\sin(\alpha)} \quad (1)$$

$$R_{UC} = 0.5D_{MP} - L_{slip} \sin(\alpha) \quad (2)$$

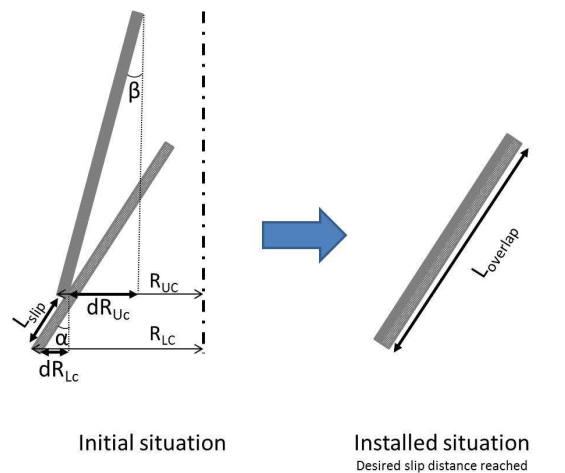


Figure 2. Slip distance clarification

Table 1. Design parameters of the slip joint case study.

	Lower cone(MP)	Upper cone(TP)	Unit
Cone angle	$\alpha=1.05$	$\beta=1.0$	$^{\circ}$
Top outer diameter	5.84	5.947	m
Bottom outer diameter	6.00	6.104	m
Wall thickness	60	60	mm
Total length TP		14	m
Total mass TP		150	Tons
Steel type	S355	S355	

To dynamically install the joint a harmonic force will be applied in vertical direction. In order to use realistic vibrations, the specifications of a vibratory driver used in the offshore industry for installing piles of +6m is taken into consideration [6]. This vibratory driver, the APE model 600, operates with frequencies of 0-20 Hz.

2.2. Scaling influences

Geometric and material similitude is kept when scaling 1:10 for this case. The loads will be scaled to keep the stress level in the material similar to full scale conditions. With the stress level equal to the full size level, the material will respond in a similar manner. The length dimensions wall thickness t_w , diameter D and length L scale proportional to scaling factor S_l . Cone angle α is kept constant, thereby the ratio of slip length over the desired overlap length stays the same. Scaling the mass of the joint and the axial force (cross sectional area) shows

the first influence of scaling. Mass scales with a factor S_l^3 and in order to keep the same axial stress level, the axial stress scales with a factor S_l^2 . Therefore additional force must be added in the installation test to mimic the downward force due to the self-weight.

To determine the forcing frequencies of the experiment, scaling of the natural frequencies of the TP is investigated. This is done using finite element models in Ansys where the upper end of the TP is considered to be fixed. In figures 3 and 4 the modal shapes and corresponding frequencies are shown of the full scale and a 1:10 scaled TP, respectively. From this analysis it can be seen that the frequencies are scaled inversely proportional to the scaling factor. Therefore the harmonic force that will be applied to the scaled slip joint should operate with a frequency spectrum of 0-200 Hz.

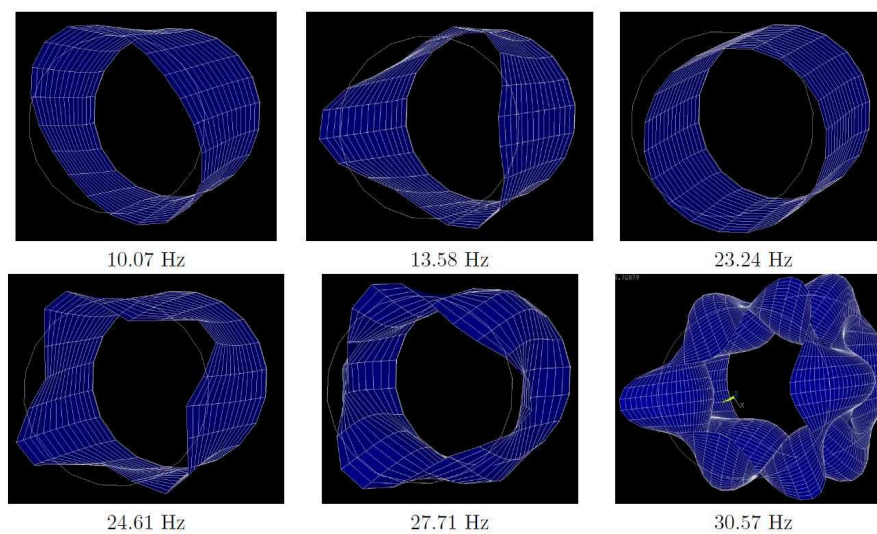


Figure 3. TP full scale modal shapes

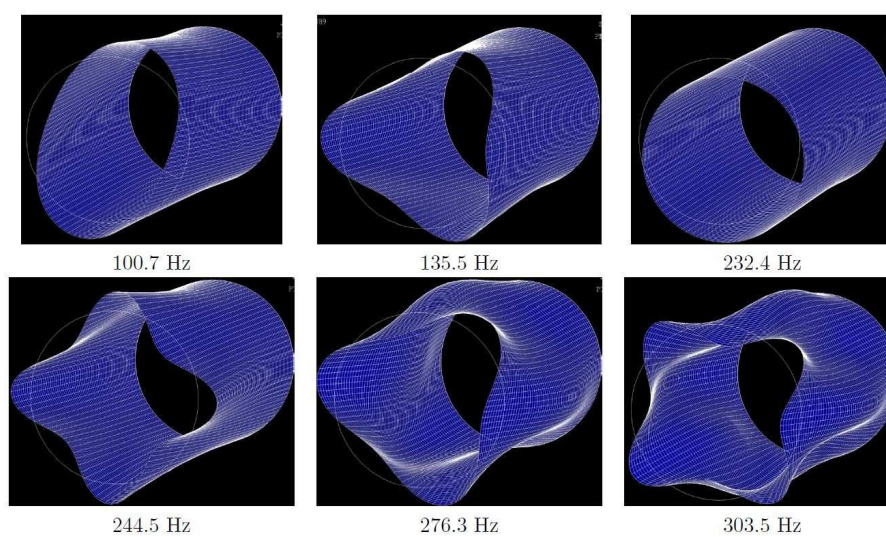


Figure 4. TP scaled modal shapes

3. Experimental setup

3.1. Introduction

To simulate the dynamic installation under self weight, the following requirements were set to the test setup:

- Additional axial load capabilities
- Allow movement in shaking direction
- Allow allow settlement between the MP and TP
- Allow slight inclination of the MP with respect to the TP

For this purpose a design of a space frame has been made, actuators for the static and dynamic load are selected and bearings that allow movements in the vibration direction are chosen. In figure 5 and 6 the design of the experimental setup and a photo of the set up are shown, respectively. The next sections explain the setup in more detail.

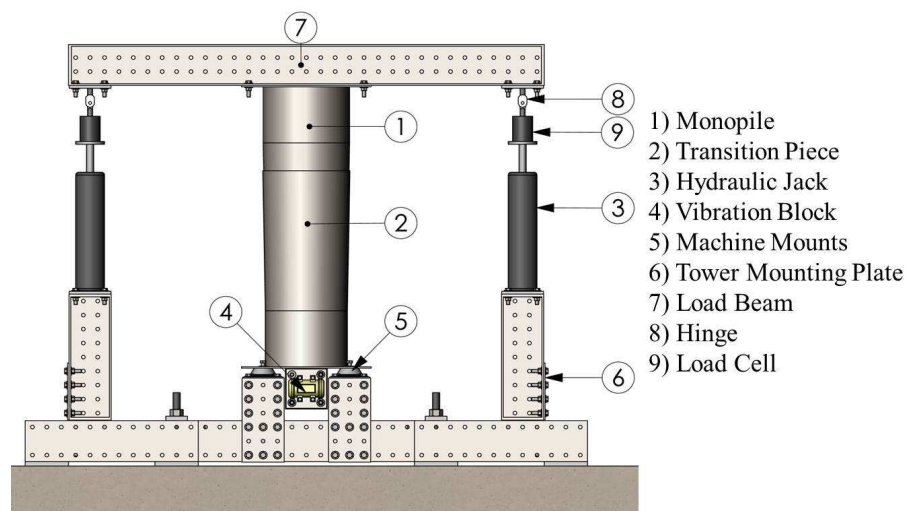


Figure 5. Design of the test setup

3.2. Orientation of the test pieces

The MP and TP have been placed upside down to allow decoupling of the vibration and static load components. Vibrations are still excited at the transition piece but static load is applied at the bottom of the MP as is shown in figure 7. Decoupling is necessary to reduce the impact of the vibrations to the static load actuators. Also, by attaching the shaker to the lower cone it can remain close to the ground thereby allowing a more safe dynamic loading procedure.

3.3. Supporting space frame and bearings

The H-profile columns are connected through a combination of mounting plates, thread rods, bolts and rings. Foot sections are connected to the floor via long tensile rods, clamped and tightened on both sides. To allow slight tilting of the MP, hinges are connected in between the standing columns and the load beam, nr. 7 in figure 5. Because the two standing columns are not free to move sideways, any tilt angle will inflict bending in the towers. The columns are mounted to the bottom frame via mounting plates solely on the outer sides of the column allowing slight bending movement if needed.

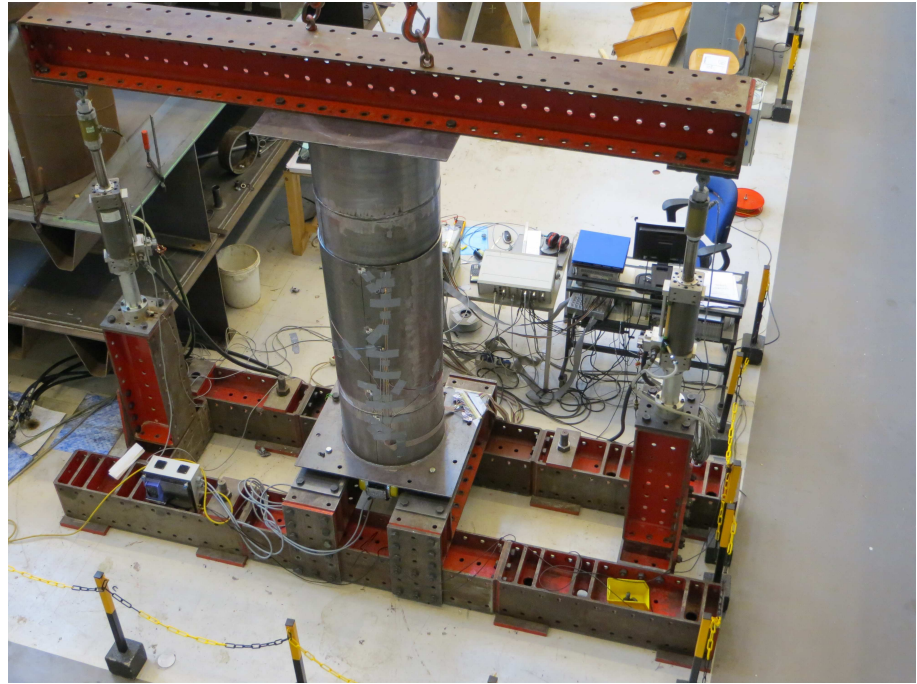


Figure 6. Test setup as built in the Stevinlab in Delft

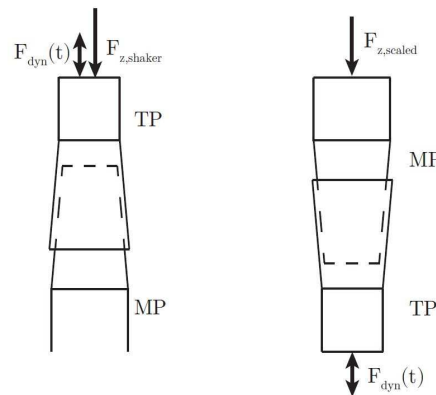


Figure 7. Explanation of the orientation of the setup

The use of bearings, called machine mounts in figure 5, allows the TP to vibrate while it is supported. A rubber bearing type of fabricator Euro-bearings is used[7]. The elastomer of the bearing is encapsulated in a conical shape, thereby providing an equal stiffness in lateral directions while allowing vertical movement as well. These types of bearings are typically used to mount vibratory machines and are called machine mounts. The stiffness in axial direction of a single machine mount is $k = 4.2 \text{ kN/mm} = 4.2 \text{ MN/m}$.

3.4. Load Actuators

The additional axial force needed to mimic the self weight on full scale is 10 kN and this will be applied using two hydraulic jacks. This additional axial load will create the same axial stress in the MP as the weight of a TP of 14m length would on full scale.

The vibration is applied using two motors with eccentric masses. Mechanical vibration motors are based on the same functionality as the commercial shakers used on full scale. A centrifugal force is excited by a spinning eccentric weight which is connected to a motor through a shaft. The resulting centrifugal force is given by equation 3. Here r is the distance from the center of the eccentric mass to the shaft center. The eccentric force vector of the eccentric weight $\vec{F}_{centrifugal}$ is pointing outwards from the center and is spinning with the rotational velocity.

$$\vec{F}_{centrifugal} = m_{eccentric} \cdot r \cdot \omega^2 \quad (3)$$

The magnitude of the eccentric force follows physical laws and is a function of the rotational/vibrational frequency. Two eccentric masses rotating in opposite direction with the same angular velocity will result in an effective linear harmonic force in either vertical or horizontal direction. In this experiment a vertical direction of the vibration is used. This direction is similar to the vibration direction of the industry vibratory devices used offshore.

3.5. Strain gages details and position

Strains are measured in axial and circumferential direction using strain gages of 6 mm configured in a rosette - figure 8(a). The strain in circumferential direction indicates the local increase in diameter of the cones. In figure 8(b) the rings on which the gages are located are indicated. On each ring there are 2-3 gages present spaced 110, 120 and 130 degrees from each other. The spacing is chosen to allow the strain gages to measure specific ring modes. With a equal spacing of 120 degrees there is a change to miss these modes.

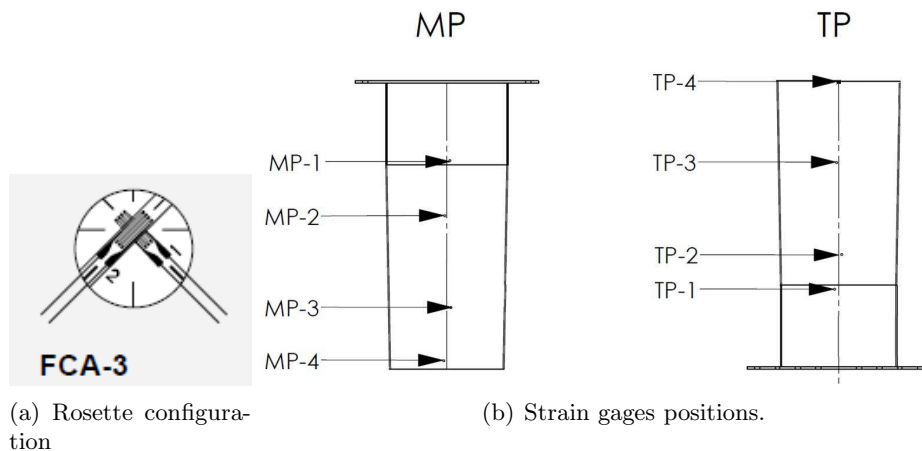


Figure 8. Strain gage configuration and location on the MP and TP

4. Dynamic installation case

4.1. Test description

To install the joint dynamically, the following installation sequence was executed after the TP was mounted on the bearings:

1. Lower the MP in the TP on self weight - Jack force = 0 kN
2. Simulate self weight - Jack force = 10 kN
3. Start vibration - Starting frequency 15 Hz
4. Increase frequency with steps of 5 Hz - from 15 -200 Hz

If settlement occurs, the vibrational frequency is kept constant until the settlement stops/stabilizes.

4.2. Settlement results of the incremental frequency test

In figure 9 the settlement of the TP and vibrational frequency over time is given. Figure 10 gives the static axial force applied by the hydraulic jacks and the amplitude of the dynamic force over time. The amplitude of the dynamic force is increasing over time with the increasing frequency. From figure 9 can be observed that at only at specific frequencies settlement occurs. These frequency lie around 30, 40, 80 and 100 Hz. At each of the settlement frequencies, the settlement stabilizes to a certain level, indicating that a controlled installation is possible. Another observation is that although the amplitude of the dynamic force is quadratically increasing with the increasing frequency these larger amplitudes do not lead to larger settlement. At the end of the test, where the frequency reaches 200 Hz the amplitude is three times larger than the amplitude at 100 Hz, the point where the last settlement occurred. This results support the assumption that settlement only occurs when the system is excited around its resonance frequencies.

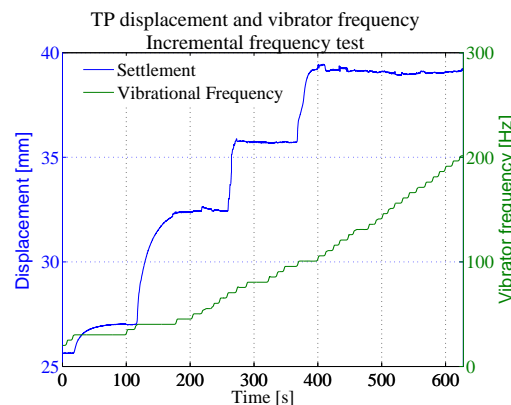


Figure 9. Settlement as function of the vibrational frequency over time

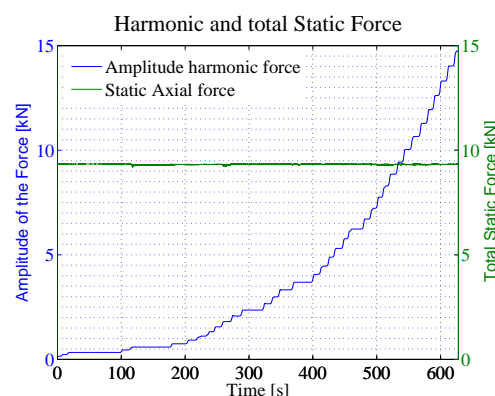


Figure 10. Dynamic and static force over time

4.3. Strain gages results during incremental frequency test

Figure 11(a) to 11(d) give the strain gages data of the top of the MP (MP-4, see figure 8(b)), the middle of the MP (MP-2) and the top and middle of the TP (TP-4, TP-2 respectively). All strains are well within the plastic limit. What is clearly noticeable from the strain data is that

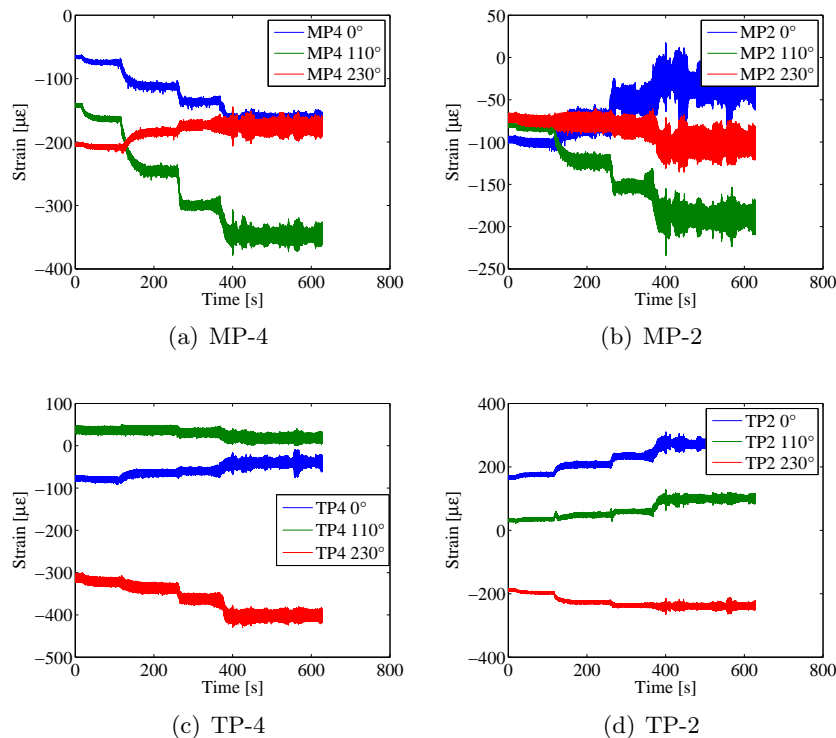


Figure 11. Strains of various rings on the TP and MP

the cones did not deform axisymmetrically during the installation. With increasing settlement of the cones each of the rings on the TP and MP have parts expanding and part compressing. This likely to the initially slight misalignment of the axes of the cones in lateral direction and the inability to freely align. In reality the upper cone is free to align, but in the current test set-up this degree of freedom is not available. A misalignment of the axis causes the contact pressure to be non-axisymmetric. Therefore a ball-bearing at the bottom of the hydraulic jacks will be introduced to allow lateral movement, better alignment of the cones and more resemblance of the installation procedure in reality.

5. Conclusion and discussion

A dynamic installation procedure of a transition piece with a slip joint connection under self weight has been investigated on a 1:10 scale. As a consequence of the scaling additional force was needed to mimic real life downward force due to the self-weight. To dynamically install the slip joint a harmonic force is applied in vertical direction using two coupled eccentric motors. The frequency of the motors and thus load is increased with steps of 5 Hz up to 200 Hz. Results show that settlement of the transition piece only occurs at specific frequencies, 30, 40, 80 and 100 Hz. The settlement at each of these frequencies shows a smooth behavior and approaches a stable settlement level. This indicates that a controlled installation of a slip joint is possible. Presumably, the frequencies at which the settlement occurs are resonance frequencies of the system. This assumption is supported by the fact that no settlement occurred at higher frequencies than 100Hz. Furthermore, at 200 Hz the force amplitude is three times larger than at 100Hz and no settlement is achieved. Therefore it can be concluded that a proper choice of frequency is necessary to install the slip joint dynamically and that adding force does not automatically lead to additional settlement. The data read from the strain gages show that during installation strains remain in the elastic region. The strain gages also showed that the

cones were not deformed axisymmetrically during installation and, therefore, an adjustment has to be made to resemble the freedom of the cones to align in reality.

Future work may be focused on the investigation of the exact mechanism of settlement during harmonic excitations and influences of fabrication and installation.

Acknowledgments

The authors like to thank Prof. Metrikine and Dr. Lourens for their valuable support and guidance on this project. The work presented in this paper is part of the 'FLOW' research program supported by the Dutch government and their financial contribution is greatly appreciated.

References

- [1] Lindoe Offshore Renewable Center 2012 *The Monopile -Close to a Monopole* (Online: www.lorc.dk/offshore-wind/foundations/monopiles).
- [2] Det Norske Veritas 2013 *DNV-OS-J101: Offshore Standard: Design of offshore wind turbine structures* Det Norske Veritas AS.
- [3] van der Tempel J and Lutje Schipholt B 2003 *DOWEC report-F1W2-JvdT-03-093/01-P: The Slip-Joint Connection, Alternative connection between pile and tower* (Dutch Offshore Wind Energy Converter project 2003) Delft University of Technology.
- [4] Segeren M L A and Lourens E 2013 *Proc. of EWEA 2013: Investigation of a slip joint connection between the monopile and tower of an offshore wind turbine (February 2013, Vienna)*.
- [5] Jonkman J and Musial W 2010 *Technical Report NREL/TP-5000-48191: Offshore code comparison collaboration (OC3) for IEA task 23 offshore wind technology and deployment* National Renewable Energy Laboratory
- [6] APE Holland (Accessed October 2013) *Product brochure Model 600 Vibratory driver/extractor*(Online:www.apeholland.com)
- [7] Euro-bearings LTD (Accessed October 2013) *product brochure: Machine mount 786010*(online:www.euro-bearings.com).