The Slip-Joint Connection
Alternative connection between pile and tower

Dutch Offshore Wind Energy Converter project

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1 Introduction

During discussions about alternative transition pieces, an idea surfaced which had been used by the former Dutch turbine manufacturer WindMaster: the slip-joint. The principle of the slip-joint is to slide two conical tower sections over each other without the use of bolts, grout or welding. Should this connection be feasible for offshore use, it could mean a reduction in offshore handling and with that, a reduction of cost.

This report explores the details of the onshore application of the slip-joint by WindMaster and the design calculations used previously. To give a more vivid image, a WindMaster turbine with slip-joint was visited, of which pictures have been included in chapter 2. Critical points for offshore application of the slip-joint are treated in chapter 3: vertical alignment, possible damage due to pile driving and corrosion. Chapter 4 gives a comparison of the slip-joint with a transition piece and the final chapter sums the conclusions and recommendations.
2 The Slip-Joint Principle

2.1 General description
The Dutch company WindMaster was one of the first manufacturers of wind turbines in the Netherlands. They had developed a special method of installation: the slip-joint, which will be discussed in this chapter [1]. WindMaster went bankrupt and was taken over by Lagerwey B.V. in 1998. After the takeover their innovative installation method fell into abeyance.
One of the wind turbines that has been installed by WindMaster is located in Scheveningen, near the harbour. Figure 1 shows a picture of this turbine with a small but distinguishable line halfway up the tower: the slip-joint.

![WindMaster Turbine in Scheveningen](image)

**Figure 1.** WindMaster Turbine in Scheveningen

The slip-joint can be visualised when looking at a pile of plastic cups. The “connection” between two plastic cups is actually a slip-joint, as can be seen in figure 2. This is the same method that was used by WindMaster on two tubular tower segments. In the slip-joint the tensile and compressive forces in the skin of the tubular tower are passed on through friction forces and for a small part through contact forces between the two parts. The weight of the structure above the joint and the conical shape of the connection cause the friction force.

![Slip-joint connection similar to a pile of plastic cups](image)

**Figure 2.** Slip-joint connection similar to a pile of plastic cups
2.2 **Installation Features**

The installation was done in three steps.

1. The lower tower is connected to the foundation (usually a concrete slab) by means of a bolted flange connection.
2. The slip-joint, the bottom of the upper tower simply slips over the top of the lower tower. The overlapping part is approximately 3 meters, with a diameter of 2.2 m.
3. The installation of the nacelle with its blades.

This tower was installed in 1995. The red numbers in figure 3 give an indication how much it has sagged since the installation: far less than 5 cm in 2003.

![Figure 3. View on the slip-joint from the inside. The picture to the right shows the sagging on the top part was far less than 5 cm over 8 years](image)

A technical drawing of the tower with the slip-joint is shown in appendix A. The drawing and figure 3 clearly show that the cone angle is very small.

The installation of the upper part of the tower has evolved over time. The first concept was to place the upper part on top of the lower part and then pull it down further with hydraulic pumps. But when after that the nacelle was placed on the tower, the extra weight caused the upper part to slip another 20 – 30 cm.

The new method to prevent this slipping was to lift the upper tower part over the lower part and as soon as the slip-joint made proper contact, the upper tower part was lifted again a few (6) centimetres. By releasing the upper part as quickly as possible, the connection slips further, preventing unwanted slip during the rest of the installation.

A copy of the original installation procedure and the justification for the drop height of 6 cm is shown in appendix B.

Using the slip-joint instead of a conventional bolted connection saved a lot of time. Allegedly, WindMaster was able to install 4 towers with a slip-joint in the time it normally took to install just 1 conventional tower.
2.3 Design considerations

In this section a general overview is given of the calculation methods as applied in the WindMaster design document [1]. To arrive at the maximum design stresses, the transfer of loads is modelled without friction. When friction is taken into account, the internal stresses will be less. The design method was checked by the critical German Bauamt to use this method for installing turbines in Germany as well.

Dimensions and Forces

The turbine design loads are overturning moment $M_B$ and gravity load $F_g$.

<table>
<thead>
<tr>
<th>$M_B$</th>
<th>Overturning momentum</th>
<th>kNm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_g$</td>
<td>Gravitational force</td>
<td>kN</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Angle of cone</td>
<td>deg</td>
</tr>
<tr>
<td>$d$</td>
<td>Average diameter of slip-joint</td>
<td>m</td>
</tr>
<tr>
<td>$t$</td>
<td>Thickness</td>
<td>m</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of slip-joint</td>
<td>m</td>
</tr>
</tbody>
</table>

The resultant force is:

$$ F_r = \frac{F_g}{\tan \alpha} $$

With the so-called “ketelformule” the stresses in the plate can be calculated:

$$ P = \frac{F_r}{h \cdot d \cdot \pi} $$

$$ \sigma_t = P \cdot \frac{d}{2t} $$

Substitution gives:

$$ \sigma_t = \frac{F_r}{2 \cdot h \cdot t \cdot \pi} = \frac{F_g}{2 \cdot h \cdot t \cdot \pi \cdot \tan \alpha} $$
The effect of friction

The slip-joint connection is manufactured in such a way that the upper and lower tower section fit perfectly. This means that both sections make contact over the entire slip-joint surface introducing a large area for force transfer via friction. The effect of this friction on the previously presented calculation of the axial stress is examined here.

<table>
<thead>
<tr>
<th>$F_w$</th>
<th>Friction force</th>
<th>kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>Friction coefficient</td>
<td>-</td>
</tr>
</tbody>
</table>

$$F_g = F_N \sin \alpha + F_w \cos \alpha$$
$$F_w = \mu \cdot F_N$$
$$F_g = F_N \cdot \sin \alpha + \mu \cdot F_N \cdot \cos \alpha \approx F_N (\tan \alpha + \mu)$$

Which results in:

$$\sigma_t \approx \frac{F_g}{2 \cdot t \cdot h \cdot \pi (\tan \alpha + \mu)}$$

Any small value for the friction coefficient will decrease the total stress in the joint. A typical value for the friction coefficient is 0.1.

Bending Moment

For the bending stress, the original calculation method assumes a linearly increasing distribution of the contact stress over the slip-joint. Though friction will also occur, it was not incorporated in the original calculation.

$$M_B = F \cdot \frac{1}{3} \cdot h$$
$$F = \frac{1}{2} \cdot P_{\text{max}} \cdot h \cdot d$$
$$P_{\text{max}} = \frac{6 \cdot M_B}{h^2 \cdot d}$$

This results in:

$$\sigma_t = P_{\text{max}} \frac{d}{2 \cdot t} = \frac{3 \cdot M_B}{h^2 \cdot t}$$

Total Stress

The total design stress, excluding friction, based on the original design document can now be calculated with:

$$\sigma_t = \frac{F_g}{2 \cdot h \cdot t \cdot \pi \cdot \tan \alpha} + \frac{3 \cdot M_B}{h^2 \cdot t}$$
3 Slip-Joint Application Offshore

3.1 Overview
The slip-joint has a large advantage over a bolted, welded or grouted connection in simplicity of installation. An ideal application offshore would be to install a foundation pile with conical upper part on top of which the entire tower and turbine can be installed in one piece, steps 1 and 2 in figure 4.

![Figure 4](image1)

Figure 4. Installation steps for slip-joint: 1 driving the pile 2 installation of tower and turbine

Though the method seems straightforward, some details require special attention. The transition piece used in a “standard” installation procedure gives the possibility to correct any misalignment of the foundation pile. This option is not available when a slip-joint is applied. Foundation piles are usually straight tubular piles to prevent deformations during driving. The conical pile head has to be strong enough to prevent deformation.

3.2 Vertical Alignment
If the foundation pile is not totally vertical, the transition piece provides the means to correct this for the tower. Although verticality looks rather nice, it is this look that is the main reason why the towers have to be in vertical position. The extra forces due to a misalignment are not devastating. To give an indication how a wind farms with different alignment tolerances looks like, figures 5 and 6 with 7 and 1.5 degrees of misalignment respectively are shown.

![Figure 5](image2)

Figure 5. Impression of 7 degrees misalignment in an offshore wind farm
It is clear that a tolerance of 7 degrees is unacceptable since the turbines do look rather unusual when they are tilted to such extend. The 7 degrees misalignment results in a nacelle offset of 8.59 meter.

The 1.5 degrees misalignment does show a more decent picture than the odd picture of 7 degrees. It is technically feasible to keep the turbine in operation under an angle of 5 degrees, although from a aesthetic point of view even this small misalignment is still undesirable. A 1.5 degrees misalignment results in a 1.83 meter offset.

Pile driving from a jack up should ensure greater control of the pile verticality. Not withstanding this, the control will remain an issue and it is anticipated that piling would be carried out either through a seabed template or preferably by using a vibratory hammer initially before switching to a conventional hydraulic hammer. In this way it is anticipated that vertically tolerances of the order of 0.5 degrees can be achieved.

The maximum tolerable misalignment for pile installation during for the foundations of the Horns Rev wind farm was 0.5 degrees. According to the contractor, they actually did much better than this and achieved tolerances of less than 0.3 degrees offset. Figure 7 shows 2 snapshots of Elsam’s promotion video where after a few blows of the hammer, the pile alignment is checked and found to be within bounds.

Should a slip-joint be placed on a foundation pile with an offset of 0.3 degrees this would result in a 0.37 meter out of plumb position of the nacelle. This is technically not any kind of a problem; the cone angle of the tower is even more than this so it will hardly be visible.
3.3 Top of the Foundation Pile

Hammering would damage a flange connection if it were on the foundation pile. When a slip-joint would be used, the hammering could damage the conical shape that is needed to ensure a tight connection between foundation pile and tower.

The first thing that will have to be determined is what the resulting forces will be in the foundation pile when it is driven into the seabed. The critical force is the one that will act on the ‘ring’ where the pile bends to the conical shape.

Effective Hammering

If the cone angle becomes too steep, the foundation pile cannot be driven into the seabed. The pile will absorb all the forces from the hammer and the required force to penetrate a certain depth is never achieved. This can be visualised when looking to an extreme situation such as a cone angle as in figure 8a.

![Figure 8. Extreme cone angle (a) and realistic cone angle (b)](image)

If this pile would be driven into the seabed, the effective force from the hammer would be absorbed by the cone and deform it. The cone angle that is used will be between 0.4 and 0.8 degrees, of which an attempt was made to visualize that in a non-technical drawing in figure 8b. Such a cone angle will hardly have an effect on the drive-ability of the pile.

Eccentric Loading

A small eccentricity in the loading on the top of the cone could result in severe damage, which could make the foundation pile totally useless for a slip-joint connection. Either the top of the cone can be made very stiff to prevent distortion or special care should be taken to distribute the driving loads equally over the surface of the pile.

The latter option is achieved with one single method: using a cap that is placed on top of the pile. This is actually common use in the offshore industry. Since offshore piles vary in size, hammers are able to adjust to the pile size by attaching this kind of cap onto it.

Figure 9 illustrates the basic assembly for Vulcan Offshore Type Pile Hammers, with the component parts. The pipe cap is one of these and is configured to adapt the hammers to various sizes of piles up to the maximum size allowed by the leaders.

This is only one example of many possible configurations of pipe caps. Others are simply placed on top of the pile and are made out of wood.
3.4 Corrosion
The turbine in figure 1 is located 100m from the North Sea. The slip-joint has no extra corrosion protection other than the layer of paint covering the entire outside and inside of the tower. According to the maintenance chief, regular inspections have shown that no significant corrosion has occurred over the last 7 years.

For installation offshore, two options are possible:
- slip-joint fully above water
- slip-joint always under the waterline.

The first option makes inspection easier, but places the slip-joint in or just above the splash zone where air and seawater provide a highly corrosive atmosphere. The second option makes inspection more complex but in that case a cathodic protection system can be used effectively.

Overall design and installation requirements will dictate which of these two options will be applied. The associated effects of both options require attention but not more attention than when considering grouted or bolted connections.
4 Transition Piece vs. Slip-Joint

In the DOWEC report on an alternative transition piece [2], the extreme load case was checked for the grouted joint. Figure 10 shows a copy of the forces and moments acting on this connection. It is assumed the configuration of a slip-joint is similar, only with a cone angle of 0.5\degree.

![Figure 10. Extreme load case an dimensions as used for the transition piece design calculations](image)

Following the design calculation methods described in section 2.3, the maximum stress in the slip-joint can be found.

\[
\sigma_t = \frac{F_g}{2 \cdot h \cdot t \cdot \pi (\tan \alpha + \mu)} = \frac{3484}{2 \cdot 0.05 \cdot 5 \cdot \pi (\tan 0.5 + 0.1)} = 20400 \text{ kN/m}^2 = 20.4 \text{ N/mm}^2
\]

\[
\sigma_{rM} = \frac{3 \cdot M_B}{h^2 \cdot t} = \frac{3 \cdot 53985}{5^2 \cdot 0.05} = 129564 \text{ kN/m}^2 = 130 \text{ N/mm}^2
\]

\[
\sigma_{total} = \sigma_{rF} + \sigma_{rM} = 20.4 + 130 = 150.4 \text{ N/mm}^2 < 240 \text{ N/mm}^2
\]

The maximum stress in this static extreme load case is below the yield stress. Note that in this example no safety factors were incorporated. The dimensions in this calculation have not been altered to make comparison with the transition piece example easier. In practice, more and more detailed design calculations must be performed to establish the optimum in cone angle and slip-joint height.

These calculations show that the slip-joint can be applied with the same dimensions as a transition piece design. Because no grout needs to be used, the costs of this material, installation of the grout and measures to transfer loads before the grout is hard enough, can be omitted. This installation option is faster, requiring smaller weather windows and making it cheaper in comparison to other methods.
5 Conclusions and Recommendations

Conclusions
The slip-joint has been applied onshore on several dozens of turbines without structural reliability problems. The method shortened the installation time considerably in comparison to a “standard” bolted connection.

No major problems are foreseen when the slip-joint is applied on offshore wind turbines. A possible installation method could be to install a foundation pile with a conical upper part, cone angle < 1 degree. The nacelle and tower, with matching cone angle at the bottom-end, could be installed in one piece.

The verticality of the foundation pile has to be guaranteed because the slip-joint does not allow verticality correction like the transition piece. Experts believe higher verticality demands can be met without major cost.

The structural integrity of the conical upper section of the foundation pile should stay intact for the solution to work. It was found that the cone angle is so small that pile-driving forces will not affect the conical part. Should this become a problem in the future, an increase in wall thickness of the conical part will be sufficient.

Eccentric loading by the hammer can be prevented by using a cap between hammer and pile, dividing the impact forces equally over the entire circumference of the pile. This is common practice in offshore pile driving.

Recommendations

Problems that have not been addressed are the pre-installation of ladders, j-tubes and other external parts, which will normally be fitted to the transition piece.

The dropping of the tower section to prevent slipping during the rest of the installation has to be looked at closer when a detailed tower design and installation method have been worked out for offshore.

The slip-joint alternative has been retrieved from the archives. This study only shows the general description of its former onshore application and an exploration into possible future offshore application. It satisfies one basic requirement: reduce installation time offshore. It would be wise to test the correctness of the assumptions in this report in a team of experts: steel manufacturer, offshore pile driver, offshore designer, wind turbine manufacturer and certification agency.
References

Appendix A. Slip-joint tower original technical drawing
Appendix B. Slip-joint original installation procedure

1. MOUNTING PROCEDURE TOWER SLIPJOINT

1. The upper towerhalf will be mounted in vertical direction. The lower tower half already has to be placed on its foundation and the anchor bolts must be fully prestressed.

2. The upper part must now be lowered over the lower part while from the inside the rotational position is corrected. The upper ladder should be opposite the platform hatch and the lifting eyes of the lower tower part should be between their guide blocks. As soon as the force meter in the crane indicates, that the slipjoint starts carrying the load, the movement is stopped.

3. Mark the position of the upper rim of the lower tower on the inside surface of the upper part.

4. Now the upper part is lifted over 60 mm. The upper part should be perfectly still in its correct rotational position.

5. Give the personnel opportunity to leave the tower!

6. Now release the load as quick as possible.

N.B. The crane must be able to lower its hook with a minimum speed of 1,5 m/s.

for justification of the given values, see annex A.
ANNEX A

DROP HEIGHT CALCULATION SLIPJOINT
WM 750 Z WINDTURBINE

Properties

Weight upper towerhalf : 15000 kg
Required supporting force : 750 kN
Slipjoint diameter : 2.2 m
Slipjoint length : 3.4 m
Wall thickness : 12 mm
Tower taper : 0.0166
Coefficient of friction : 0.1

To generate the supporting force of 750 kN by friction, a radial force is necessary of:
750/0.1 = 7500 kN, resulting in a wall pressure of:
7500/\pi \times 2.2 \times 3.4 = 319 \text{kN/m}^2 = 0.319 \text{MPa}

The wall stress is now:
0.319 \times 2200/2 \times 12 = 29.2 \text{MPa}

The circumference will be stretched resp. upset by:
29.2 \times \pi \times 2200/210.000 = 0.96 \text{mm}

The diameter of the outer tube therefore grows with:
0.96/\pi = 0.31 \text{mm}.

Since the inner tube is pinched with the same value, the axial displacement to generate this, will be:
2 \times 0.31/0.0166 = 36.9 \text{mm}

The required energy to overcome the friction is now:
1/2 \times 36.9 \times 750 = 13.84 \text{kJ}.

This energy can be produced by gravity by dropping the tower mass over a height of:
13840/g \times 15000 = 0.094 m = 94 \text{mm}

The drop height above the point of first pressure build-up is there for:
94 - 37 = 57 \text{mm}, rounded off: 60 \text{mm}

The maximum vertical speed will be:
13840 \sqrt{0.5 \times 15000} = 1.36 \text{m/s}