CPT and Borings
The rotation of the bucket is scaled by a factor = 20

Future Offshore Foundations
Investigating of soil strength after bucket installation
Results of CPT before and after installation

POS 0 & 1 & 2

CPT PENETRATION TEST

POS 3 & 4 & 5

CPT PENETRATION TEST

References and Case Story

Frederikshavn

Ability to compete

Economics

Conclusion
How does the suction affects the surrounding soil?

- If the installation is designed and executed properly the suction does not affects the surrounding soil.
  - No influence on the bearing capacity or settlements.

- After decommission the soil is left intact without any scars visible after a few days.
Reference 2: Wilhelmshaven 2004

Vestas V90 – 3.0 MW

ENERCON E-112 – 4.5 MW
Soil Profile Wilhelmshaven
Debunking Myths about the installation failure in Wilhelmshaven
Debunking Myths about the installation failure in Wilhelmshaven

- The bucket foundation is a thin shell structure
- At deeper waters, the diameter of the bucket increases
- Large aspect ratio between caisson diameter and wall thickness
- Instability (buckling) critical issue during installation

- Crucial case of buckling in Wilhelmshaven, Germany in 2005
  - Bucket diameter 16 m, height 15 m, and skirt thickness 25 mm
  - 6 MW offshore wind turbine
  - The Giant Barge came in drift and hit the skirt at a penetration depth at 3m resulting in a 80-160mm bump. (back calculated)
  - Buckling at a penetration of 6.8 m
Figure 8. Measured versus penetration on site.
**Methods – Procedure**

- **Linear Eigenvalue buckling analysis**
  - Estimate of initial imperfect geometry
- **Non-linear buckling with imperfect geometry**
  - Material model for steel: Elastic, perfect plastic
  - Imperfections from linear pre-buckling

<table>
<thead>
<tr>
<th>Initial analysis</th>
<th>Second analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition of initial &quot;perfect&quot; geometry</td>
<td>Definition of imperfect geometry defined by mode shape n and scaling factor α</td>
</tr>
<tr>
<td><strong>Linear buckle analysis</strong></td>
<td>dead load is applied</td>
</tr>
<tr>
<td>Output: N buckle mode shapes</td>
<td><strong>Post buckling analysis</strong></td>
</tr>
<tr>
<td></td>
<td>Output: Maximum allowable suction for imperfect geometry</td>
</tr>
</tbody>
</table>

**References and Case Study**

- **Buckling analysis**
- **Ability to compete**
- **Economics**

**Conclusion**
Analysis in ABAQUS

- Initial analysis:
- Post-buckling analysis
Results – Nonlinear Buckling Analysis with Imperfections

- Which imperfect geometry to introduce?
Results – Nonlinear Buckling Analysis with Imperfections

- The first 21 modes are included as imperfect geometries
  - Mode 1 is not the worst mode
  - For large imperfections higher modes are more critical

![Graph showing buckling pressure vs. scaling factor of imperfection for Modes 1, 7, and 14 with penetration depth = 3 m]
Results – Post-buckling Analysis with Imperfections

- Buckling load from GMNIA analysis with mode 1 matches “Elastic” solution from DNV.
Results – Post-buckling Analysis with Imperfections

- The only method capable of capturing the buckling incident in Wilhelmshaven is the GMNIA analysis, considering the first 21 mode shapes.

- One could get the impression that only the “elastic” lateral buckling strength from DNV, assuming a cylinder height equal to the free height, was considered for the design in Wilhelmshaven.
The geometric skirt imperfections were measured by a 3D point cloud laser scanner.

- The maximum out-of-roundness was ± 50mm.
- The largest imperfections were along the vertical welding’s.
Penetration depth = 3 m

- Mode(s) = 1
- Mode(s) = 7
- Mode(s) = 14

Buckling analysis

Multi-shell
Multi-shell

- Alternative cross section with longitudinal stiffeners
- The cross section is denoted “multi-shell”
- Maximum diameter 15 m, shell radius 5 m, HE300M profiles
Results – Laterally loaded multi-shell with S3 boundary conditions

- Shape of mode 1 depends on $L$
Results – Laterally loaded multi-shell with S3 boundary conditions

- Equivalent circular cylinder

\[ \frac{t_{\text{cyl}}}{t_{\text{multishell}}} \approx \begin{cases} 1.32 & \text{for } L < 10 \\ 1.16 & \text{for } L > 10 \end{cases} \]
Conclusions

- For cylinder bucket using the “elastic” lateral buckling strength from DNV, assuming a cylinder height equal to the free height, is efficient when the fabrication tolerances is specified, and controlled.
- If the imperfect geometries is unknown the buckling pressures can be calculated using the GMNIA analysis using the first 21 mode shapes.
- For large imperfections higher modes are generally more critical than lower modes.
- Buckling load of multi-shell significant larger than traditional circular cylinder
Cylinder Diameter 15m - 25mm skirt
max 100 kPa pressure difference

Multi-Shell Diameter 15m - 25mm skirt
max 300 kPa pressure difference
References


- Madsen, S., Andersen, L.V. & Ibsen, L.B. “Numerical Buckling Analysis of Large Suction Caissons for Wind Turbines on Deep Water”. Accepted for publication in Engineering Structures.

"The Mobile Met Mast" is a prototype of a bucket foundation designed as support structure for a met-mast.

**Purpose:**
- To gain **confidence** that a monopod bucket foundation can be successfully installed offshore.
- To obtain a **movable met-mast**, which can be used in several offshore wind farms.
- Test and the floating installation method.

**Specification**
- Total height: 34 m
- Weight: 165 tones
- Skirt length: 6 m
- Skirt diameter: 12 m

Fabricated in Aalborg at Blad in August 2008.
Installed at Horns Rev 2 Offshore wind farm in March 2009.
Transport Concept

- Production in Northern Europe, facilities placed by a harbour.
- Transport to site on barge
- Installed by DP2 vessel
Launching
- Floated to site using 2 tug boats

- 40 m³ water was pumped into the head of the Mobile Met Mast to ensure a horizontal orientation when floating.
Horns Rev 2

Wind turbines:
- 91 Siemens 2.3MW
- 200 MW

Scheduled installation:
- 2008: Foundations
- 2009: Turbines

The Mobile Met Mast

- 3 installation tests were planned at different locations. (depending on weather)
- Was only installed on the final location.
- No data from CPT or borings are available (yet)
Future Offshore Foundations

Offshore Foundations Group

Introduction
References and Case Study
Horns Rev II
Ability to compete
Economics
Conclusion
The Mobile Met Mast
Offshore installation Horns Rev II 2009
Dogger Bank East

Installation time laps

Dogger Bank West:
Installation time **7 hours**
from lifting to fully installed
DOGGER BANK MET MAST INSTALLATION

Figure 2.10: Penetration depth versus Time.

Figure 2.13: Inclinations experienced plotted versus time.

Figure 2.8: Inclination vector plotted versus time.
The Click-on Pump Unit

Electrical driven

A-frame with umbilical winch

Universal Foundation
No noise issue
No noise restrictions
Installation 2013 Dogger Bank

- No noise issue
- No noise restrictions
Future Offshore Foundations

Offshore Foundations Group

Range coverage:
- 3MW to 8 MW turbines
- 15-55 meters water depth
- 300 -1200 tons

Turbine Size

- Platform cost graph showing different technologies.
- Universal Foundation highlighted.

Introduction
References and Case Story
Ability to compete
Economics
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Water Depths

<table>
<thead>
<tr>
<th>Substructure</th>
<th>small (0 to 25 m)</th>
<th>water depth average (25 to 50 m)</th>
<th>large (&gt;&gt; 50 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tripod</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suction bucket</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jacket</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floater</td>
<td></td>
<td></td>
<td>&gt;100 m</td>
</tr>
</tbody>
</table>

: well  : fair  : poor
A. RWE Innogy Offshore

RWE Innogy is involved with Universal foundations through the Doggerbank met masts and through the N1 foundation demonstration field concept.

An EU-tender calling for innovative WTG substructures & foundations was launched in August 2012, after more than 45 companies registered interest in a pre-qualification was performed in April 2012. A final decision to halt the project was made in summer 2013.

in total 17 designs of 13 EPCI consortia were reviewed by RWE-I
## 1. Technology readiness level assessment

### ‘The RWE-I Offshore Foundation TRL’

<table>
<thead>
<tr>
<th>TRL Level</th>
<th>TRL score</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>280</td>
</tr>
<tr>
<td>6</td>
<td>210</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### TRL Development stage

- **Field proven**
- **System installed ( >20 WTG foundations)**
- **Complete concept demonstration**
- **WTG tested / Environment track record**
- **Modelling / prototype tested no WTG**
- **Validated Concept**
- **Proven Concept**
- **Unproven concept**
CUSTOMER (XXX) CONCLUSIONS

- The Bucket Foundation is the foundation with the 2nd highest Technology Readiness Level ranking – only surpassed by the traditional grouted MP
- The Bucket Foundation is on total cost neck to neck with the Mono pile for our 50 unit commercial project
- The Bucket Foundation holds potential for further design and SC optimizations – all contributing to significant cost reductions
- German and Dutch projects are struggling with piling restrictions – the Bucket Foundation can solve this issue.

PROJECT DETAILS

- Water depth: 29 meters
- Distance to shore: 45km
- WTG: 6.xx MW
- # units: 2 or 50 units
- Interface point: LAT +5.5m (ex. TP)

Technology Readiness Level (TRL)

<table>
<thead>
<tr>
<th>Foundation type</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopile</td>
<td>280</td>
</tr>
<tr>
<td>Suction mono-bucket</td>
<td>120.66</td>
</tr>
<tr>
<td>GBF</td>
<td>57.00</td>
</tr>
<tr>
<td>Modified jacket</td>
<td>98.92</td>
</tr>
</tbody>
</table>
OWA focuses on strengthening economics of offshore wind
Stage I (Oct ’08 to Apr ’10) examined four technical areas

Offshore wind returns

CAPEX

OPEX

Yield

Financing costs

Four technology areas, selected on basis of detailed analysis of over 70 technical barriers

Foundations

Access

Electrical systems

Wake effects

Source: Carbon Trust
Foundations vision: Reduce cost of deeper water foundations

- To demonstrate new, lower-cost foundation designs
  - For 30-60m depths expected in late Round 2 & Round 3

- To reduce lifecycle cost of foundations by 30%
  - TDC target £0.4-0.6m/MW

- To stimulate the supply chain
  - Particularly in volume manufacturing and installation
  - To provide more competition and flexibility in the market

Offshore wind CAPEX breakdown

- Development & consent: 4%
- Electrical: 15%
- Integrated support structure: 22%
- Production, Installation & commissioning: 26%
- Turbine: 33%

Source: Carbon Trust
Foundation Designs total 72

- Fixed prices
- Two turbine: 3.6 and 5 MW
- Water depts.: 35m, 45m and 55m
- Two see condition Aver. and Exp.
- 6 seabed profiles
Estimated installed costs show promise
5MW turbine, normal climate

Estimated installed cost per MW (£m)

Depth

35m

45m

0.46

0.55

0.60 Target

Leading designs at 35m & 45m depths

Equivalent to 15-30% cost reduction
### Cases: Carbon Trust Wind Accelerator Project

<table>
<thead>
<tr>
<th>Water depth</th>
<th>5 m</th>
<th>15 m</th>
<th>25 m</th>
<th>35 m</th>
<th>45 m</th>
<th>55 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment kNm</td>
<td>127.000</td>
<td>156.000</td>
<td>196.700</td>
<td>255.000</td>
<td>300.000</td>
<td>350.000</td>
</tr>
<tr>
<td>Bucket size m</td>
<td>Ø14x11</td>
<td>Ø15x12</td>
<td>Ø16x13</td>
<td>Ø17x14</td>
<td>Ø17x15</td>
<td>Ø17x16</td>
</tr>
<tr>
<td>Weight tons</td>
<td>295</td>
<td>392</td>
<td>503</td>
<td>640</td>
<td>780</td>
<td>952</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water depth</th>
<th>35 m</th>
<th>45 m</th>
<th>55 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment kNm</td>
<td>355.000</td>
<td>405.000</td>
<td>480.000</td>
</tr>
<tr>
<td>Bucket size m</td>
<td>Ø18x15</td>
<td>Ø18x16</td>
<td>Ø18x17</td>
</tr>
<tr>
<td>Weight tons</td>
<td>760</td>
<td>920</td>
<td>1080</td>
</tr>
</tbody>
</table>
### Comparison of Foundation Types

**Basis of Comparison - Tenders for Manufacture of 80 No. Foundations**

<table>
<thead>
<tr>
<th>Foundation Type</th>
<th>Steel Weight (Gross) each</th>
<th>Cost % comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tripod</td>
<td>1453</td>
<td>1.00</td>
</tr>
<tr>
<td>3-Leg Jacket</td>
<td>1394</td>
<td>0.96</td>
</tr>
<tr>
<td>4-Leg Lightweight Jacket</td>
<td>1170</td>
<td>0.84</td>
</tr>
<tr>
<td>Universal Foundation</td>
<td>992</td>
<td>0.50</td>
</tr>
</tbody>
</table>

**Comments**

- Note to balance the cost, Insurance, Bonds and Guarantees have been removed, where appropriate, as these were not applied equally to all tenders.
- Where service cranes were required to certain types, these have been removed.
- Load out and transportation has been removed, where appropriate.
Installation cost of 100 foundations incl. of turbine installation

Carbon Trust installation derisk study

<table>
<thead>
<tr>
<th></th>
<th>XX</th>
<th>YY</th>
<th>ZZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckets</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Ref jacket</td>
<td>128</td>
<td>162</td>
<td>149</td>
</tr>
</tbody>
</table>
MARKET FEEDBACK

CARBON TRUST / OWA FEEDBACK – June 2013

CARBON TRUST / Offshore Wind Accelerator FEEDBACK

Presented during Renewable UK Conference – Manchester June 2013

Carbon Trust OWA perspective of UF competitive advantage
Potentially significantly cheaper vs optimised jacket for 30-60m

Universal Foundation

- Fabrication
  - Simple welds
  - Fits well with established monopile supply chain
  - Reduced weight
- Installation
  - Reduced vessel requirements
  - Fewer offshore operations
  - No piling noise
- O&M, decommissioning
  - No grout failures
  - Easy decommissioning
- Commercial
  - Fred. Olsen end-to-end EPC model

Image: The Guardian 2013

Future Offshore Foundations
Conclusion

Mono buckets - Competitiveness versus Mono piles

- Reduced steel consumption.
- No transition peace - Adjusting the upper part of the shaft to fit the standard wind turbine tower.
- Faster installation. Few offshore operations, with utilizing smaller equipment/vessels during installation.
- Environment friendly installation
- No noise, no noise restriction
- No seabed preparation and no or reduced need for scour protection.
- Simple decommissioning.
- Cost is reduces cost up to 20%
Mono buckets - Competitiveness versus Jackets

- **Reduced steel** consumption compared to any other substructure solution.
- Use of simple geometric welded steel structures **suitable for mass production**.
- **Faster installation**
- **Few offshore operations**, with utilizing smaller equipment/vessels during installation.
- **No seabed preparation** and no or reduced need for **scour protection**.
- **Simple** decommissioning.
- **Cost is reduktion 30-50%**.