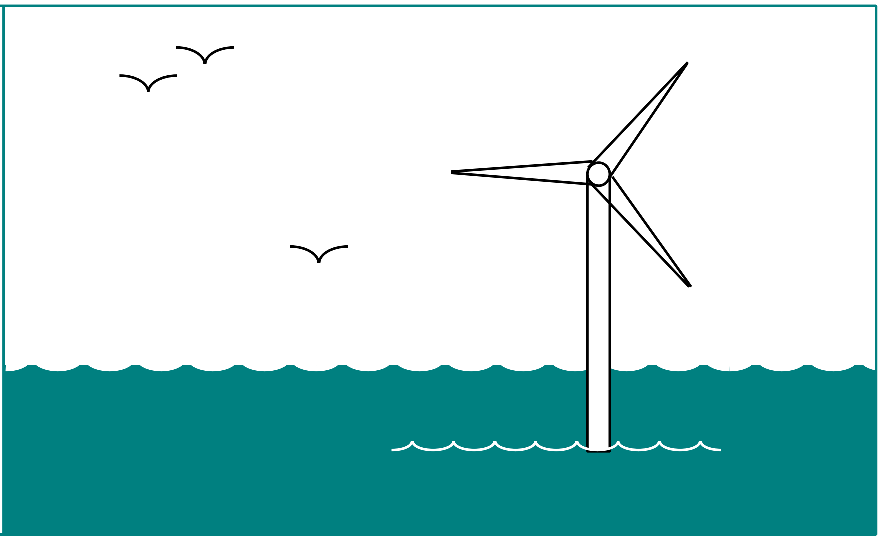
EPSRC

OFFSHORE
WIND
ENERGY
NETWORK



OWEN workshop on

Structure and Foundations Design of Offshore Wind Installations

DATE: Wednesday 1 March 2000

VENUE: CLRC Rutherford Appleton Laboratory

FINAL REPORT

Gillian Watson

This document is available online at
http://www.owen.org.uk/workshop_3/ws3_final.pdf

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1. Background

The Offshore Wind Energy Network (OWEN) hosted a workshop on *Structure and Foundations Design of Offshore Wind Installations* on 1 March 2000 at CLRC Rutherford Appleton Laboratory (RAL). The workshop aimed to present a scientific background to the challenges of structure and foundation design in offshore and coastal environments, to highlight areas where knowledge gaps exist and to draw on experiences from existing offshore wind structures. The event acted as a forum for OWEN members from different backgrounds to discuss their data requirements and experiences and to consider resource assessment strategies. Finally, the workshop provided an opportunity for delegates to meet and discuss possible collaborations, research projects *etc.*.

Dr Jim Halliday (RAL) began the day by introducing the OWEN network, outlining its objectives and giving some general administrative details on how OWEN is run. The remainder of the workshop was divided into three main sessions:

Environmental loading and structural modelling

Ground conditions and foundations

Practical experiences

This report concentrates on only the **main points** raised during the presentations and discussions.

2. Research funding opportunities and timetables

Speaker: Dr Jim Halliday – Energy Research Unit, CLRC Rutherford Appleton Laboratory
Tel: 01235 445559, Email: J.A.Halliday@rl.ac.uk

Dr Halliday drew attention to the four principal funding bodies available to UK researchers and industry for research in this topic area. These are:

- Engineering and Physical Sciences Research Council (EPSRC)
- Natural Environment Research Council (NERC)
- UK Government Department of Trade and Industry (DTI)
- European Union (EU)

It is important to note that EPSRC and NERC funding is open only to **eligible** academic institutions in the UK. In general, research council funding is restricted to UK universities, together with a limited number of other institutions (contact EPSRC and NERC directly for further clarification). However, on many projects, collaboration with industry is seen as highly desirable. UK **Research Council** funding is most suited to **medium to long-term research** (results in 2 – 5 years or more).

By contrast, **DTI funding** is aimed primarily at commercial organisations in the UK and is suitable for **short to medium-term research** (results in less than 2 years). The funds can be used for commercial applications on the basis of co-funding with UK industry.

EU R&D funds are awarded by the European Commission to collaborative groups drawn from at least two EU member states. This source of funding is open to all organisations and is best suited to **medium to long-term research** projects (results in 2 - 5 years or more).

Dr Halliday went on to briefly discuss NERC and EU R&D funds before handing over to Dr Alyson Thomas (EPSRC) and Ian Fletcher (ETSU) who discussed their funding strategies.

2.1 NERC funding

NERC currently has no Thematic programme in place for supporting research on offshore wind energy topics. The next possible date for a Thematic funding programme for this subject area to be considered is the autumn of 2000.

In the meantime, offshore wind related research that falls within NERC’s remit may be funded in one of two **Non-Thematic areas**; Marine Science (£5 – 6 million per annum) or Atmospheric Science (£3 – 4 million per annum). Within these Non-Thematic areas there are various funding schemes that can be applied to:

• Small Research Grants	<£35k, 3 calls p.a.
• Standard Research Grants	>£35k, up to 3 year project duration, 2 calls p.a.
• CONNECT Scheme	In collaboration with industry, 2 calls p.a.
A – “proof of concept” studies	<£5k
B – requires 50% industrial funding	>£5k
• Long-Term Support Scheme	up to 5 year project duration

NERC funded research

Non-Thematic Mode Research Grants: Marine Science/Atmospheric Science

Announcements and information relating to NERC research funding are available on the NERC web site at:

http://www.nerc.ac.uk

under the Awards and Training, Funding opportunities pages.

2.2 EU funding

EU funding is currently made available under the *Fifth Framework Programme for Research, Technological Development and Demonstration 1998-2002* (FP5). All funds are made on a shared costs basis.

Research on offshore wind energy is likely to come under the *Energy, Environment and Sustainable Development* (EESD) programme. Within EESD the relevant section is Part B: Energy (also known as ENERGIE), which is further subdivided into three sections – Cleaner Energy Systems (including Renewables), Economic and Efficient Energy and a provision for R&D of a generic nature. The emphasis for the FP5 programme is as follows:

- ⇒ Adopting a **problem solving approach**. FP5 turns away from the technology push of previous Framework RTD programmes - there should be quantified objectives wherever possible, and the programme is concentrated on a limited number of strategic issues. **Demonstration projects** are particularly encouraged.
- ⇒ The benefits of the research should give **European “added value”**, with scope for replication in several parts of the EU.
- ⇒ **Scientific and technological excellence**, with **effective project management**.

⇒ There is a move towards **larger projects** and **clustering** of a number of allied projects.

EU funded research

Fifth Framework Programme for Research, Technological Development and Demonstration (FP5)

Announcements and information relating to this call for proposals are available on the CORDIS web site at http://www.cordis.lu under the *Energy, Environment and Sustainable Development* programme pages.

Budget: 1998 – 2002:

Energy, Environment and Sustainable Development = 2125 million Euro

of which Part B: Energy (also known as ENERGIE) = 1042 million Euro

of which Cleaner Energy Systems (inc. Renewables) = **478 million Euro**

Total FP5 = 14960 million Euro

Timetable: First call for research proposals closed June 1999 (included offshore wind)

Call 2 closed October 1999 (did not included offshore wind)

Postscript: Energy Call 3 was issued on 14 March 2000 (closing deadlines 31 May 2000). For full details visit the web site at: http://www.cordis.lu/eesd/calls/b_200001.htm

Call 4 (~September 2000) and Call 5 (~September 2001) *may* include offshore wind energy topics.

NO CALL IS EXPECTED IN 2002.

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2.3 EPSRC funding

Speaker: Dr Alyson Thomas - Engineering and Physical Sciences Research Council, EPSRC
Tel: 01793 444441, Email: Alyson.Thomas@epsrc.ac.uk

Dr Thomas introduced EPSRC and its role in promoting and supporting UK science research and training and also highlighted its duty to ensure that research effort is appropriate to the end-users of the scientific advances achieved.

Research on issues related to offshore wind energy is supported by the **EPSRC Renewable and New Energy Technologies (RNET) programme**. This is a joint initiative by the Engineering and Materials sections of EPSRC which commits around £4 million per annum to research on all related technologies. The programme operates through calls for research proposals which have two closing dates per annum – May and October.

The first RNET funding round is now complete. In total, 18 projects have been funded covering a wide range of topics including three projects specifically investigating offshore wind energy issues:

Topic	*Number of projects funded in first RNET funding round*
Wind energy	*4 including:* *Safe and Cost-Effective Maintenance Access to Offshore Wind Farms* Dr A J Day and Prof N D P Barltrop (University of Glasgow) *Electrical Stability of Large Offshore Wind Farms* Prof N Jenkins and Dr G Strbac (UMIST) *Dynamic response of Wind Turbine Structures in Waves* Prof J M R Graham (Imperial College), Prof A Incecik and Dr M J Downie (Newcastle University), Prof N D P Bartltrop and Dr S Huang (University of Glasgow)
Tidal Energy	1
Photovoltaic Materials	3
Photovoltaic Systems	1
Biomass	1
Electrical Networking	2
Thermoelectric Energy	1
Fuel Cells	2
Networks	2

The second RNET funding round from the first call for proposals is still on-going.

A second call for RNET proposals is expected by the end of March 2000, with closing dates likely to be May and October 2000. The priorities for this call will be:

Supply technologies	Biomass, marine, fuel cells, solar, wind
Enabling technologies	e.g. distributed generation/fully integrated systems; energy storage and recovery; hydrogen storage
Demand-side technologies	Innovative energy efficiency technologies
Associated issues	e.g. techno-economic analysis, social/environmental research *(as part of an engineering project)*

Once again, researchers will be asked to submit outline proposals. Authors of subset of these outlines proposals are invited to develop their project ideas into full proposals on which the final funding decision is made.

POSTSCRIPT: From the end of March 2000, Dr Thomas will no longer be the RNET programme manager - her replacement will be Dr Edward Clarke (contact details will be available via the EPSRC web site (see below for URL)).

The second RNET call was issued on 23 March 2000. The deadline for outline proposals is 5pm on 19 May 2000, full proposals (if shortlisted) by September 2000 with an earliest start date of January 2001. The subsequent outline proposal deadline is 5pm on 6 October 2000.

EPSRC funded research
Renewable and New Energy Technologies Programme (RNET)

Announcements and information relating to this call for proposals, the outline proposal form and, in time, details of awarded projects, are available on the EPSRC web site at:

http://www.epsrc.ac.uk

under the *Engineering for Infrastructure, the Environment and Healthcare* programme pages.

Budget: ~£4 million per annum

Timetable: Second call for RNET research proposals issued March 2000

Closing date for third set of RNET outline proposals:	19 May 2000
Short-listed full proposals invited:	September 2000
Earliest project start date:	January 2001

Note: There will be a rolling process of grant assessment. The second closing date for outline proposals is 6 October 2000, with submission deadlines at approximately 6 month intervals thereafter.

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2.4 DTI funding

Speaker: Ian Fletcher – Wind Programme Manager, ETSU, AEAT Environment
Tel: 01235 433266, Email: ian.fletcher@aeat.co.uk

Ian introduced the UK DTI Offshore Wind Programme which is managed by the Energy Technology Support Unit (ETSU) of AEA Technology Environment. He stressed that policy and market support mechanism decisions, as well as final approval for all research projects, originates from the DTI *not* ETSU.

Ian outlined what work has already been completed in the field of offshore wind as well as future areas that have been highlighted for support. Full details of these aspects are given in the DTI Offshore Wind Programme document available online at:

http://www.owen.org.uk/workshop_3/dti.pdf

Finally Ian explained the mechanisms available for project funding. There is a nominal budget of £2 million (plus) available each year within the wind programme. The DTI will consider part or whole funding for different categories of projects within the following guidelines:

⇒ Up to **100% funding** on **deployment constraint issues** – these projects must be generic in nature, non-commercial and "far from market"

⇒ Up to **50% funding** for "**industrial research**"

⇒ Up to **25% funding** for "**pre-competitive development**" – e.g. demonstration projects

For more information, please contact Ian Fletcher directly (contact details given below).

DTI funded research and development

New and Renewable Energy Support Programme (NRES)

ETSU co-ordinates *New and Renewable Energy Support Programme* on behalf of the DTI. For more information visit the DTI web site at:

http://www.dti.gov.uk/renew/condoc

Budget: £43.5 million to end of March 2002

1999/2000 - £11.5 million
2000/2001 - £14.0 million
2001/2002 - £18.0 million

(~£2.0 million per annum for wind energy research and development)

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3. Environmental loading and structural modelling

Session chair	David Quarton, Garrad Hassan & Partners Ltd.
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David pointed out that design of safe and cost-effective offshore wind structures brings a series of new challenges. However, he also stressed that there is a high level of expertise within the traditional wind energy and offshore industries. He suggested the best way forward is to marry the skills that already exist.

3.1 Wave and current characterisation and modelling

Dr Bob Standing, BMT Fluid Mechanics Ltd.

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Dr Standing noted that sea states are usually characterised in terms of their **significant wave height** (H_s) and an associated **wave period**. The significant wave height has two possible definitions – traditionally H_s has been taken to equal the mean height of the 1/3 highest waves, $H_{1/3}$, however it can also be taken to equal four times the area under the wave spectrum, H_{m0}. Various wave periods are in common use including the zero up-crossing wave period (T_z) and the spectral peak period (T_p). The relationship between these and other wave periods were discussed briefly.

The wave climate at a particular location is generally represented using a wave scatter table. Wave height persistence (the occurrence/duration of waves greater than a specified level) may also have to be considered when determining a suitable weather window for an offshore operation. The wave spectrum describes the frequency content of a sea state. The **Pierson-Moskowitz spectrum** is commonly used to describe a well-developed sea state, whereas the **JONSWAP spectrum** is used to describe a sea state which has developed over a limited fetch and duration.

Unidirectional (2D) waves (described as long-crested) are the easiest to characterise. However, in practice unidirectional waves are rare and real sea states tend to be made up from components of waves from many directions. These waves are known as **short-crested waves**. The energy in a short-crested sea can be represented by including a directional spreading function – often based on a cosine^n function – to the wave spectrum.

Finally, a sea state may also be described in probabilistic terms. Wave elevations are usually treated as a Gaussian (normal) process, whereas wave heights are usually assumed to be Rayleigh distributed. The maximum wave height in a sample time series depends on the length of the record, and on the phasing of wave components within it. The '**most probable maximum**' **wave height** (H_{MPM}) is the average of maxima obtained from many such samples, and is commonly used in offshore design. It is important to realise that H_{MPM} is *not* the maximum wave height possible and that the probability of encountering a higher wave in a given sea state is about two thirds. Long-term **extreme events** may be estimated by extrapolation of the data. The 100-year wave height (i.e. the value exceeded on average only once in 100 years) is now the design wave condition most commonly used in the offshore industry.

Offshore structures have traditionally been designed using only the highest wave in an extreme storm sea state. This highest wave is often modelled/represented as being regular and of constant form. In modelling these waves, Linear **Airy wave theory** is easy to use, but a non-linear regular wave model, such as Stokes or stream function theory, is likely to be more appropriate in extreme sea conditions, especially for modelling particle motions in the wave crest. Various empirical stretching models are also in use. Wheeler stretching is particularly simple to apply, and may be used in conjunction with a linear irregular wave model. It should be remembered that wave loads depend on the water particle velocity. In deep water, wave particle orbits are unconstrained and form circles. However, in shallow water the depth restriction is reflected in elliptical particle orbits that have an exaggerated horizontal component to their motion. This means that horizontal wave loads in shallow waters may be severely underestimated if the calculations are based on deep water equations.

Breaking waves are generally characterised as either **surging, spilling or plunging**. In deep water waves tend to be of the spilling type, and are often modelled using stream function theory. Plunging breakers occur in shallower water, especially on shelving slopes. Very high particle velocities can occur at the crest of a plunging breaker, and require a suitable unsteady numerical model. In general, the offshore industry has been designing for deep water where breaking wave loads are relatively insignificant and therefore wave breaking is often ignored. However, wave breaking will be much more prevalent in the relatively shallow waters being considered for wind energy structures.

If the structure has a platform deck, the wave crest height has to be considered carefully when choosing the minimum air gap beneath it. The wave crest height to wave height ratio is sometimes described as the **wave skewness ratio**. It can be significantly greater than the value 0.5 predicted by Airy wave theory, and may be underestimated using regular Stokes or stream function models. Recent research suggests that there may also be important differences between skewness ratios occurring in long-crested and short-crested waves.

Currents may have components due to the tide, wind, breaking waves and ocean circulation (e.g. the Gulf Stream). The waves and current are often assumed to be statistically independent. Hydrodynamic interactions between waves and currents are generally ignored in design, although strongly sheared currents can cause local wave steepening and breaking.

Various current models are in common use. A 1/7 power law is generally used to describe the tidal component. The wind-driven component is sometimes assumed to have a linear profile, whereas others prefer a boundary-layer type log law.

Questions and comments:

Questions and comments on this presentation are grouped at the end of the session.

3.2 Hydrodynamic Loads

Prof Nigel Barltrop, Department of Naval Architecture and Ocean Engineering, University of Glasgow

Tel: 0141 330 4322, Email: nigel.barltrop@eng.gla.ac.uk

Prof Barltrop outlined the main types of hydrodynamic loading and the parameters will that effect the level of loading on a wind energy structure in waves. He then illustrated environmental loading cases that could occur at an offshore site.

Wave and current forces on small or slender structures can be evaluated using **Morison's equation**, which divides the forces into two terms, the drag force and the inertia force.

Drag forces are caused by viscous effects and vortices resulting from water passing the structure. Hence drag loads are related to water particle velocities associated with waves and currents. The drag force, F_d is proportional to the square of the *overall combined* water particle velocity, V:

$$dF_d = \tfrac{1}{2} C_d \rho D V^2 dL$$

where ρ = water mass density

D = tower diameter
dL = elemental length of tower
C_d = drag coefficient

Drag forces tend to be dominant in large waves.

By contrast, the **inertia force** is related to the acceleration of the water particles rather than their velocity and is made up of two parts – Froude Krylov and added mass forces. Froude Krylov forces, F_{fk}, result from hydrostatic pressure gradients which tend to accelerate the flow and can be thought of as similar to buoyancy forces:

$$dF_{fk} = \rho\ A\ a\ dL$$

where A = cross sectional area of tower
a = water particle acceleration

Added mass forces, F_a, arise from the modification to the accelerating flow caused by the presence of the structure:

$$dF_a = C_a\ \rho\ A\ a_r\ dL$$

where C_a = added mass coefficient
a_r = relative acceleration of water particles/tower

If the turbine support tower is fixed, $a_r = a$ and these component inertia forces combine to give the total inertia force, F_i:

$$dF_i = dF_{fk} + dF_a = C_m\ \rho\ A\ a\ dL$$

where $C_m = 1 + C_a$ = inertia coefficient.

If the support tower is large compared to the wavelength of the waves, then **diffraction effects** will tend to alter the wave pattern and the loading changes. However, diffraction effects only become significant when D is greater than ~wavelength/5. Therefore for a support tower has D=6m, diffraction effects only become important for waves with wave period < 4.5s.

Highly localised impact loads can be experienced if the support tower is engulfed by a steep wave crest. These **slap (or slam) forces**, F_s, are associated with the rate of change of added mass:

$$F_s = d/dt\ (MV) = M\ dV/dt + V\ dM/dt$$

$$dF_s = \tfrac{1}{2}\ C_s\ \rho\ D\ V^2\ dL$$

In traditional multiple member offshore structures, slap/slam forces are distributed through the structure and are not synchronised, however in single member structures such as monotowers, the slap/slam forces can prove more important to the global design.

The wave loading, and in particular the slap/slam and Morison drag loading may be applied impulsively and result in an increased dynamic response in the structure. Finally, the fatigue response in structures may be increased by resonant effects, however this may not prove to be a significant concern in the type of structures being considered for wind installations.

If the wave steepness is kept the same and the wave height is scaled with the water depth, d, then for a pile of diameter, D:

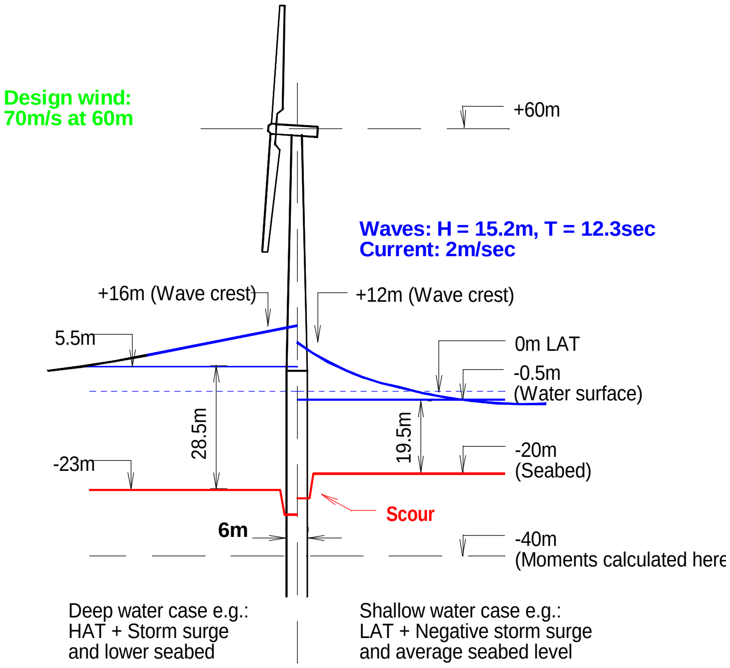
Drag Force μ d^2 D

Slap Force μ d^2 D

Inertia Force μ d D^2

Prof Barltrop then proceeded to discuss an offshore wind turbine loading case study for a hypothetical development in an area with a mobile seabed. Nigel acknowledged that the wave data is based on the conditions at the Leman G platform designed for Shell and the wind turbine data is based on turbine audits undertaken in conjunction with WS Atkins.

The case study investigated a 1MW turbine supported by a monotower on a single piled foundation. The turbine has a hub height of 60m above the Lowest Astronomical Tide (LAT) level. The tests considered a storm sea state (H=15.2m, T=12.3s although shallow water effects will modify these characteristics) and a relatively strong current (2m/s). The site has an average water depth of 20m at LAT but the variation in seabed, tide and storm surge levels as well as possible localised scour action means that the water depth at the structure can vary greatly and may fall in a range where waves are just breaking at the structure. Figure 1 indicates the structure under consideration as well as its setting. The case study considered the site under two scenarios – a deep water case represented on the left hand side of the diagram (high tidal level (Highest Astronomical Tide, HAT), a positive storm surge and a low seabed) contrasting with a shallow water case shown on the right hand side of the diagram (low tide level (LAT), a negative storm surge and an average seabed level).

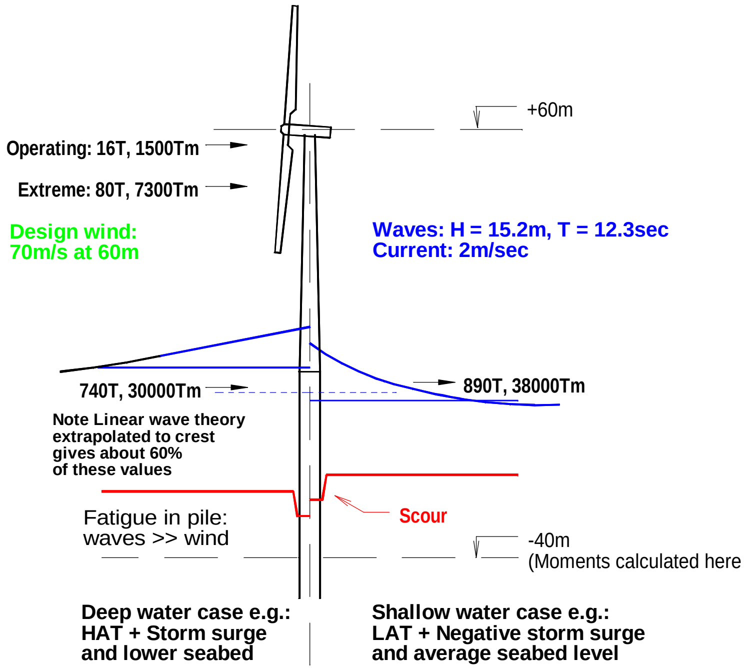


1MW Turbine in 20m (LAT) water

Figure 1 – Case study structure and setting

Forces and moments in the structure have been evaluated for both scenarios and the results are illustrated in Figures 2 and 3. Note that the moments are calculated about a point in the tower foundation that is at –40m LAT.

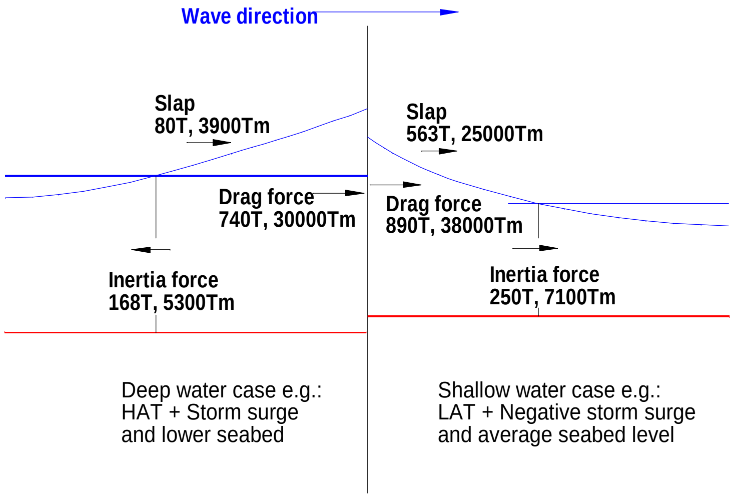
The results in Figure 2 show that for this particular structure and setting, the structure loading and fatigue is dominated by the effect of the waves rather than the wind. Note also that although less of the structure is wetted in the shallow water case (right hand side of diagrams), the reduced water depth acts to make the waves very steep and therefore the structure is subjected to high wave forces associated with spilling breakers. By contrast, in the deep water case (left hand side of diagrams) the waves will be larger but less steep and therefore exert slightly lower wave loads on the structure. This result is perhaps counter-intuitive and highlights the need to consider the characteristics of the waves very carefully.



1MW Turbine in 20m (LAT) water
Forces, Moments about -40m

Figure 2 – Structure forces and moments

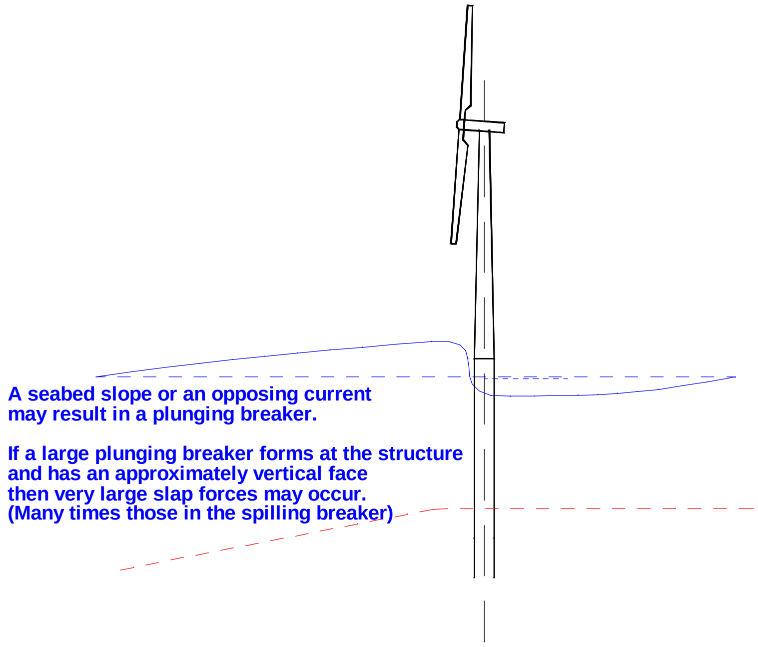
This point is further emphasised in the breakdown of the wave forces and moments into drag, inertia and slap components shown in Figure 3. These results indicate that for this structure and setting the drag forces are dominant in both scenarios. However, the slap and inertia forces evaluated in the deep water and shallow water cases are markedly different. The slap forces (and moments) expected in the shallow water case are several times greater than in the deep water scenario. Furthermore, the deep water case inertia forces are not only smaller in magnitude than the equivalent shallow water case, but also the inertia force maxima occur at different points in the wave cycle and in fact act in opposite directions. These differences are primarily due to water depth modifications to the shape of the waves reaching the structure.



1MW Turbine in 20m (LAT) water
Forces, Moments about -40m
Drag, Inertia and Slam forces
(showing position along wave of maximum force)

Figure 3 – Structure forces and moments – drag, inertia and slam force components

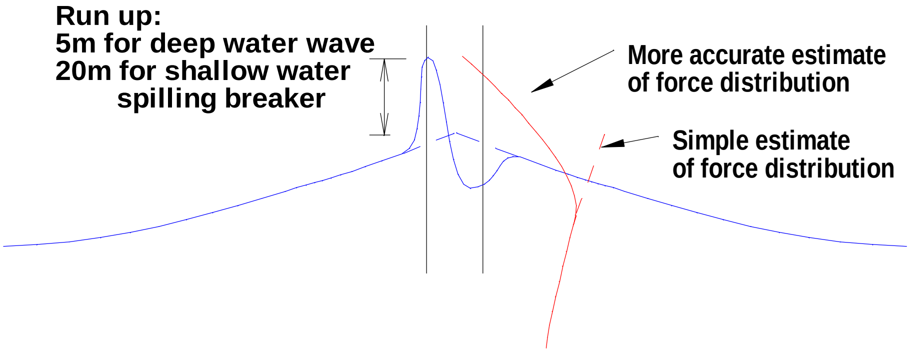
Figure 4 indicates the effect of increasing the seabed slope immediately before the structure. This may cause the waves to form into a plunging breaker, rather than the less onerous spilling breaker. In these circumstances, *very* large slap forces may occur that could be many times those from spilling breaking waves.



1MW Turbine in 20m (LAT) water
Slap force in a plunging breaker

Figure 4 – The effect of plunging breakers on slap forces

Finally Nigel explored briefly the issue of wave run-up on the support tower. In storm conditions, the run-up on the up-wind side of the tower will be significantly larger than on the leeward side which could significantly modify the forces in the region of the water air interface, as indicated in Figure 5. This may cause a stagnation point to form at which point the simple Morison equation starts to breakdown.



1MW Turbine in 20m (LAT) water
Run-up and force modification

Figure 5 – Wave run-up on a tower structure

Research into improving techniques for estimating the size of wave forces on seabed-mounted wind structures is currently on-going. Prof Barltrop took the opportunity to draw attention to the tri-party EPSRC project that has just been funded under RNET (see section 2.3) to investigate wave loading of turbine structures.

Questions and comments:

Questions and comments on this presentation are grouped at the end of the session.

3.3 Structural modelling

Dr Colin Billington, BOMEL Ltd

Tel: 01628 777707, Email: bomel@compuserve.com

Dr Billington briefly introduced the main offshore wind turbine support structure concepts currently being considered - piled tubular caisson (monotower), piled braced tubular caisson, piled tubular jackets (with 3 – 4 legs), piled tower and gravity base structures. Each support structure could be fabricated from steel and/or concrete and will consist of a set of basic components e.g. tubular members, fabricated tubular joints, castings, grouted connections, grout/concrete filling, concrete cellular bases, stiffened cylinders etc..

Colin emphasised that although the offshore oil and gas industry is well know for designing large and highly complex structures such as the high profile platforms found throughout the North Sea, they also have plenty of experience designing much simpler structures more akin to wind installations.

Offshore wind installations are likely to be subject to many loading types including the self-weight and buoyancy of the structure as well as the influence of winds, waves, currents and temperature effects. In addition the design must account for risk factors such as ship impact, anchor damage, movement of the seabed, scour and erosion. Finally, over time the design must allow for corrosion/deterioration of the structure and the effects of bio-fouling (marine growth both adds weight *and* alters the roughness of the structure which changes the loading on the structure).

A great deal of expertise in design of offshore structures already exists. Dr Billington drew attention to a series of **well-established offshore structural design codes** that have been developed and used by the offshore industry over many years. They include: **API RP2A (LRFD/WSD)** – American design codes on Load Resistant Fatigue Damage and Working Stress Design; the Health and Safety Executive (HSE) guidance notes – *now withdrawn* but the key sections which are based on large amounts of research are being issued as **Offshore Technology reports**; **ISO 13819-2** – similar to RP2A but set to include some significant additional sections (*currently at the final draft stage*). There are also a series of national and industry guidelines available such as Classification Society rules (e.g. **DNV**), national regulations (e.g. **HSE, NPD, MMS**) and industry guidelines (e.g. **OPG, CRINE, NORSOK**). *These design codes are based on many years of research and experience*. They provide information and guidance on definition of limit states, partial factors, loads and load calculation, definition of resistance and resistance formulation (e.g. members, joints, piles, grouted connections, stiffened cylinders, stiffening plating etc.), fatigue, system behaviour and robustness, structural modelling and analysis, foundation design, materials, corrosion protection, welding and fabrication, load out, transportation and installation, in-service inspection and structural integrity management.

The main structural design considerations for an offshore wind energy installation are:

- **Dynamic response and interaction** - Due to the size and nature of offshore wind structures, dynamic responses and interactions are likely to be more significant than for traditional offshore structures. To model the behaviour of the overall structure, a global model can be developed that represents the structure as a series of elements such as beams, beam/colums, non-linear soil springs and masses. Due the importance of (and level of uncertainty about) the **dynamic sensitivity** of offshore wind structures it is essential to perform a **natural frequency analysis**. This should establish the sensitivity of the structure to foundation stiffness and determine the important mode shapes and frequencies. Comparison of the natural period of the structure with the loading periods will reveal how dynamically sensitive the structure is. The size and nature of offshore wind structures means that they are more likely to be dynamically sensitive than traditional offshore structures.

- **Strength – survivability under extreme environmental loading** –The structure must be tested for its response to extreme storm loading based on extreme wind, wave and current conditions at the site and taking into consideration the joint probabilities of occurrence. In extreme waves the buoyancy loading of the structure will be highly variable. Although this variability is likely to be less important for wind structures than traditional offshore oil and gas installations, in some cases the buoyancy loads may alter by +/-20%. The wind turbine loads can be modelled by superposition of steady state loads and turbulence. It must be remembered that offshore wind structures are likely to have very little redundancy. In particular, single member structures (such as a monotower) cannot redistribute load if they become damaged. In structures that behave linearly and which are *not* dynamically sensitive, a **quasi-static** extreme storm analysis can be performed. The loading is stepped through the structure and analysed for various wave directions. The dynamic response is allowed for by applying a global dynamic amplification factor to the stresses. The strength of members and joints can then be checked against design codes. However, if the structure behaves non-linearly or is dynamically sensitive, the structure must be evaluated using a **dynamic transient** analysis. In these cases a detailed time-history loading must be applied to the model and dynamic amplification is automatically included. Any damping inherent in the structure and soil (including the cyclic behaviour of the soil, if known) should also be included.
- **Fatigue** – The design of wind turbine structures onshore is often dominated by fatigue considerations. Fatigue in wind structures is also likely to be VERY important offshore. The offshore industry commonly use **deterministic fatigue analysis** techniques on offshore structures. However, these techniques are only applicable to structures with natural periods that are different to the period of waves with significant energy and which exhibit little or no dynamic amplification and hence display quasi-static behaviour. Fatigue in wind turbine support structures that *are* dynamically sensitive should be evaluated using a **spectral fatigue analysis** method. The advantage of this method is that it provides a statistical assessment of the structural response in a sea-state defined by a wave spectrum (say Pierson-Moskowitz or JONSWAP) by combining stress results from a series of regular wave analyses. However, it assumes *linear* loading, structural behaviour and foundation models and the waves used as input to the analysis must be selected with care.
- **Serviceability** – This is likely to become important if excessive deformation in the structure results in a significant reduction in the operating efficiency of the turbines.
- **Reliability**- Offshore wind structures will be difficult to access and maintain, therefore it is essential that the design be reliable.

Finally, Dr Billington noted that offshore wind structures are complex structures that must be designed with care. Although the existing offshore design codes provide useful guidance, offshore wind structures are likely to be exposed to non-linear wave loading, caused by shallow water wave effects and wave breaking, as well as additional loads associated with the presence and operation of the wind turbines. Furthermore, the foundations are likely to be non-linear. Colin suggested that the structures should be designed so that the response is linear and exhibits acceptable levels of yield.

Questions and comments:

Questions and comments on this presentation are grouped at the end of the session.

3.4 Fatigue loading of offshore wind turbines: wind and waves combined

Dr Tim Camp, Garrad Hassan & Partners Ltd

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Tim Camp presented results from an investigation into **fatigue damage** in offshore wind turbines under the **combined action of wind and waves**. The simplest method of estimating fatigue damage in offshore wind installation components is to merely add the fatigue damage caused by winds (based on onshore wind industry models and experience) to the fatigue damage expected from the waves (based on conventional offshore industry models and experience). Unfortunately this approach ignores an important phenomenon; when in operation wind turbine rotors produce **aerodynamic drag and lift** which has a considerable **damping** effect on the structures which in turn potentially reduces the level of fatigue damage. This study has shown that an integrated treatment of wind and waves is essential for predicting fatigue damage and could result in significant cost savings as over-conservative designs can be avoided. Tim also described briefly a model that has been developed recently to predict combined wind/wave fatigue damage. A more detailed description of this piece of work is included in the document available online at:

http://www.owen.org.uk/workshop_3/tim_camp.pdf

Tim highlighted the urgent need for verification of the new model. There are plans to use the turbines off Blyth (scheduled for installation during the summer of 2000) as a test bed to verify the design methods, but more validation is needed.

Finally Tim suggested the following issues still need to be addressed:

1. **To consider the duration of offshore simulations in more detail (currently the offshore industry standard of 3 hour simulations has been adopted, but this is computationally expensive – could it be reduced?).**
2. **To perform extensive correlation of wind strength and wave heights on which to base more reliable fatigue and extreme loading calculations.**
3. **To question the acceptability of using linear wave theory for fatigue calculations at shallow water sites.**

Questions and comments:

Questions and comments on this presentation are grouped at the end of the session.

3.5 Analytical tools for tailoring the dynamics of cost effective offshore wind energy converters

Martin Kühn, Tacke Windenergie GmbH

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To produce the final design of offshore wind structures it is clearly necessary to carry out a detailed assessment of the structure that is as full and comprehensive as possible. This may involve integrated, non-linear time domain simulations of the structure (turbine, support tower plus foundation) which are very time consuming. However, this depth of analysis (and the time and effort required) is not appropriate for early project design stages (e.g. producing preliminary and conceptual structure designs) when a large number of outline designs must be evaluated quickly for a large number of loading cases, but a very high degree of accuracy is not required. For these tasks, a **simplified structural design tool** that is **less time consuming** to run would be highly desirable.

Martin introduced a simplified (but not simplistic) approach to fatigue analysis. The methods he suggested use standard design tools to consider **separate analyses of the wind (aerodynamic loading) and wave (hydrodynamic loading) responses**. Time domain simulation of a wind turbine and its support structure in a calm sea can be used to make a good approximation of the aerodynamic fatigue loading. In addition, a linear spectral analysis of the support structure (with a top mass/inertia representing the wind turbine) can be used to approximate the hydrodynamic fatigue loading. The aerodynamic damping experienced when the turbine is in operation can be approximated by adding structural damping in the appropriate direction. The final stage is to combine the results from the time domain and spectral analyses to estimate the **equivalent fatigue loads**. This may be done by superposition of either short-term or long-term fatigue loads. Note that the aerodynamic and hydrodynamic fatigue *damage* CANNOT be simply added together since the level of fatigue damage incurred is highly non-linear with stress). If properly applied these methods are likely to produce results with an acceptable accuracy for conceptual design studies.

Martin also noted that the offshore industry commonly reduce the number of loading cases that must be considered by adopting the technique of **load case lumping**. He suggested a method for constructing a small number of lumped loading cases that represent the full environmental characteristics of a site. This should reduce the overall design effort required further.

More details of this piece of work are included in a document available online at:

http://www.owen.org.uk/workshop_3/martin_kuehn_1.pdf

3.6 Questions and comments

Would it be possible to determine a set of standard loading conditions for offshore wind turbines (similar to the standard loading conditions currently used on land)?

> Offshore design constraints (e.g. wave characteristics, current patterns, seabed mobility etc.) will be very much more site specific than onshore. Therefore, in general it will not be possible to produce a set of standard offshore design conditions that would be appropriate for large sections of UK waters.

Given that the presentations have made it clear that the magnitude of environmental loading on wind turbines is not linearly related to the water depth, what are the cost implications for designs?

> Nigel Barltrop recommended that sites with a water depth such that the largest waves in the design sea state are breaking at the wind turbine structure should be avoided because this scenario results in very high hydrodynamic loads. If the structure is sited in deeper water the wave loads could be reduced, but it may not prove to be cost-effective as the structure may require deeper piles in the foundation etc.
>
> Existing offshore wind turbine developments are sited in very shallow water and therefore the wave loads are much reduced (because the large waves will have already broken and the lever arm for moments is small). In these circumstances, wind loads may begin to dominate.

Onshore wind turbine load simulations typically have 10 minute duration, whereas the offshore industry has typically used 3 hour simulations. 3 hour simulations are computationally expensive so could the simulation be reduced?

> It could be feasible to shorten simulation times for fatigue analyses, but it may be more difficult to use these to get extreme loads based on such a limited simulation. However,

it should be easy to pick out an extreme event which results in an extreme loading event (note that this does not necessarily coincide with a maximum wave height event) which can be embedded in a short 10 minute simulation.

4. Ground conditions and foundations

Session chair Mr Tony Hodgson, Fugro Ltd.
Tel: 01442 240781, Email: ajhodgson@fugro.co.uk

4.1 Ground conditions

Mike Horsnell, Fugro Ltd.
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Mike first outlined the ground conditions found in each of the primary areas of interest for offshore wind development in UK waters (the Northeast coast, the Lincolnshire coast, the East Anglian coast, the Thames Estuary, the South Wales coast and Liverpool Bay). He also noted the main challenges in each area for a geotechnical engineer including mobile sand features and difficulties in piling in areas with clay with boulders etc.. He suggested the most geotechnically difficult of the areas is likely to be Liverpool Bay because of the combination and highly variable nature of the quaternary sediments, till mounds (with numerous cobbles and boulders) and sand features that occur in this region.

Before the foundation can be designed in detail, it is essential to understand the behaviour of the soil at the site. Comprehensive investigations of the seabed are needed to evaluate the **soil parameters**. The exact information required depends to some extent on the type of foundation structure being considered, but it generally includes the basic soil classification (e.g. the liquid limit, plasticity etc.), the soil stratigraphy, the unit weight, shear strength (clays), friction angle (sands), soil stiffness, cyclic behaviour, dynamic behaviour etc.. Coastal site **geotechnical investigations** use a number of well-established sampling techniques to obtain the information required. The investigations may be performed from either a jack-up rig (1.5 – 25m water depth) or from a geotechnical drill ship (minimum 15m water depth) using a heave compensated drill rig. The resulting ground condition data as well as details of the structure designed to transfer the loads and moments into the ground (e.g. the pile or gravity base) are used to predict the overall response (displacements and resonance) of the foundation for input into the dynamic structural design models.

Loose sand and soft clays are sensitive to seabed currents that develop around the base of the structure. This can lead to **sediment scour** which may become particularly prevalent in areas with strong tidal streams or wave breaking zones. Scour will effect foundation types differently – for example, piled foundations will suffer from a localised reduction in over-burden pressure and a loss of lateral resistance at the seabed while gravity base structures may undergo erosion of soil from beneath the base of the structure. There are two main design options for dealing with scour; allow for scour in the foundation design or monitor the scour that occurs and replace the material if necessary.

The offshore and coastal engineering industries already have a large amount of expertise in marine foundation design. There are **well-established design codes** available which provide a good basis for offshore wind turbine foundation design, but in general the codes do not cover the more difficult design aspects often encountered in practice such as layered soils or cyclic loading effects. **There is considerable scope for additional work to develop design codes applicable to more challenging (and realistic) ground conditions.**

4.2 Types of foundation and foundation modelling

Prof Guy Houlsby, Department of Engineering Sciences, Oxford University

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The technology and design of foundations on offshore structures is both well developed and well established and therefore there is **huge scope to draw on the accumulated knowledge within the existing offshore oil and gas industry**. Many different offshore foundation designs are in use today, each tailored to a specific application including piles (up to 80m long and 2m diameter), suction caissons, gravity structures (which rely on their own mass to provide stability) and temporary foundations such as spud cans for jack-up rigs (shallow conical structures up to 20m in diameter). Many of these technologies can be drawn on for the design of offshore wind installation foundations, however, there are a few major differences which must be considered in the design:

	Traditional offshore structures	*Wind energy structures*
Water depth	20m – 120m	10m – 25m
Loading - vertical	5 000- 30 000 tonnes	100 – 300 tonnes
- horizontal	10% - 20% of vertical load	70% - 150% of vertical load
Overturning moment	Water depth x horizontal load	(water depth + 50m) x horizontal load
Number of installations	1	20 - 100

It is clear that the foundations for wind energy structures will be in much shallower water, and must support much smaller vertical loads but much larger horizontal loads and overturning moments. Furthermore, as so many foundations are required, the cost per structure must be proportionately lower.

There are basically six structure/foundation design types to choose from – either a **monopod** or tripod structure each supported by **gravity base**, **caisson** or **pile** foundation. Of these options, the tripod structures are not as attractive geotechnically, because they result in complex structures and with multiple installations envisaged it is probably necessary to keep the design as simple as possible. Each of the monopod solutions has its advantages and disadvantages - for example, gravity base and caisson foundations are likely to be particularly good in homogeneous soils, whereas pile foundations will be better in highly variable soils – however, it is **unlikely that one foundation solution will be the best in all situations**. At the moment the most popular design is the monopile foundation, but in the long-term this may not be the most economic foundation option.

Ultimately the design of offshore wind structure foundations is likely to be driven by the following design considerations:

- **Cost of installation** – this will be crucial to the economic viability of offshore wind farms because so many individual structures will be required.
- **In service performance** – The foundation must cope with repeated cyclic loading and large overturning moments. Furthermore the design is likely to be dominated by serviceability rather than failure and at some sites sediment scour could be very severe.
- **Removal** – When the offshore wind farm is decommissioned, operators may be required to remove entirely all obsolete structures. Therefore the foundation should be designed with the feasibility and cost of removal in mind. (*Note, as yet no-one knows how to remove piles*).

Offshore pile foundations have evolved from onshore designs. This type of foundation is supported by a large amount of empirical experience and so there is no need to develop the science further. Similarly there is extensive experience of gravity base foundations and the designs can follow accepted procedures.

By contrast, caisson foundations have no precedent onshore and there is also relatively little experience of these structures offshore. As a result there are few design procedures available and there is considerable scope for further scientific investigation of caisson foundation behaviour and design. At present caisson behaviour is understood for simple cases, but more information is urgently required on caisson foundation responses to horizontal, overturning and cyclic loading.

Finally, Prof Houlsby predicted that early offshore wind farms will use adaptations of conventional offshore foundations (as seen in offshore wind farm developments completed to date), but that in the *long-term* the industry is likely to develop radically different foundation designs because offshore wind structure design considerations are significantly different to the traditional offshore scenario.

4.3 Buildability

Paul Heywood, Kvaerner Oil and Gas

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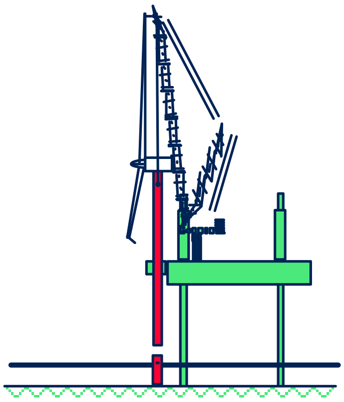
An offshore wind farm requires much closer integration of the design and construction activities than an onshore wind farm because of the additional challenges of operating at sea. In this presentation Paul discussed the construction requirements for an offshore wind farm with particular emphasis on the foundation components. He highlighted some fundamental differences in terms of the **size**, **weight** and **installation demands** of the main foundation types under consideration. Some typical examples are given below:

FOUNDATION TYPE	*SIZE (diameter)*	*WEIGHT*	*CONSTRUCTION SEQUENCE*
GRAVITY BASE	12 – 15 m	500 – 1000 tonnes	1. Prepare Seabed 2. Placement 3. Infill Ballast
MONOPILE	3 – 3.5 m	175 tonnes	1. Place Pile 2. Drive Pile
MULTIPILE	0.9 m	125 tonnes	1. Place Base 2. Drive Pile
BUCKET (CAISSON)	4 – 5 m	100 tonnes	1. Place Base 2. Suction Installation

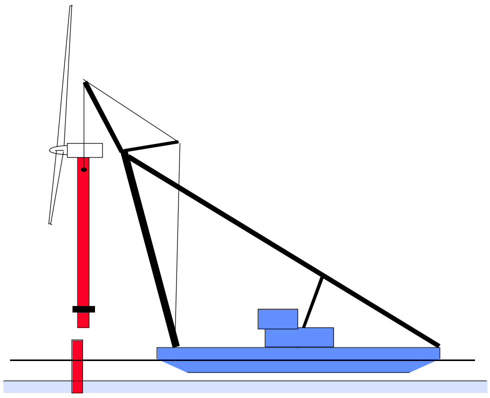
Furthermore, each type of foundation will be subject to certain **construction constraints**. A comparison of the construction differences for monopile and gravity base foundations is summarised below:

CONSTRUCTION PHASE	*GRAVITY BASE FOUNDATION*	*MONOPILE FOUNDATION*
Onshore construction	Local to Site	No Constraints
Transport offshore	More Complex	Lift onto Barge
Pre-placement activities	Seabed Preparation	None
Placement	Lift or Float-over	Lift
Fixing	Grouting	Pile Driving
Installation of tower / turbine	Potential Obstruction to Lift	No Hindrance to Lifting

Offshore wind turbines are most likely to be installed from either a **jack-up barge** or a **floating crane vessel** with typical examples illustrated below.



a) Jack-up barge construction



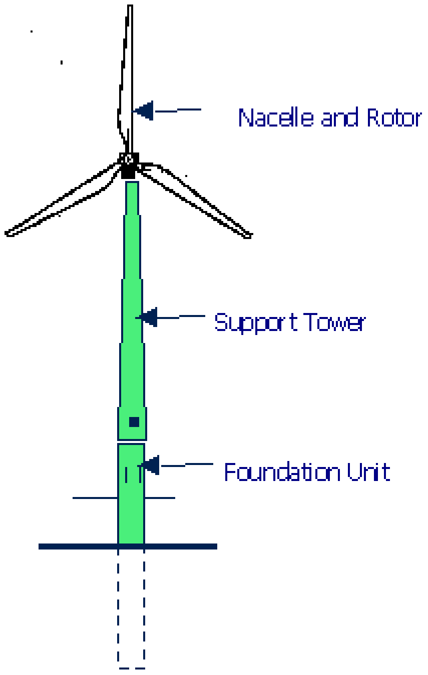
b) Floating crane vessel construction

The choice of plant will depend on the **water depth**, the **crane capability** and **vessel availability**. The crane must be capable of lifting the structures, with hook heights greater than the level of the nacelle to enable the tower and turbine assembly to be installed. Examples of vessels that may be suitable for offshore wind farm installation operations are given below:

VESSEL	*VESSEL SIZE*	*GROSS TONNAGE*	*LIFT CAPACITY / HEIGHT*
FLOATING CRANE VESSELS			
Smit Land LM Balder	110m 30m 7.6m	7772t	500t / 60m
Smit Tak Taklift 4	83m 35m 7.0m	4854t	2400t / 75m
Smit Tak Taklift 7	73m 30m 5.5m	3513t	1200t / 65m
Bugsier Thor	76m 24m 4.7m	2667t	350t / 80m
Ugland Uglen	78m 26m 4.3m	1589t	600t / 75m
JACKUP VESSELS with integral crane			
Ballast Nedam Buzzard	43m 30m 4.2m	c1750t	198t / 62m
Interbeton IB909	43m 30m 4.4m	1796t	272t / 57m
Amec Wyslift	38m 32m 4.4m	1410t	280t / 50m
Seacore Deep Diver	30m 20m 4.5m	1675t	50t / 51m

Existing crane vessels have not been specifically designed for installing offshore wind turbines. For large offshore wind farms, greater than 50 units, significant time (and therefore cost) savings could be made by using an installation vessel **purpose built** for the task. This philosophy has been adopted elsewhere in the civil engineering industry and for the wind sector outline vessel concepts have been prepared by Kvaerner.

The total build duration for a multi-unit wind farm is likely to take several months. All installation operations will be subject to **weather constraints** and there will inevitably be periods of non-operation/weather down-time. This can be minimised by scheduling installation operations during the relatively calm summer months, when both wind speeds and wave heights are most frequently within safety limits. (It should be noted that lifting at the limit of a crane's capabilities imposes particularly severe weather restrictions on lifting operations.)



Paul went on present some results from a comparison of relative **build duration** estimates for different offshore wind turbine installation/construction methods. Actual construction time for a driven pile foundation from a floating barge was initially shown to be less than other methods. But when weather downtime was included, the overall installation durations were similar (within 20%) for gravity base foundations and driven pile foundations installed either from a jack-up vessel of floating barge. The weather downtime allowance required for a 50 unit wind farm is considerably, approximately doubling the floating barge installation duration. Finally, the results showed that significant build duration savings could be made by installing the structure in two pieces (first the foundation unit followed by the assembled support tower, nacelle and rotor as one unit) compared to three pieces (installing each of the foundation, support tower and nacelle and rotor units in a separate operation).

In view of issues discussed here, Paul suggested that offshore wind energy structures and their foundations must be designed to accommodate exposed weather and equipment workability, with support towers designed to be compatible with the available construction equipment. Finally, he highlighted three areas where additional work is required:

1. **Improved dissemination of knowledge of offshore marine related construction procedures and techniques amongst designers/developers.**
2. **Evaluate the robustness of existing offshore pile design techniques for low mass, fatigue dominated applications.**
3. **Optimise the cost-effectiveness of offshore wind structure installation operations by making use of novel construction sequences and scenarios.**

5. Practical experiences

Session chair	Nick Bristow, RES Ltd. Tel: 01727 797942, Email: nick.bristow@res-ltd.com

5.1 Design of solid concrete foundations for the 40MW offshore wind farm at Middelgrunden

Per Vølund, SEAS

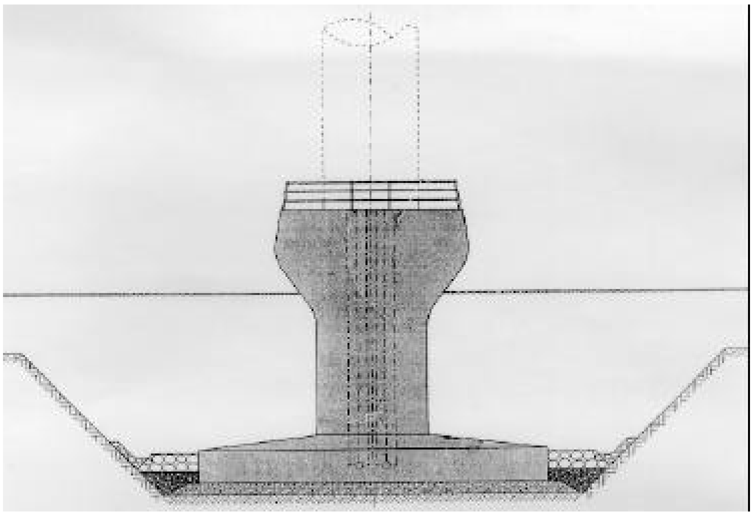
Email: per.volund@seas.dk

Per introduced the Middelgrunden project in which twenty Bonus 2MW turbines will be installed on a shoal just offshore of Copenhagen. He described the environmental and ground conditions at the site as well as the process used to select the foundation design finally adopted. The wind farm is scheduled to be fully operational by November 2000.

The site occupies a shallow bank (water depth 3 – 6m) where the seabed consists of a layer of polluted sand over 10m of till clay lying on top of limestone embedded with flint. The site can expect mean wind speeds of 7.2m/s at 50m height and (by UK standards at least) the wave regime is benign with a maximum wave height of only 3.8m (H_s=2.6m). However the area is prone to sea ice (design values for ice: thickness 0.6m, flake size 2*2km, speed 1.0m/s).

The structure is designed to include an ice-cone that reduces ice loads by a factor of 5-10. This means that ice loads are no longer the design loading case for the structure and foundation. Wave loads at the site are relatively small (because the water is very shallow and maximum wave height is small) and therefore environmental loads are dominated by the wind. A statistical study was performed to estimate the correlation between winds and waves. However, given the scarcity of data available to validate the correlation, the final design loads included a conservative reduction (of only 15% of the superposed wind and wave loads) to account for structure wind and wave interactions.

Following a tendering process, three foundation concepts – two gravity base structures (one a solid concrete plate, the other a ballasted steel caisson) and a monopile design - were developed and submitted for consideration. The concept selected for the project was the cheapest solution, which turned out to be the solid concrete plate foundation developed by Carl Bro AS. This design is similar to the foundations commonly used in megawatt-size turbines on land. There is a hollow steel cylinder between the concrete plate and the tower that is surrounded by a layer of concrete, which not only protects the steel from corrosion but also forms the ice-cone. Unlike on land, no ballast is added to the base plate however additional ballast is incorporated by filling the inside of the steel cylinder with sand.



Solid concrete plate foundation used at Middelgrunden (Carl Bro AS)

The ballasted steel caisson and monopile foundations were costed as 10-20% and 20-40% more expensive respectively than the concrete plate option. (The relative expense of the monopile design results from difficulties with piling into limestone embedded with flint.)

5.2 Dynamics of offshore wind energy converters on monopile foundations – experience from the Lely offshore wind farm

Martin Kühn, Tacke Windenergie GmbH

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Martin briefly described the Lely wind farm which consists of four 500kW NedWind 40 turbines at a site in the IJsselmeer. The structures are approximately 800m from the shore in water depths that range from 5 - 10m.

The project was commissioned in 1994 by PEN Energiebedrijft Noord-Hooland (now Energy Noord West), and used innovative monopile foundations. The variation in water depth and ground conditions across the site meant that three of the foundations were designed as soft-stiff characteristics, but the fourth (deepest) foundation was intended to display soft-soft characteristics as structural dynamic calculations predicted the first natural frequency of the structure would be below the rotor frequency.

Martin explained that six months after the installation a series of follow-up measurements were gathered from two of the support structures. Analyses showed that both structures displayed *stiffer* behaviour than predicted by the design calculations. Furthermore, in the deepest structure this error was so marked that the foundation actually displayed soft-*stiff* rather than soft-*soft* characteristics! Fortunately the magnitude of the change in behaviour of this structure means that it has in effect "leap-frogged" the intermediate dynamic state where resonance would have caused very severe structural problems.

Finally Martin outlined the findings of a parametric study that aimed to identify possible explanations for the mismatch between the predicted and measured behaviours of the structures. It is thought that the relatively low pile penetration depth and the inherent uncertainties about the in situ soil parameters are the most likely causes. He also presented an example of an optimised design for this site with tailored dynamics.

More details of this piece of work are included in a document available online at:

http://www.owen.org.uk/workshop_3/martin_kuehn_2.pdf

5.3 Application of rock socket monopile techniques to offshore wind farm construction

Peter Clutterbuck, Seacore Ltd.

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Peter was keen to highlight that the offshore oil and gas industry is *not* the only source of expertise for design and construction of marine structures. He drew attention to the vast amount of experience in such matters within the port and marine works industry.

The use of monopiles in port construction works is very well-established with a wide range of applications. The monopile is a very flexible component that can be easily fabricated with a range of diameters and wall thicknesses. They can either be driven into position using a hammer or a plug or rock socket can be created before the pile is placed into position. Monopiles are simple and economic to fabricate and allow scope for extensive pre-assembly of the units. Furthermore, repetitive installation operations can result in significant further cost savings. Compared to gravity base foundations, use of monopiles can avoid long lead times required for complex unit fabrication and eliminates the logistical problems associated with transporting and installing heavy structures. The piles can be fitted with end-caps that allows them to be floated out to the site. Added advantages of this technique include a reduction in the risk of damage during the lift and the fact that the crane does not take the full weight of the pile at any point in the installation sequence.

Peter outlined some of the lessons learnt gained during the recent Bockstigen-Valar project in Sweden, where five offshore wind turbines were installed on rock-socket monopile foundations using a jack-up vessel:

- Pre-assembly of the pile could have been extended to include the ice shields, access ladders etc.
- The build demonstrated the ability to achieve the required level of accuracy for flange connections etc.

- It is vital to have a truly integrated design team including a representative with construction/installation expertise and to have excellent communication within the team from the earliest project planning stages.
- Delays to this project force the build to be much later in the year than expected. However, this demonstrated that it is possible to operate in late season weather.

The experience gained so far will be applied to future offshore wind energy projects (e.g. Blyth). Furthermore, Peter dismissed claims that it is not possible to install large diameter piles. He suggested that all monopile foundation designs currently being contemplated for offshore wind energy structures *could* be built.

Finally, Peter outlined ideas for further research and development effort for monopile foundations including:

1. **Development of alternative/novel monopile installation methods e.g. pile oscillation or rotation techniques**
2. **Optimisation of the empirical design methods currently used through monitoring of structures and comparison of actual behaviour with design calculations.**
3. **Investigations to improve the understanding of pile/soil interactions and in particular the impact of soil disturbance during installation.**

6. Summary of principal knowledge gaps identified

Speaker Dr John Carey, Sage Engineering Ltd.
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WAVE CHARACTERISATION

- Wave spectra models that have been developed and tailored for deep water offshore locations (e.g. JONSWAP and Pierson-Moskowitz) may not be ideal for modelling waves in very shallow coastal waters such as are currently being considered for offshore wind structures. Shallow water effects (e.g. wave breaking) and the influence of the coastline dynamics and the seabed profile will have a significant effect on wave heights/periods/directions especially in storm conditions.
- The expertise and software models necessary to study the wave and current related phenomena, such as shoaling, refraction and sediment transport already exists in the coastal sciences community.
- Cross-fertilisation of knowledge is required between the "offshore" and "coastal" communities in order to develop the required wave spectra for structural analysis of offshore wind strucutres

HYDRODYNAMIC LOADING

- Impulsive loads, such as slam/slap forces caused by breaking or near-breaking waves, can be significant in terms of global structural design. Typically offshore structural engineers are used to designing structures in "deep water", where slam/slap has been a local rather than a global design issue.
- To address this lack of understanding, the dynamic behaviour of wind turbine support structures under impulsive loads due breaking waves is currently being researched.
- Impulsive loading can have resonance effects even when the period of the breaking waves and the natural frequency of the structure do not coincide. Therefore, for monotower-type structures subject to breaking or near breaking waves it is necessary to ignore the general rule commonly used for offshore structures which states that if a structure has a natural

period less than 2 seconds it will not be dynamically sensitive to wave loading and a global dynamic analysis will not be required (so-called "2.5 second" rule).

- The coastal engineering community has extensive experience/knowledge of designing structures in the breaking wave zone and possess methods for calculating the slam/slap forces due to breaking waves.
- Cross-fertilisation of knowledge between these different communities on this particular topic would be very useful.

FATIGUE ANALYSES

- Is there a true need for a fully integrated treatment of wind and wave loading?

    YES: for detailed design stages where accuracy is crucial

    NO: for preliminary and conceptual design stages where speed is more important than extreme accuracy

- There is an urgent need for validation of offshore wind turbine structural design tools currently available.
- Research on the correlation of wind speeds and wave heights is urgently required (for both fatigue and extreme loads).

GROUND CONDITIONS AND FOUNDATIONS

Optimum foundation configuration

- Although monopiles are the current popular choice for foundations, the optimum foundation configuration will be site-specific and depend on the soil conditions, seabed stability, environmental loading, etc. Further study/research on various types of foundation in different conditions would be useful.

Novel foundations

- For novel foundations, such as suction caissons, design needs to be more scientifically based than for piles since very little empirical data or experience exists.
- The behaviour of novel foundations under complex loading conditions (e.g. cyclic loads) needs more research.

Buildability

- Should turbines/towers/foundations be designed to suit construction plant or vice versa in order to minimise the overall costs? Should there be more collaboration between wind turbine manufacturers and offshore contractors?

PRACTICAL EXPERIENCES

Middelgrunden:	Confirmed requirement for wind and wave correlation
Lely	Beware "soft-soft" designs incorporating a “short rigid" piles because soil stiffness is difficult to predict accurately and is invariably underestimated.
Bockstigen-Valar:	Experience highlighted need for an integrated team to include wind turbine/foundation designers, fabricator and installer. Foundation installation contractors are capable of developing new methods of pile installation should increases in pile size make it necessary. However, this would need to be backed-up by research into the influence of the new techniques on the in-situ pile behaviour if existing empirical design methods were deemed to be no longer valid.