INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

66nd IEA Topical Expert Meeting

OFFSHORE FOUNDATION TECHNOLOGY AND KNOWLEDGE, FOR SHALLOW, MIDDLE AND DEEP WATER

September 20-21, 2011

Vattenfall WT Control Centre

Exnersgade 2, DK-6700 Esbjerg, Denmark

Organized by: CENER

Scientific Co-ordination:

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For more information about IEA Wind see www.ieawind.org

International Energy Agency

Implement Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems: IEA Wind

The IEA international collaboration on energy technology and RD&D is organized under the legal structure of Implementing Agreements, in which Governments, or their delegated agents, participate as Contracting Parties and undertake Tasks identified in specific Annexes.

The IEA's Wind Implementing Agreement began in 1977, and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 24 contracting parties from 20 countries, the European Commission, and the European Wind Energy Association (EWEA) participate in IEA Wind. Australia, Austria, Canada, Denmark, the European Commission, EWEA, Finland, Germany, Greece, Ireland, Italy (two contracting parties), Japan, the Republic of Korea, Mexico, the Netherlands, Norway (two contracting parties), Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States are now members.

The development and maturing of wind energy technology over the past 30 years has been facilitated through vigorous national programs of research, development, demonstration, and financial incentives. In this process, IEA Wind has played a role by providing a flexible framework for cost-effective joint research projects and information exchange.

The mission of the IEA Wind Agreement continues to be to encourage and support the technological development and global deployment of wind energy technology. To do this, the contracting parties exchange information on their continuing and planned activities and participate in IEA Wind Tasks regarding cooperative research, development, and demonstration of wind systems.

Task 11 of the IEA Wind Agreement, Base Technology Information Exchange, has the objective to promote and disseminate knowledge through cooperative activities and information exchange on R&D topics of common interest to the Task members. These cooperative activities have been part of the Wind Implementing Agreement since 1978.

Task 11 is an important instrument of IEA Wind. It can react flexibly on new technical and scientific developments and information needs. It brings the latest knowledge to wind energy players in the member countries and collects information and recommendations for the work of the IEA Wind Agreement. Task 11 is also an important catalyst for starting new tasks within IEA Wind.

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

The objective of this Task is to promote disseminating knowledge through cooperative activities and information exchange on R&D topics of common interest. Four meetings on different topics are arranged every year, gathering active researchers and experts. These cooperative activities have been part of the Agreement since 1978.

Two Subtasks

The task includes two subtasks. The objective of the first subtask is to develop recommended practices for wind turbine testing and evaluation by assembling an Experts Group for each topic needing recommended practices. For example, the Experts Group on wind speed measurements published the document titled "Wind Speed Measurement and Use of Cup Anemometry". A document dealing with Sodar measurements are presently under development.

The objective of the second subtask is to conduct topical expert meetings in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates topics in research areas of current interest, which requires an exchange of information. So far, Topical Expert Meetings are arranged four times a year.

Documentation

Since these activities were initiated in 1978, more than 60 volumes of proceedings have been published. In the series of Recommended Practices 11 documents were published and five of these have revised editions.

All documents produced under Task 11 and published by the Operating Agent are available to citizens of member countries participating in this Task.

Operating Agent

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COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
COUNTRY	**INSTITUTION**
Canada	National Resources Canada
Denmark	Risø National Laboratory - DTU
Republic of China	Chinese Wind Energy Association (CWEA)
European Commission	European Commission
Finland	Technical Research Centre of Finland - VTT Energy
Germany	Bundesministerium für Unwelt , Naturschutz und Reaktorsicherheit -BMU
Ireland	Sustainable Energy Ireland - SEI
Italy	CESI S.p.A. and ENEA Casaccia
Japan	National Institute of Advanced Industrial Science and Technology AIST
Republic of Korea	POHANG University of Science and Technology - POSTECH
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	SenterNovem
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Spain	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas CIEMAT
Sweden	Energimyndigheten
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	Uk Dept for Bussines, Enterprises & Regulatory Reform - BERR
United States	The U.S Department of Energy -DOE

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SUMMARY

a) **Participants**
b) **Discussion**
c) **Future actions under the umbrella of IEA Wind**

a) Background

Wind energy installations offshore are increasing year by year and are expected to grow even faster in the future. Currently, March 2011, there is 3.6GW[1] of production capacity installed offshore globally. Forecasts indicate that there will be 40GW[2] installed 2020. That is 10 times more than the currently installed capacity. This tremendous development will pose significant requirements in many areas of wind engineering and especially on foundation development. The challenge is to find structures that can be utilized in an economic, safe and reliable way.

Foundations come in many different shapes and design solutions. To date, offshore wind farms have been constructed in relatively shallow waters with up to 20−25 m water depth. Concrete gravity-based structures and monopiles have been the preferred foundation concepts for these water depths. The next generation of wind farms could be constructed in waters up to 50−60 m deep. To meet the site specifications at these water depths, further development and improved design are clearly needed. The foundations are usually adapted to the prevailing conditions, such as water depth, sea floor conditions and wave/wind/ice-conditions, this may require site specific foundation designs.

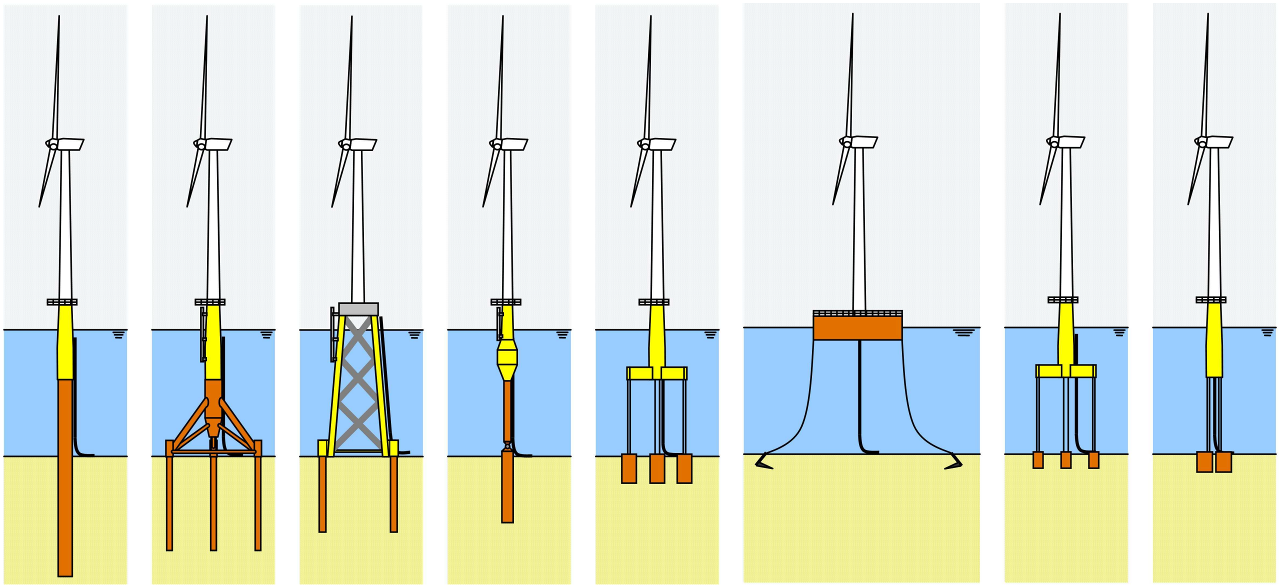

Figure taken from ref [3]

A systems approach to the design of foundations is vital. The reason is that the system dynamic behaviour is very dependent of the flexibilities of the support structures and sea bottom. This puts new and increased requirements on the structural models of the whole system. This becomes even more important when WT systems are up-scaled. The reason for this requirement is the need to understand

[1] BTM World amrket Update 2010

[2] EWEA Pure Power, Wind Energy Targets for 2020 and 2030. 2009 update

the up-scaling effects. It is not necessary possible just to scale up components. An innovative approach is vital when designing larger structures. It is considered that there is a great possibility and need to improve performance of coming foundations in both economic and technical terms.

The EU UpWind project has a separate Work Package on foundation and support structures. Chapter 4.3 in the summary report[3] is an excellent introduction to offshore foundations.

http://www.ewea.org/fileadmin/ewea_documents/documents/upwind/21895_UpWind_Report_low_web.pdf

b) Topics to be addressed

The meeting will mainly focus on bottom fixed structures, but floating structures may also be addressed.

1. General challenges with offshore foundations
2. Up-Scaling
3. Loads, from winds, waves and ice as well as dynamic effects
4. Experiences from other offshore areas
5. Access systems
6. Operation and Maintenance Aspects
7. Research needs

c) Expected outcomes

The outcome of the meeting is the proceedings including a short summary of the presentations and a compilation of topics that are crucial for future development of foundation structures.

Networking is also an important part of the outcome of the meeting.

[3] UpWind – Design limits and solutions for very large wind turbines, March 2011

e) Agenda

Tuesday, September20th

9:00 **Registration**. Collection of presentations and final Agenda

9:30 **Introduction by Host**
Jens I. Madsen , Acting Competence Unit Manager, BD Asset Development / BU Engineering, Vattenfall Research & Development AB,

10:00 **Introduction by AIE Task 11 Operating Agent. Recognition of Participants**
Mr. Felix Avia, Operating Agent Task 11 IEAWind R&D

10:20 **Introduction of Attendees**

10:30 **Presentation of Introductory Note**
Jens I. Madsen , Acting Competence Unit Manager, BD Asset Development / BU Engineering, Vattenfall Research & Development AB,

1st Session Individual Presentations:

11:00 **The European offshore wind industry 2010**
AA Arapogianni, European Wind Energy Association, Belgium

11:30 **Status Some Key Offshore Wind Energy Research Activities in the Unites States**
Walt Musial, National Renewable Energy Laboratory, USA

12:00 **Offshore Overview at Riso**
Thomas Buhl, Riso-DTU, Denmark

●12:30 Lunch

2nd Session Individual Presentations

13:30 Market oriented Evaluation and Development of Offshore Foundations for OWECs. *Júrge Reimers, Offshore Structure, Areva Wind GmbH, Germany*

14:00 Experiences with different foundation types

Frank Hermes, RWE Innogy Offshore Wind, Germany

14:30 Testing and Optimization of Support Structures for Offshore Wind Turbines

Martin Kohlmeier, Fraunhofer Institute for Wind Energy, Germany

15:00 Physical and numerical modeling of the high cycle fatigue loading of offshore wind turbine foundations - some research results

Peter Kudella, Institute for Soil Mechanics & Rock Mechanics, Germany

●15:30 Coffe Break

16:00 Improvements to soil-structure interaction and foundation modeling

E. Van Buren, Norwegian University of Science & Technology, Norway

16:30 Modelling of transition piece in structural and aerolastic codes
Elena Menéndez, Alstom Wind, Spain

17:00 Efficient foundation design of monopile, jacket and hybrid structures: Limitations of current practice, Recent research and Practical Design Tools
Paul Doherty, University College Dublin, Ireland

17:30 End of the Tuesday meeting

Dinner at Fanø Krogård

Wednesday, March 21st

3rd Session Individual Presentations

09:00 Ice loads and ice-induced vibrations in offshore wind turbines
Dr J Heinonen, VTT Technical Research Centre of Finland, Finland

09:30 Simulation and assessment of wind turbines
Urs Wihlfahrt, Fraunhofer Institute for Wind Energy, Germany

10:00 Simulation of support structures for offshore wind turbines and large scale tests
Jan Dubois, Leibniz University Hannover Germany

●10:30 Coffe Break

11:00 Life Cycle Cost for Offshore Wind Farms
François Besnard, Chalmers, PhD student
Thomas Stalin, Vattenfall, Senior Project Manager

11:30 Presentation 13
PKP Passon, Ramboll Offshore Wind, Denmark

●12:00 Lunch

13:00 Discussion and summary of Meeting

14:00 End of the meeting

●14:00-16:00 Optional tour to the Vattenfall WT Control Centre

PRESENTATIONS

EWEA
THE EUROPEAN WIND ENERGY ASSOCIATION

The European offshore wind industry 2010

Athanasia Arapogianni
Research officer
The European Wind Energy Association

21st Sep.2011

EWEA
THE EUROPEAN WIND ENERGY ASSOCIATION

Outline of presentation

- 2010 annual offshore wind power market
- 1991 – 2010 cumulative offshore wind power market
- Main trends 1991 – 2010
- Market outlook: 2011 and beyond

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- 2010 annual offshore wind power market
- 1991 – 2010 cumulative offshore wind power market
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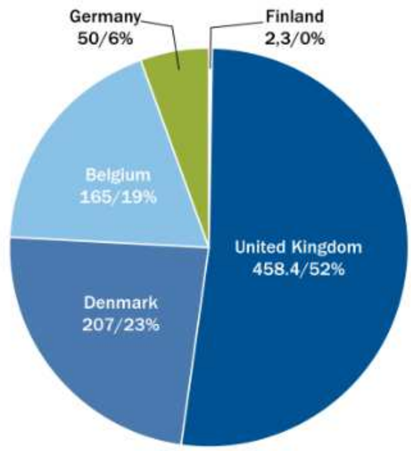
2010 Annual offshore wind power market

- 308 new offshore wind turbines installed and connected
- 883 MW in total – increased by 51% on the previous year
- During 2010, work was carried on 18 offshore wind farms among which
  - Eight wind farms were fully completed and grid connected
  - One wind farm partially completed and grid connected
  - One wind farm completed but not grid connected

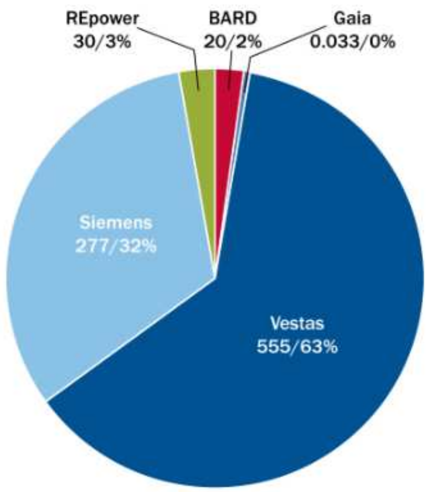
EWEA
THE EUROPEAN WIND ENERGY ASSOCIATION

INSTALLED CAPACITY: SHARE OF 2010 INSTALLATIONS (MW) BY COUNTRY

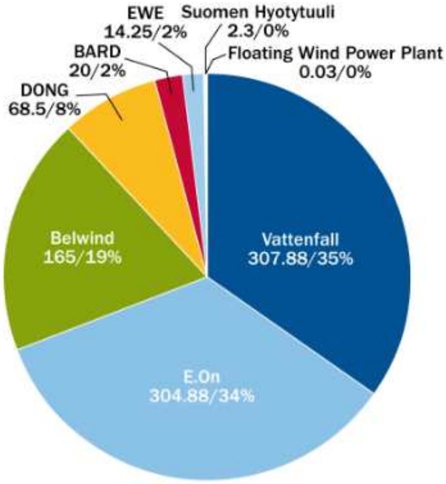


EWEA
THE EUROPEAN WIND ENERGY ASSOCIATION

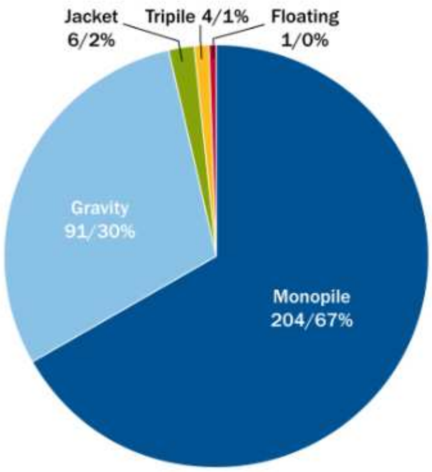
WT MANUFACTURERS: SHARE OF 2010 INSTALLATIONS (MW)



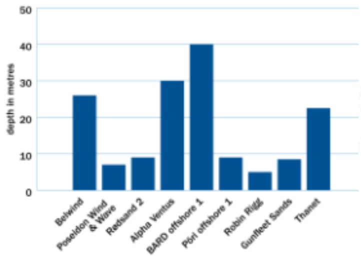
DEVELOPERS: SHARE OF 2010 OFFSHORE MARKET IN

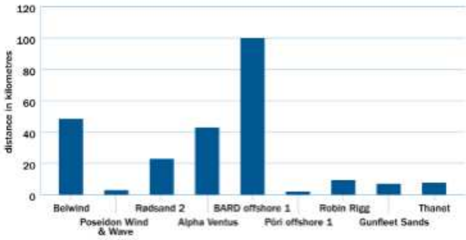


FOUNDATION TYPE IN 2010 OFFSHORE WIND FARMS



AVERAGE WATER DEPTH AND DISTANCE TO SHORE - 2010





- Average water depth: 17.4 m in 2010
- Average distance to shore: 27.1km

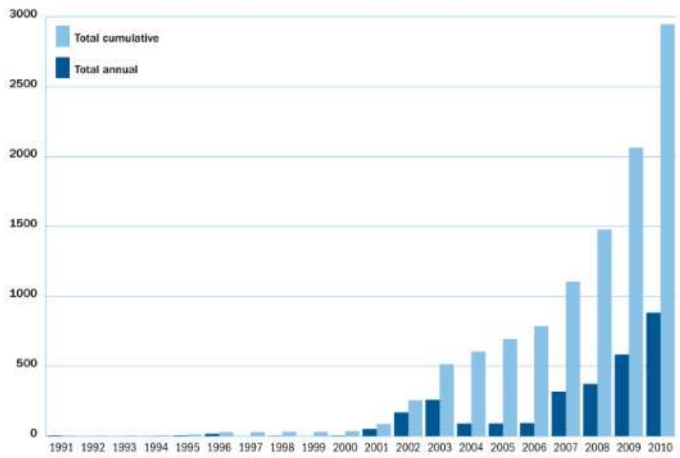
Outline of presentation

- 2010 annual offshore wind power market
- 1991 – 2010 cumulative offshore wind power market
- Main trends 1991 – 2010
- Market outlook: 2011 and beyond

Cumulative Market

- 1,136 turbines installed and grid connected
- 2,946 MW in total
- 45 wind farms in nine European countries
- Produces 11.5 TWh of electricity in a normal year
- Average wind turbine size 3.2 MW

CUMULATIVE AND ANNUAL OFFSHORE WIND INSTALLATIONS (MW)



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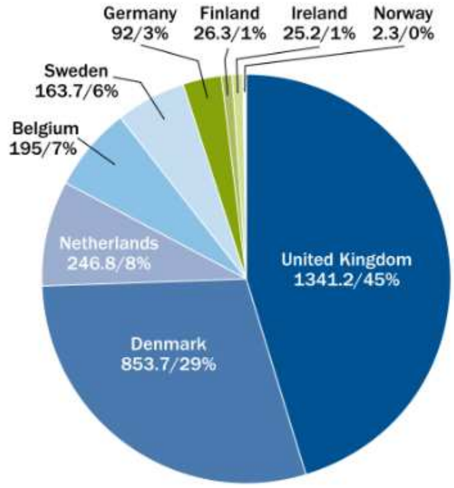
INSTALLED CAPACITY: CUMULATIVE SHARE BY COUNTRY AT END 2010 (MW)



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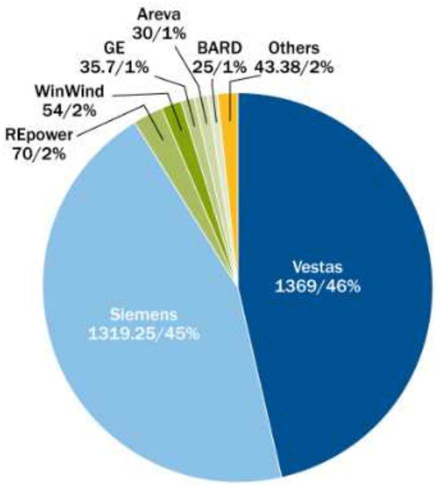
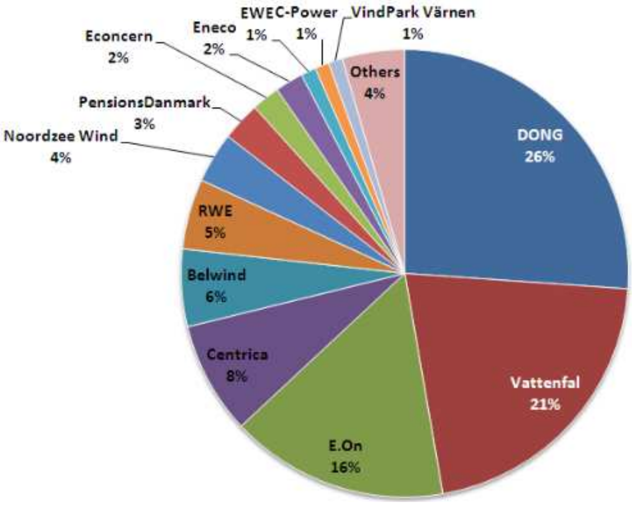
WT MANUFACTURERS: CUMULATIVE MARKET SHARE IN MW - END 2010



EWEA

OWNERS / DEVELOPERS: CUMULATIVE MARKET SHARE IN MW - END 2010



EWEA

Outline of presentation

- 2010 annual offshore wind power market
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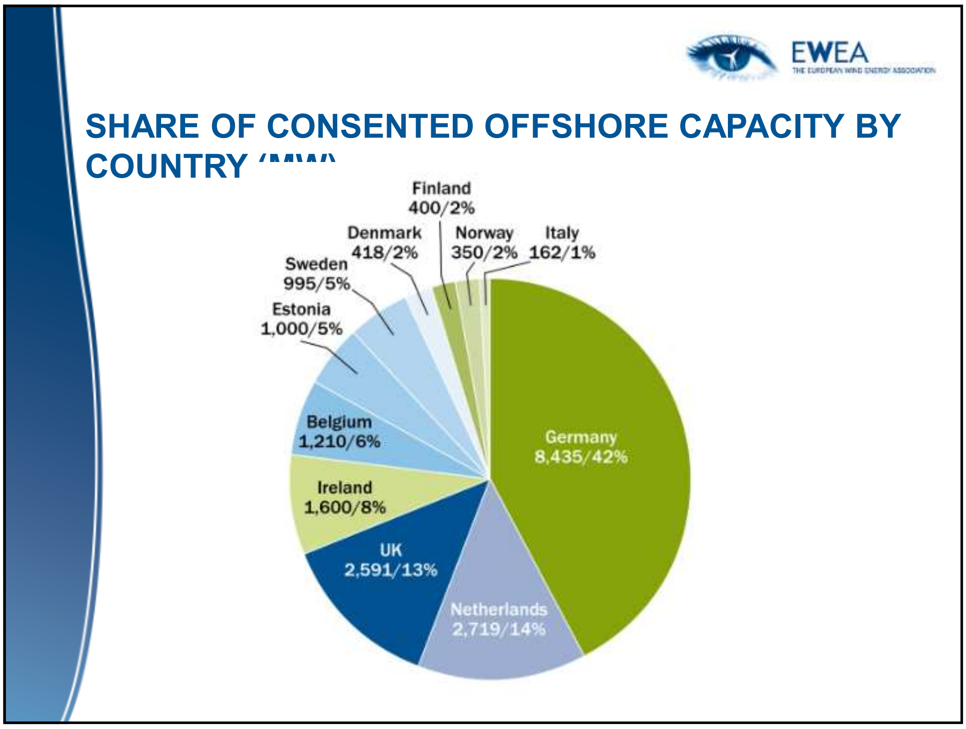
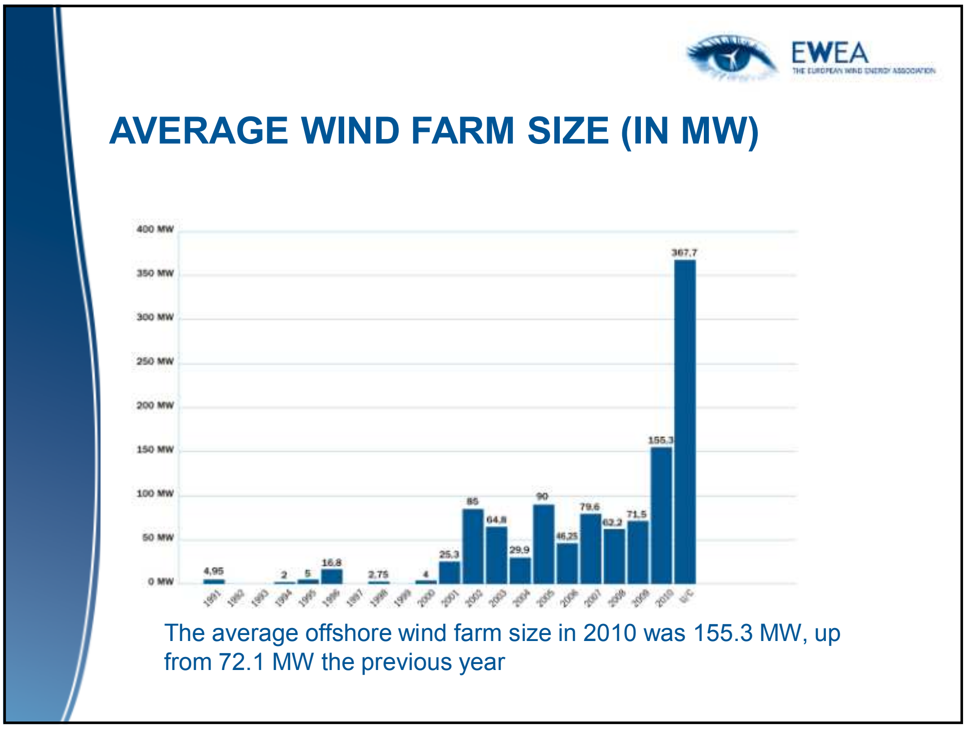

EWEA
SHARE OF CONSENTED OFFSHORE CAPACITY BY COUNTRY (MW)
Finland 400/2%
Denmark 418/2%
Norway 350/2%
Italy 162/1%
Sweden 995/5%
Estonia 1,000/5%
Belgium 1,210/6%
Ireland 1,600/8%
UK 2,591/13%
Netherlands 2,719/14%
Germany 8,435/42%


EWEA
AVERAGE WIND FARM SIZE (IN MW)
400 MW
350 MW
300 MW
250 MW
200 MW
150 MW
100 MW
50 MW
0 MW
4,95
2
5
16,8
2,75
4
25,3
85
64,8
29,9
90
46,25
79,6
62,2
71,5
155,3
367,7
The average offshore wind farm size in 2010 was 155.3 MW, up from 72.1 MW the previous year

EWEA
THE EUROPEAN WIND ENERGY ASSOCIATION

Trends: water depth and distance to shore

- Average water depth in 2010 was 17.4m, a 5.2m increase on 2009, with projects under construction in water depth averaging 25.5m
- Average distance to shore increased in 2010 by 12.7 km to 27.1 km substantially less, however, than the 35.7 km average for projects currently under construction

EWEA
THE EUROPEAN WIND ENERGY ASSOCIATION

Outline of presentation

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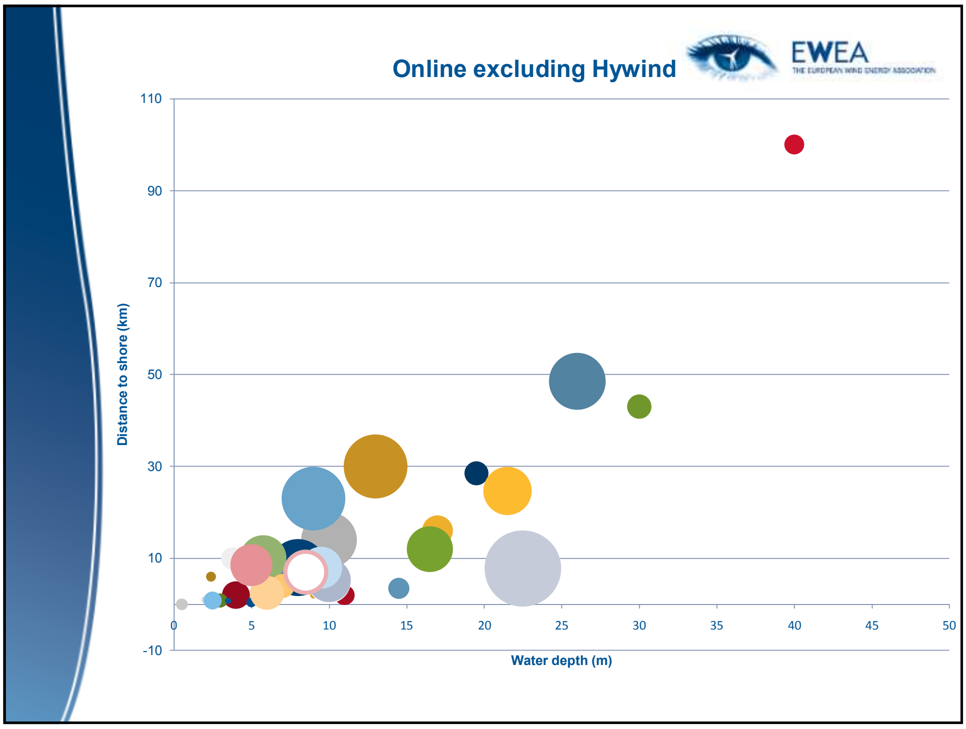
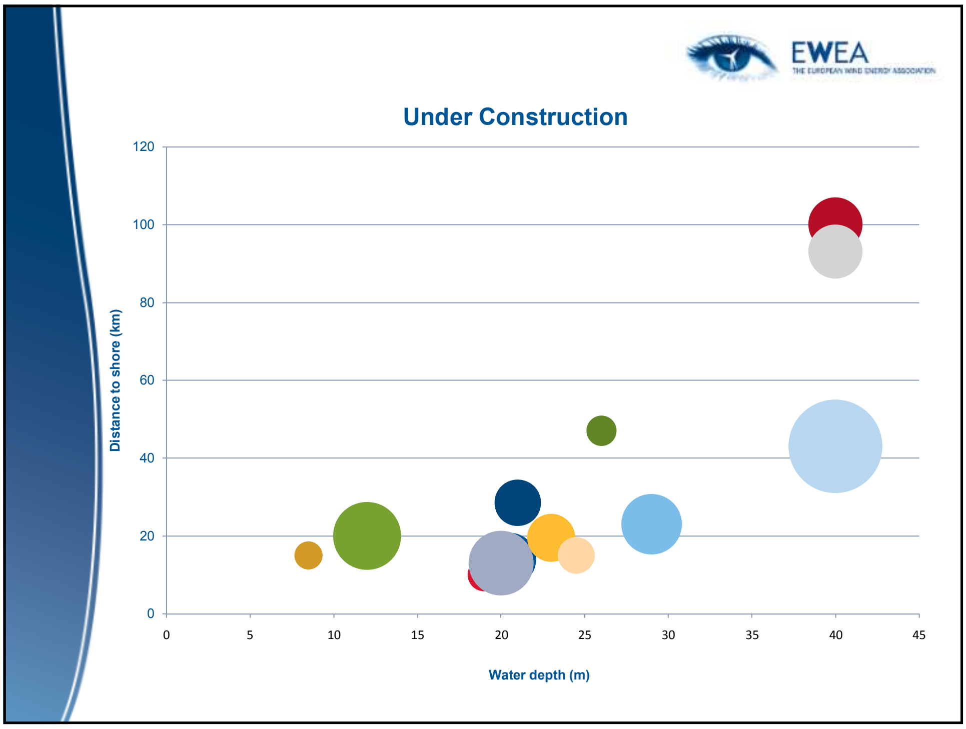
Snapshot of activity in the first six months of 2011

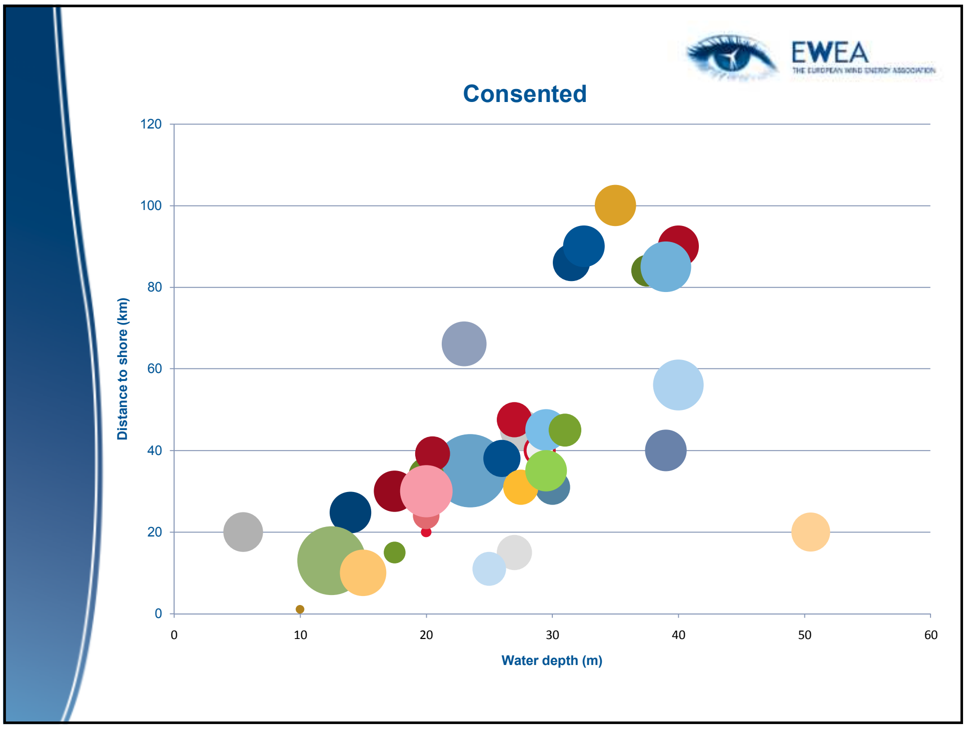
	BELGIUM	UK	GERMANY	NORWAY	TOTAL
Nr. of farms	1	7	2	1	11
Nr of foundations installed	4	108	16	1	129
Nr of turbines installed	0	101	6	1	108
Nr of turbines connected	0	68	32	1	101
MW fully connected to the grid	0	244.8	103.3	0.015	348.1
Total MW of projects (once completed)	148	2238	448.3	10	2844.3

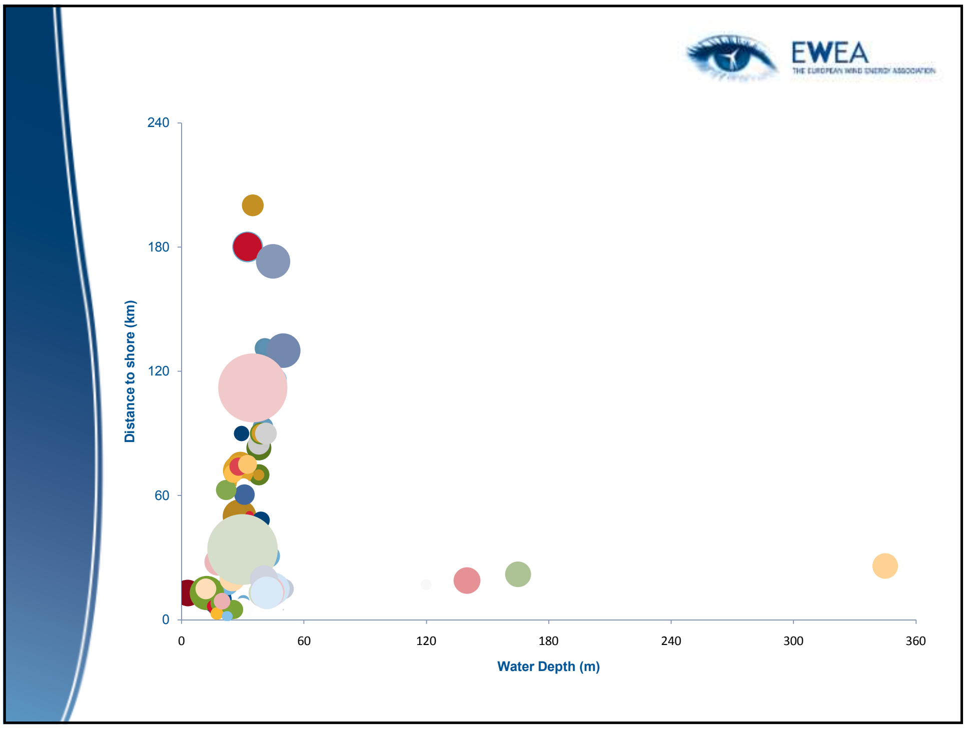
Market outlook: 2011 and beyond

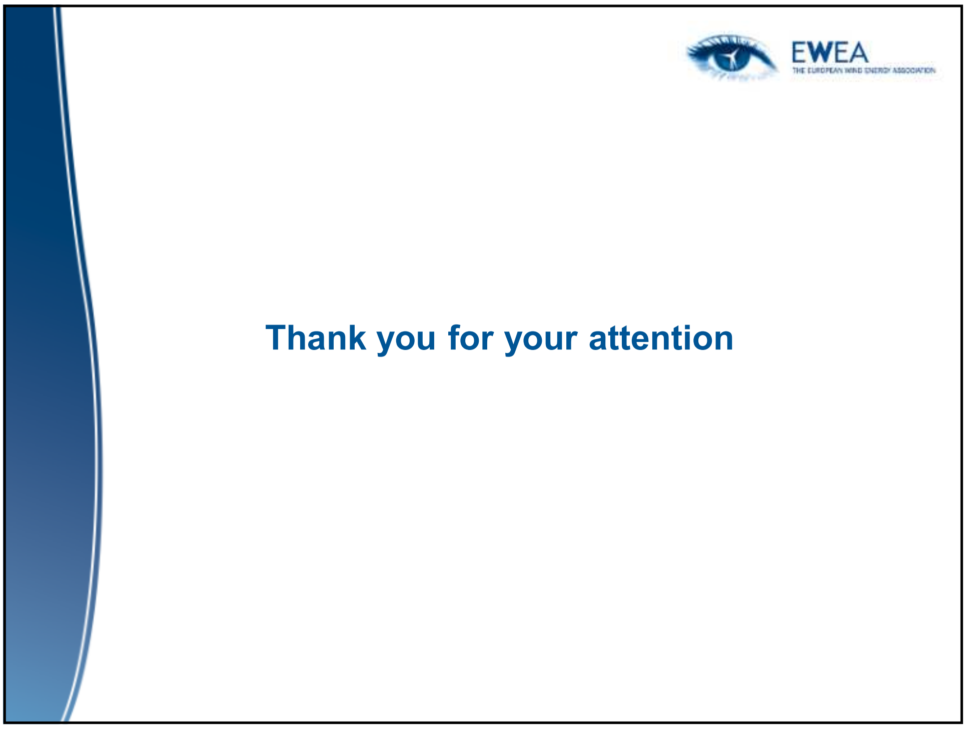
- EWEA forecasts that between 1,000 and 1,500 MW of new offshore wind capacity will be fully grid connected in Europe during 2011
- 11 wind farms, totalling 3,000 MW, are currently under construction. When completed, Europe's installed offshore capacity will increase to 6,200 MW
- 19,000 MW are currently fully consented
- 150,000 MW announced projects


Online excluding Hywind
EWEA
Distance to shore (km)
110
90
70
50
30
10
-10
0
5
10
15
20
25
30
35
40
45
50
Water depth (m)


EWEA
Under Construction
Distance to shore (km)
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
45
Water depth (m)


EWEA
THE EUROPEAN WIND ENERGY ASSOCIATION
Consented
Distance to shore (km)
0
20
40
60
80
100
120
Water depth (m)
0
10
20
30
40
50
60


EWEA
THE EUROPEAN WIND ENERGY ASSOCIATION
Distance to shore (km)
0
60
120
180
240
Water Depth (m)
0
60
120
180
240
300
360


EWEA
Thank you for your attention

National Renewable Energy Laboratory
Innovation for Our Energy Future

Offshore Wind : Status of Key Research Activities in the United States

National Wind Technology Center

Walt Musial

Principal Engineer

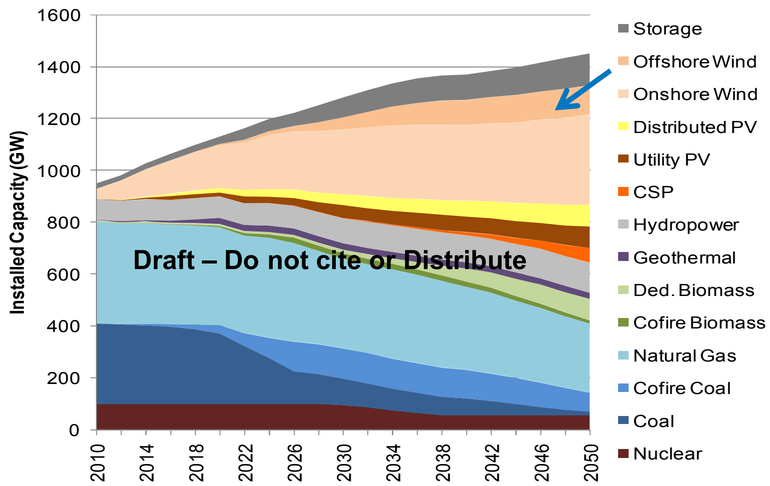
Manager Offshore Wind and Ocean Power Systems

Sept 20-21, 2011

Topical Expert Meeting #66
on
Offshore Foundation Technology and Knowledge, for shallow, middle and deep water

Long Term: Offshore Wind on Par with Other Renewables

"Core Scenario of 80% Renewable Electric Future Scenario predictions for United States



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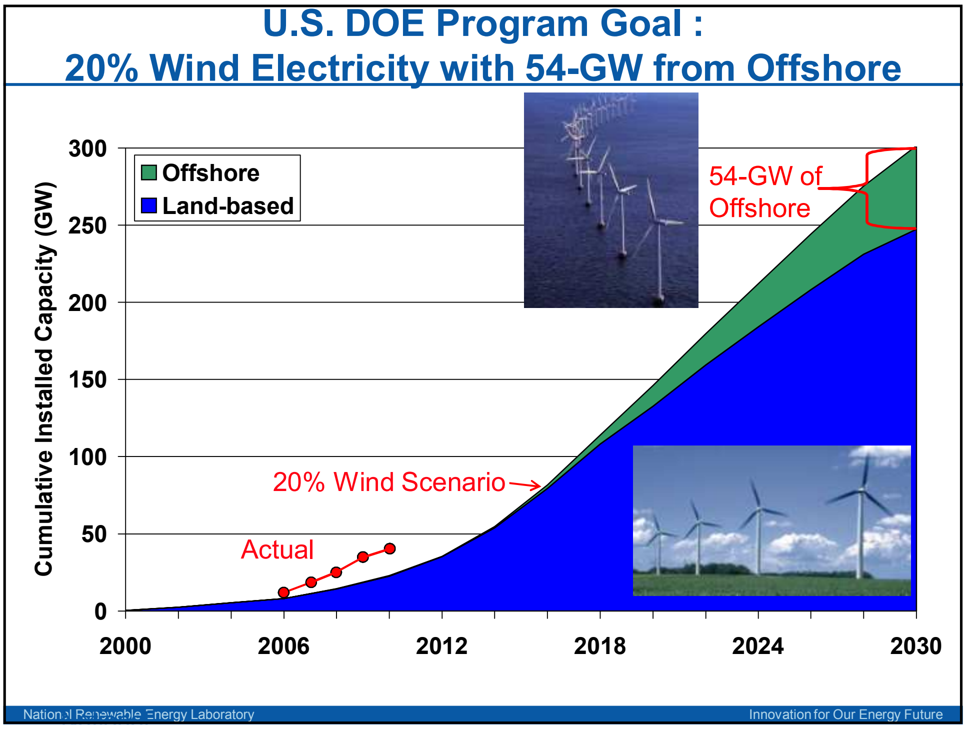
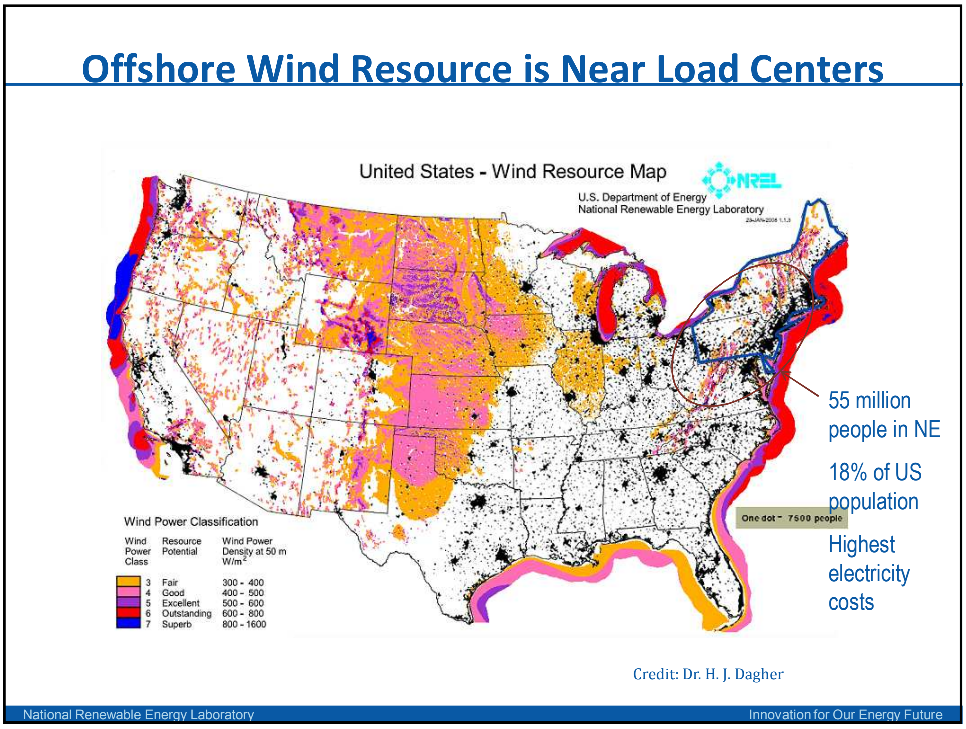
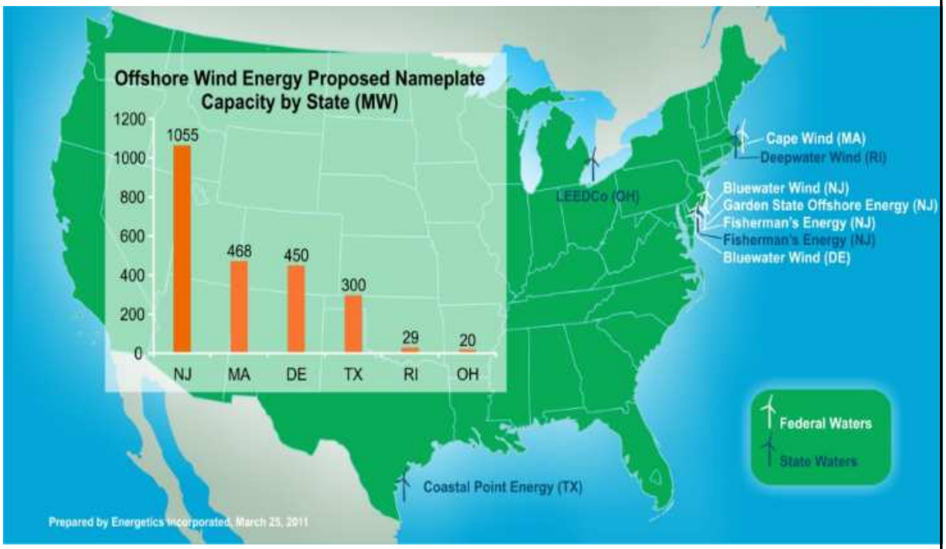

U.S. DOE Program Goal :
20% Wind Electricity with 54-GW from Offshore
Offshore
Land-based
Cumulative Installed Capacity (GW)
300
250
200
150
100
50
0
2000
2006
2012
2018
2024
2030
54-GW of Offshore
20% Wind Scenario
Actual
Innovation for Our Energy Future


Offshore Wind Resource is Near Load Centers
United States - Wind Resource Map
U.S. Department of Energy
National Renewable Energy Laboratory
55 million people in NE
18% of US population
Highest electricity costs
Wind Power Classification
Credit: Dr. H. J. Dagher
National Renewable Energy Laboratory
Innovation for Our Energy Future

U.S. Commercial Offshore Wind Projects

In permitting process



Delays due to cost, regulatory uncertainty, and immature infrastructure

National Renewable Energy Laboratory   Innovation for Our Energy Future

NREL View of Offshore Wind

Offshore wind is a strategic imperative

- Increase collaboration with Europe
- Leverage 30-years of land-based wind expertise
- Establish U.S. ocean-based facilities
- Build a strong program to respond to research needs

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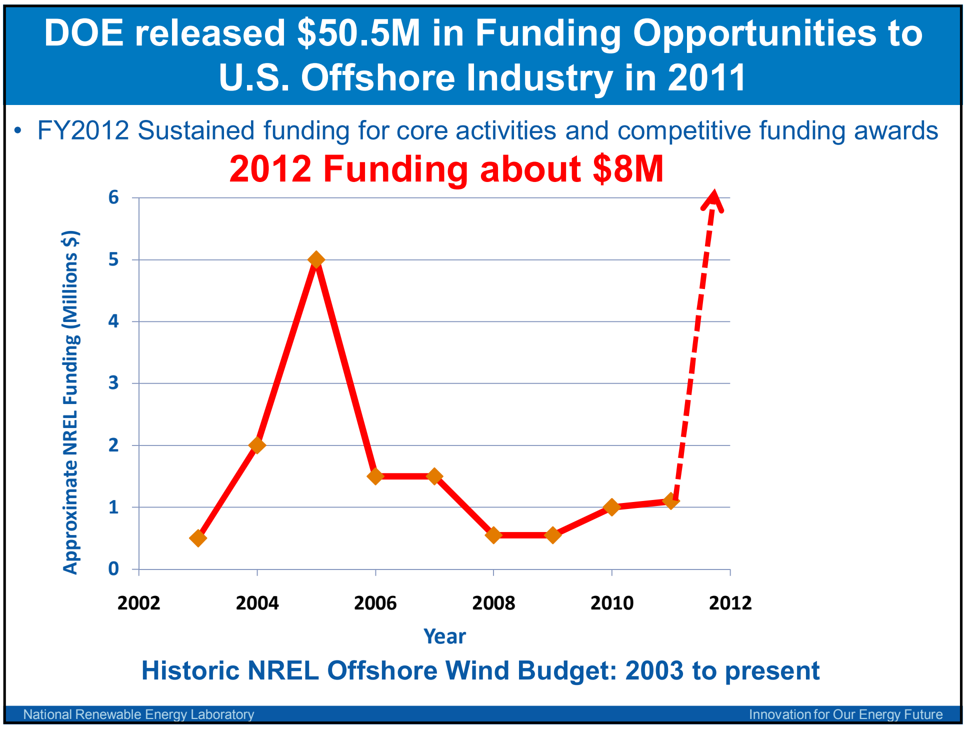
DOE released $50.5M in Funding Opportunities to U.S. Offshore Industry in 2011
• FY2012 Sustained funding for core activities and competitive funding awards
2012 Funding about $8M
Approximate NREL Funding (Millions $)
0
1
2
3
4
5
6
2002
2004
2006
2008
2010
2012
Year
Historic NREL Offshore Wind Budget: 2003 to present
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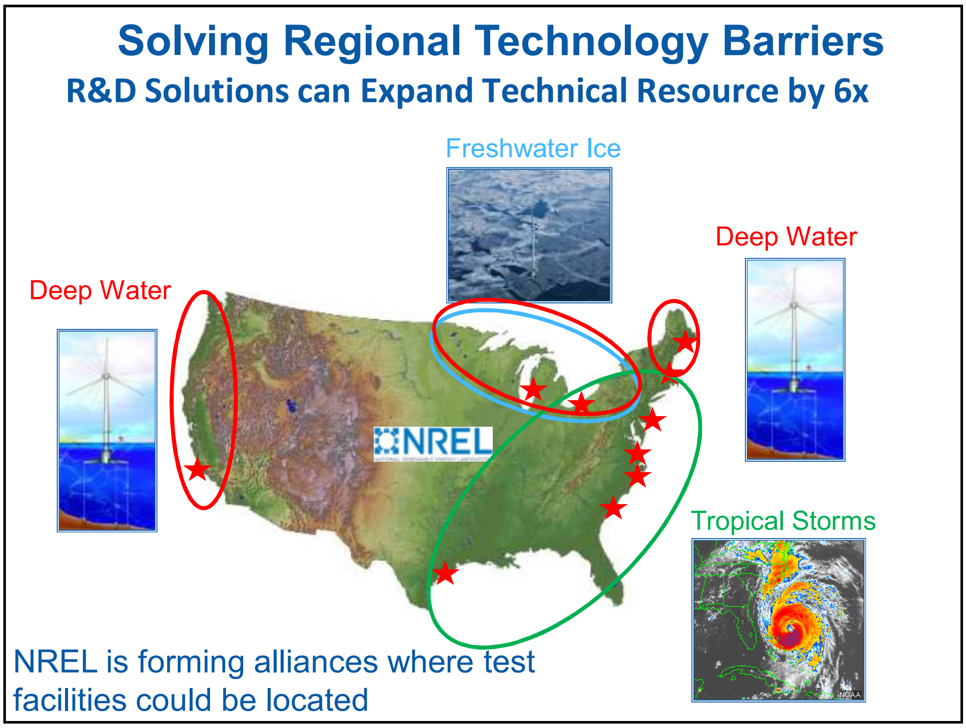
Solving Regional Technology Barriers
R&D Solutions can Expand Technical Resource by 6x
Freshwater Ice
Deep Water
Deep Water
NREL
Tropical Storms
NREL is forming alliances where test facilities could be located

Key need : Offshore Test Facilities

- Regional test facilities to address technology barriers and deployment issues:
  - Stimulate **U.S. market supply** for offshore turbines
  - Overcome **deep water** technology barriers
  - Develop mitigation strategies for **hurricanes**
  - Address **freshwater Ice** design requirements
- Establishing and operating major ocean based offshore wind testing facilities key to NREL strategy
- Implementation of Offshore testing strategy underway:
  - Offshore training,
  - Targeting new hires in offshore oil &gas
  - Active formation of partnerships in resource area

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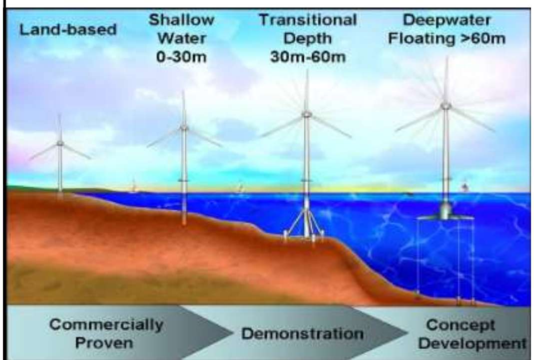
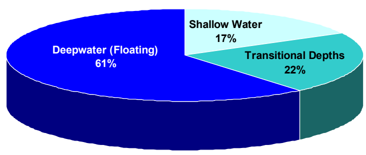
US Offshore Resource: Deep Water Dominates

Technology advances are needed to solve current problems and to expand the number of viable sites to achieve the needed deployment



~4000-GW Total Technical Potential



Approximate percentage of Gross Offshore Wind Resource Area for Three Technology Stages (based on NREL estimates – 0-50nm from shore, 60% of resource excluded, AK and HI not included, Class 5 winds and above only)

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Lower Cost Floating Wind Turbines

- **Decoupling from bottom** reduces site design dependency and work at sea
- **Maximizing land-based labor** for lowest cost:1-3-8 rule of ship building
- Integrating **quayside assembly and float-out** strategies
- **Reducing anchoring and mooring costs** through automated deployment
- **Reducing system weight** for lower system cost.

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Floating wind turbines resolve the resource barrier of deepwater but also have the potential to reduce COE

NREL Research includes:

- Develop and validate design tools: ***FAST/Hydrodyn***
- Develop ***integrated control systems*** for platform stability and load management
- Develop system ***economic models*** and evaluate
- Conduct ***design optimization*** studies for lowest cost
- **Test** and validate deployed systems
- Establish floating ***design requirements and standards***

Target: Floating offshore technology that can compete with shallow water offshore systems in 15-20 years.

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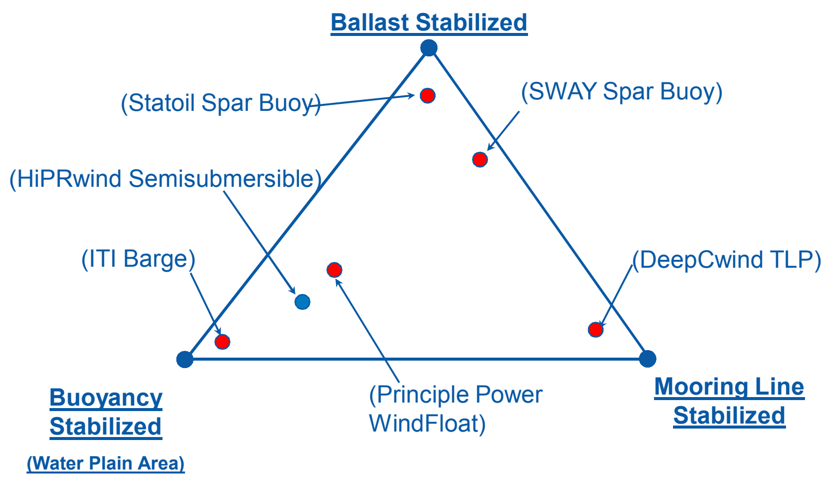
Evaluate Design Space of Static Stability Triangle for Floating Wind Turbine System



Multiple concepts need to be studied for design validation and optimizatio

(Positions shown on triangle are approximate)

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SWAY 1:5 Scale Demonstration

Characteristics	
Country/Sponsor:	Norway
Major Partners:	AREVA
Turbine Size/Description:	1/5 scale 12.9-m rotor downwind prototype
Deployment date :	June 2011
Platform Type:	Tension leg –Spar
Site:	50-m from shore
Water Depth	25 m
Approx Budget:	NA

1:5 scale SWAY deployment in April 2011

The 1/5th scale SWAY prototype tension-leg spar with downwind turbine concept is a unique design. DOE/NREL are participating as a partner to help testing and collect data for model validation of platform and to ensure that a full-scale system can be properly designed.

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Principle Power 2-MW Demonstration

Characteristics	
Country/Sponsor:	Portugal
Major Partners:	Vestas, EDP
Turbine Size/Description:	Vestas V-80, 2 MW wind turbine
Deployment date :	September 2011
Platform Type:	Three – tank semisubmersible – 6 line mooring
Site:	Aguçadoura, Portugal
Water Depth	40 to 50-m
Approximate Budget:	$ 25M USD

The PPI WindFloat semi-submersible wind system is scheduled for installation and commissioning off the Portuguese coast in Sept 2011. The installation includes a grid-connected Vestas V80 2-MW wind turbine. Testing for at least 12 months is planned and will focus on performance validation. An EU Framework 7 award recently increased their testing capability. DOE and NREL are participating in data analysis and modeling.

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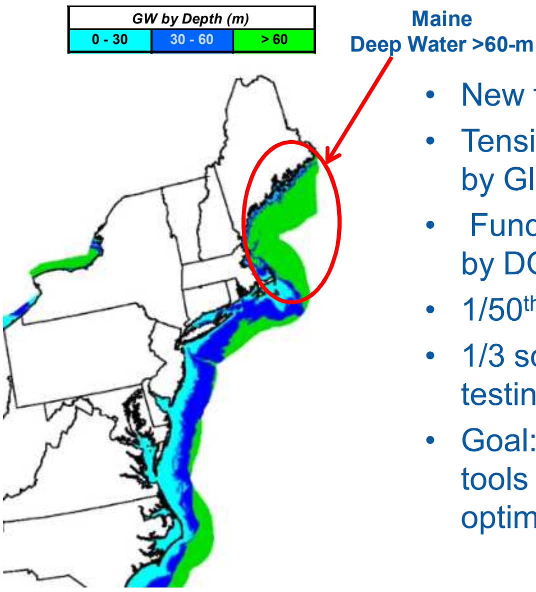
DeepCwind Project – Maine, USA



- New floating wind technology
- Tension leg platform design by Glosten Associates
- Funding ~$15M US Dollars by DOE
- 1/50th Scale Model Testing
- 1/3 scale V-27 open ocean testing
- Goal: Develop engineering tools to enable the design of optimized full-scale systems.

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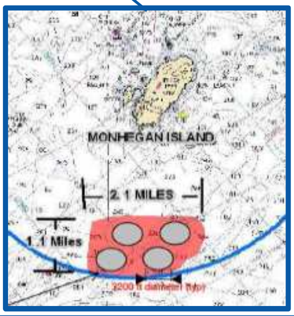
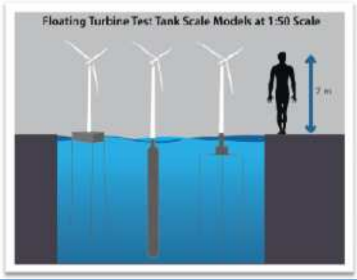
DeepCwind Project – Maine, USA

Deep Water >60-m



- TLTP Technology Development Initiative for floating wind
- Funding ~$15M US Dollars
- 1/50th Scale Model Testing
- 1/3 scale open ocean testing (2012)
- **Goal: Develop engineering tools to enable the design of optimized full-scale systems.**



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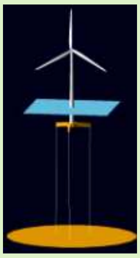
Concept Designs for 1/50th Scaled Model Tests

1:3 Scale concept

UMaine TLP



UMaine Hywind Spar

UMaine Semisubmersible

18

Mooring Line Stabilized	Ballast Stabilized	Buoyancy/ Ballast Stabilized

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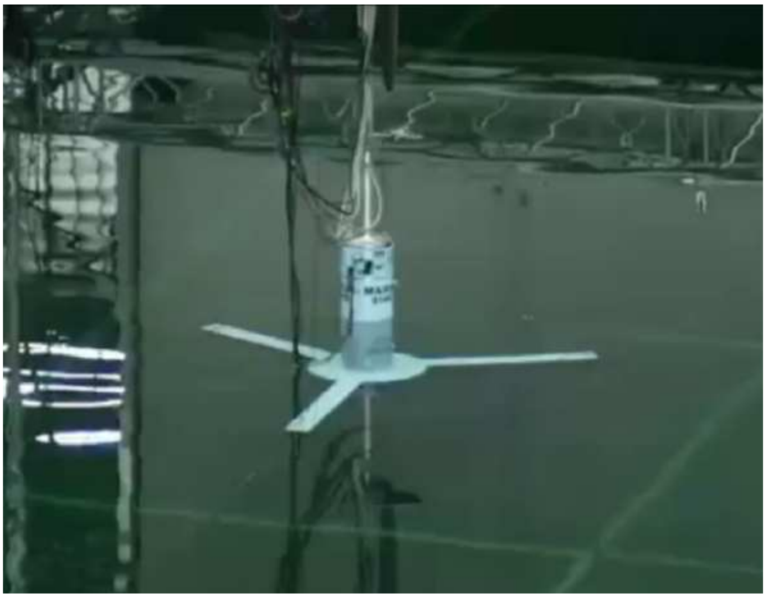
TLP Design



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Scaled Wind Turbine Issues

- Incorrect Reynold's #
  - Factor of 350
- Thrust is important for purpose of test
  - Low -> increase wind speed
  - Still small torque – RE#?

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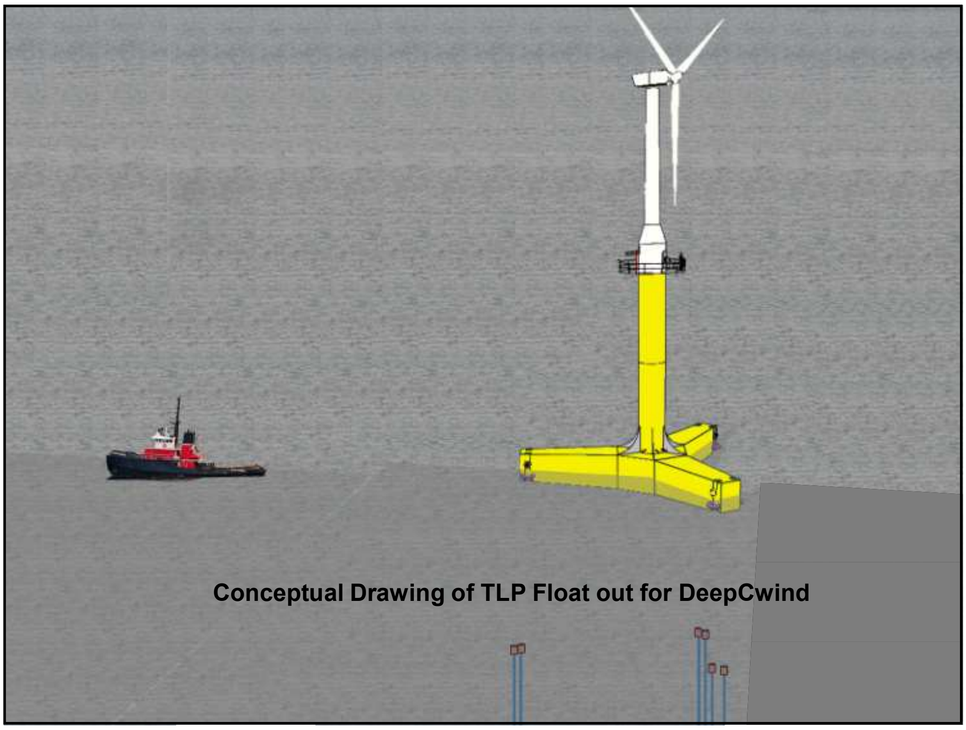
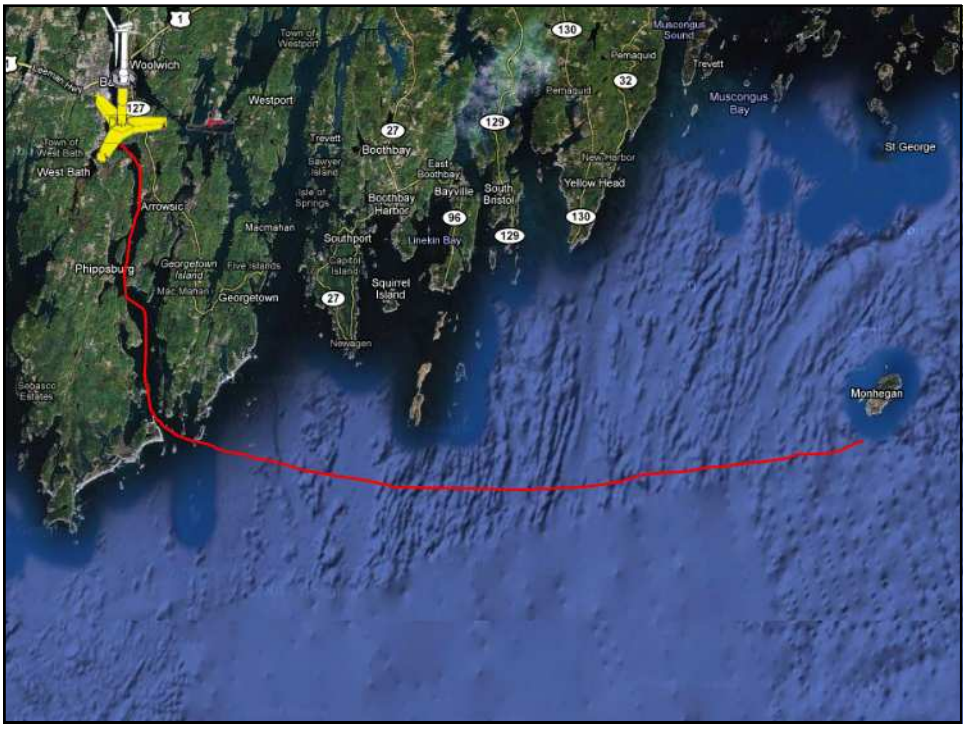
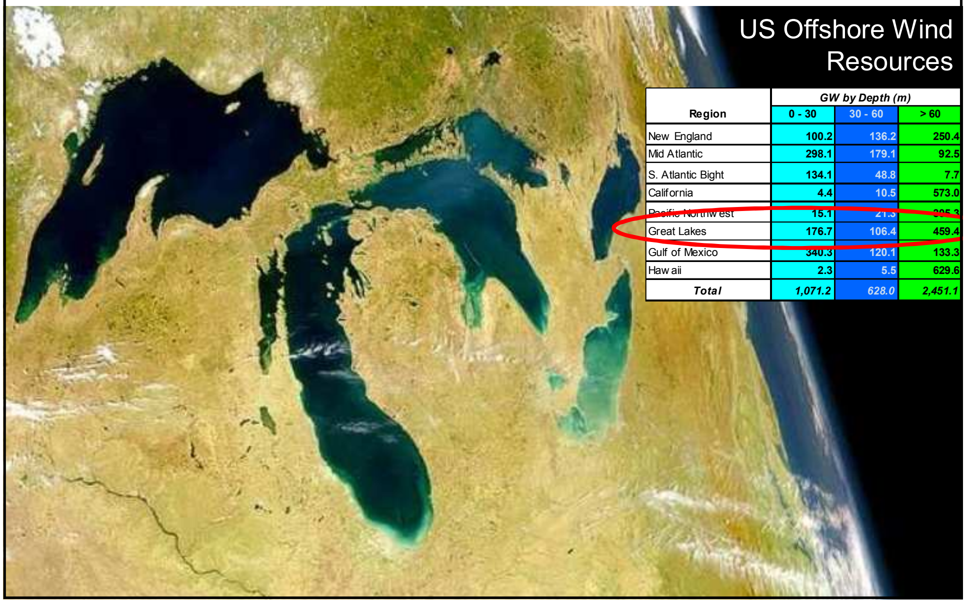


Conceptual Drawing of TLP Float out for DeepCwind



Great Lakes Ice Regime
Freshwater Offshore Resource



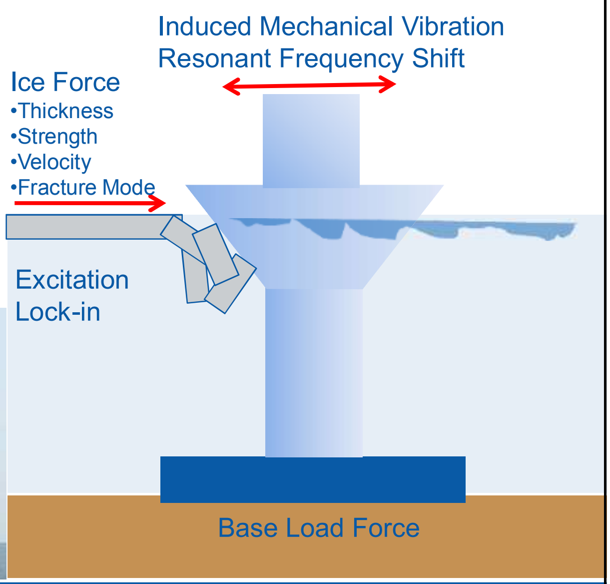
US Offshore Wind Resources

Region	GW by Depth (m)		
	0 - 30	30 - 60	> 60
New England	100.2	136.2	250.4
Mid Atlantic	298.1	179.1	92.5
S. Atlantic Bight	134.1	48.8	7.7
California	4.4	10.5	573.0
Pacific Northwest	15.1	21.3	305.3
Great Lakes	176.7	106.4	459.4
Gulf of Mexico	340.3	120.1	133.3
Hawaii	2.3	5.5	629.6
Total	*1,071.2*	*628.0*	*2,451.1*

Freshwater Ice Loading Design and Mitigation

Baltic Sea – Windpower Monthly Cover Photo Feb 2003

Wind Turbines at Nysted with Ice Cones



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Wind Turbine Hurricane Design

- Wind Turbines are Type Certified before exact site conditions are known
- U.S. Hurricane conditions can exceed IEC Class 1A wind specifications
- High uncertainty in predicting hurricane probability and intensity

Table 1. Saffir/Simpson Hurricane Scale, modifed from Simpson (1974).

Scale Number (Category)	Winds (Mph)	Typical characteristics of hurricanes by category (Millibars)	(Inches)	Surge (Feet)	Damage
1	74-95	> 979	> 28.91	4 to 5	Minimal
2	96-110	965-979	28.50-28.91	6 to 8	Moderate
3	111-130	945-964	27.91-28.47	9 to 12	Extensive
4	131-155	920-944	27.17-27.88	13 to 18	Extreme
5	> 155	< 920	< 27.17	> 18	Catastrophic

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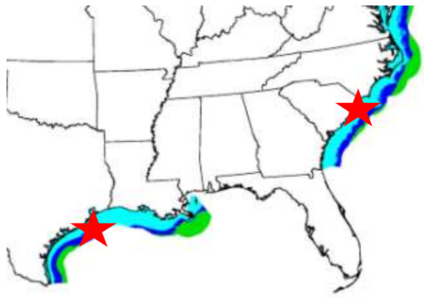
Hurricane resilient designs are needed to deploy in hurricane prone regions

- Turbine modifications may be needed; current designs may need incremental upgrades to blades an substructure.
- Texas and South Carolina have proposed offshore wind projects
- Standards need to be upgraded to address hurricanes in USA and Asia. (IEC 61400-03 MT)
- AWEA/NREL/BOEMRE are organizing to address hurricanes in the U.S. regulations.



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Offshore Wind U.S. Summary of Issues

- No Offshore Wind Projects Installed in U.S. Yet
- About 2500-MW in regulatory pipeline
- First adopters will have higher risk due to cost, regulatory delays, and immature infrastructure
- First floating turbine is scheduled to be installed in Maine in 2012.
- Ice loading may define Great Lakes designs and installation practices
- Hurricanes may become a design driver in Atlantic and Gulf of Mexico

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Thank You for Your Attention
Questions?

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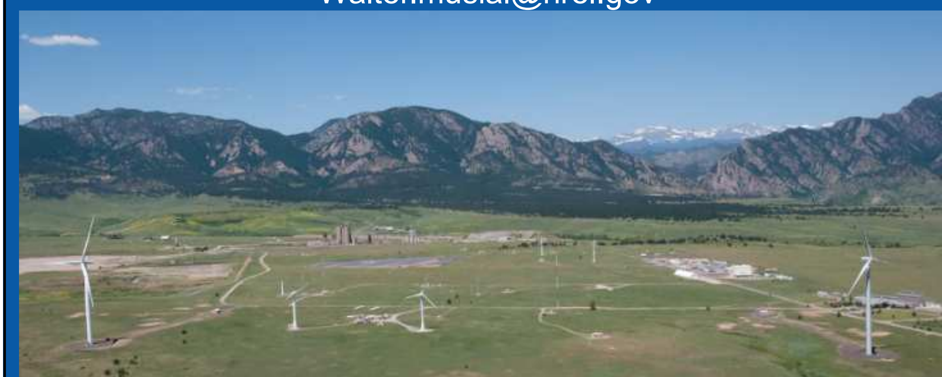
Walter.musial@nrel.gov



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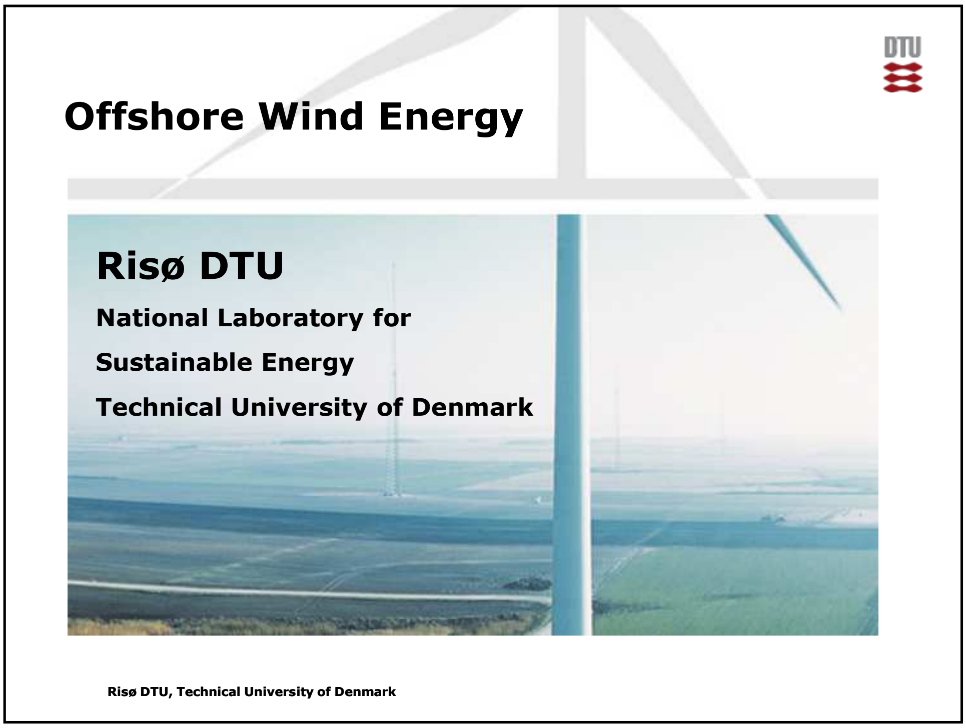
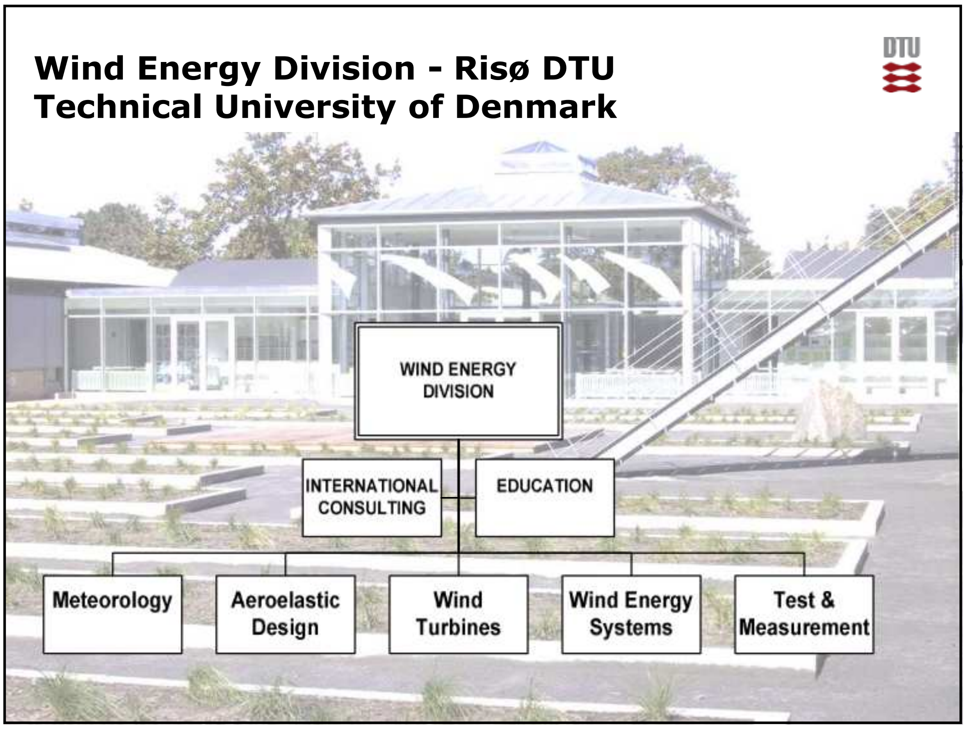

Offshore Wind Energy
Risø DTU
National Laboratory for
Sustainable Energy
Technical University of Denmark
Risø DTU, Technical University of Denmark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INTERNATIONAL CONSULTING
EDUCATION
Meteorology
Aeroelastic Design
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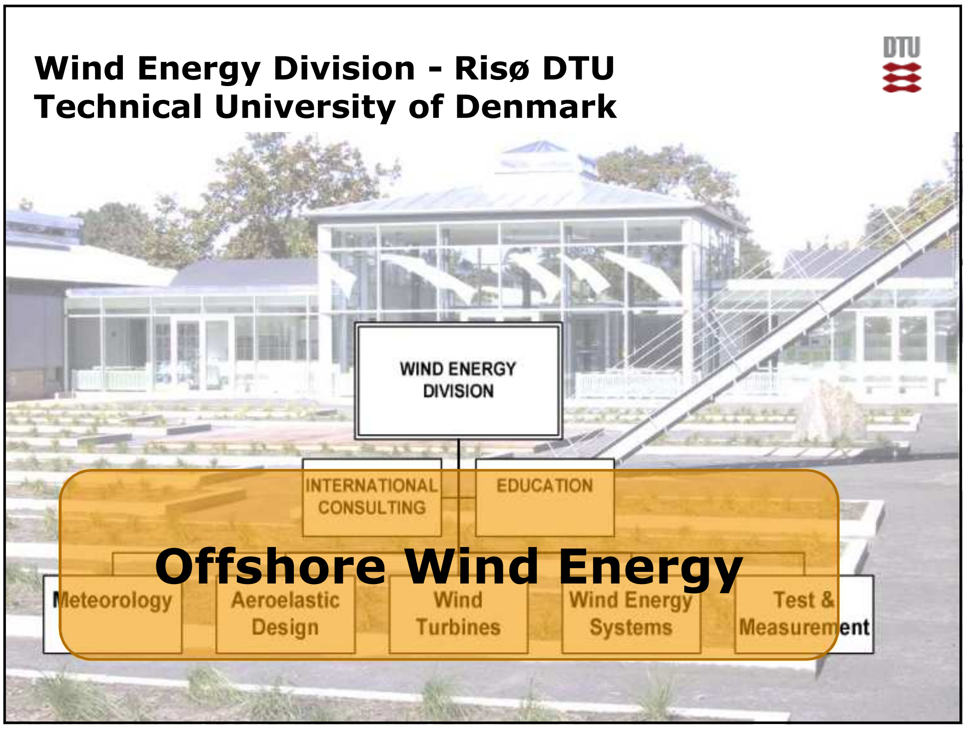
Wind Energy Systems
Test & Measurement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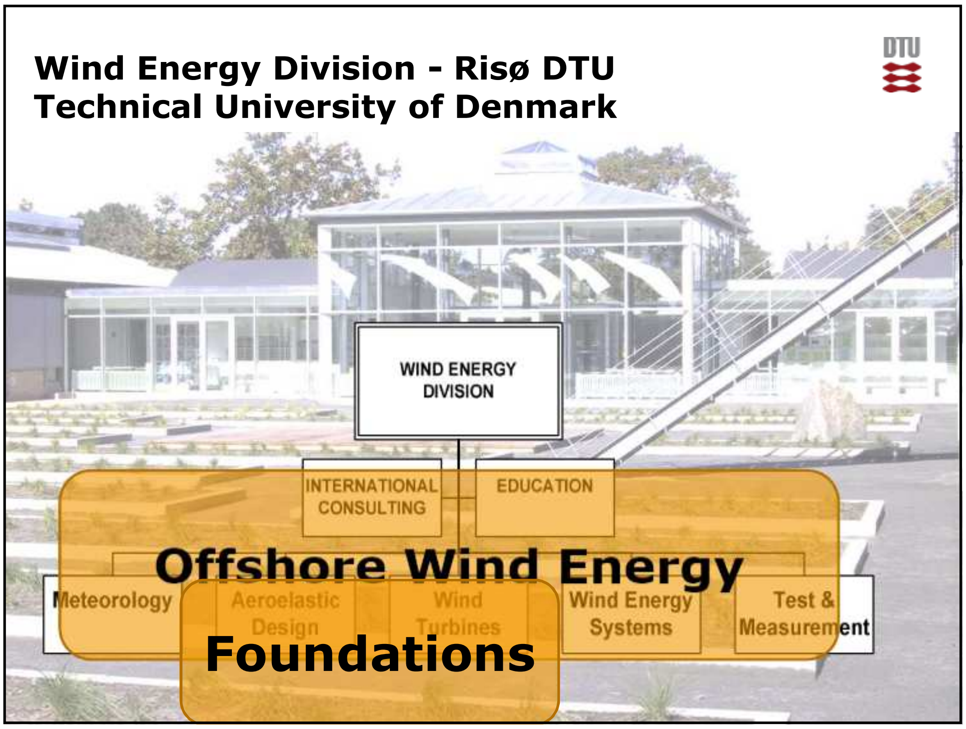
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Test & Measurement
Foundations

Research project overview nov. 2010

- TWENTIES – EU – Storm control– TB 56 M€ (8 my)
- HTF foundations – Cost efficient foundations – TB 80 MDKK (11 my)
- EUDP Walney – wake and foundations measurements - TB 7 MDKK (6 my)
- EUDP Wave loads on offshore structures
- EUDP resonant wave
- PSO Wake effects
- Wake effects of large offshore wind farms
- HYWIND – Floating turbine
- MARINA
- Poseidon – Wind and wave concepts
- IEA Annex 30 – Code comparison
- DeepWind – New offshore floating concept
- EU-Norsewind – Wind resources
- Radar@Sea – PSO - Wind resources
- ORECCA
- South Baltic offshore
- Wasp offshore
- etc.

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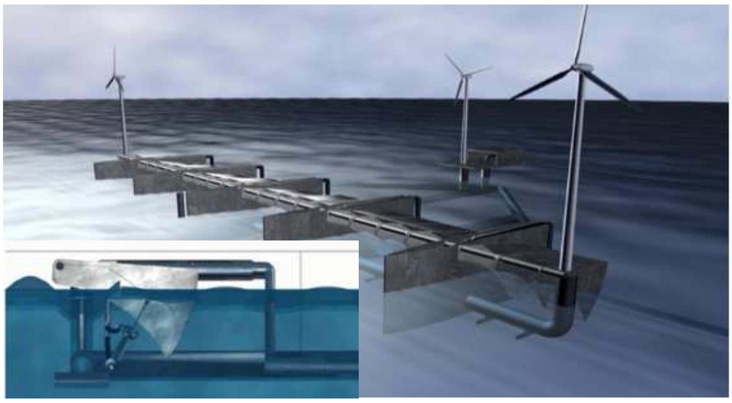
Combined floating wind- and wave energy converter -



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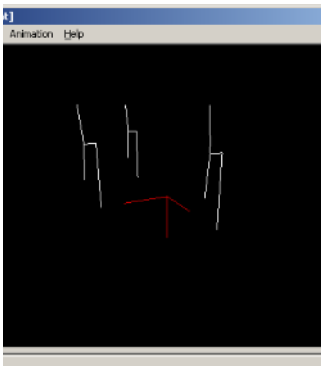
Poseidon: Modeling Challenges

- Three rotors in one simulation
  - Structural modeling already possible in the multi-body formulation
  - Aerodynamic model updated to handle this
- Wake from upwind rotors
  - Already possible with the dynamic wake meandering model in HAWC2
- Large water surface area
  - Full coupled HAWC2-WAMSIM simulations
    - HAWC2 validated aeroelastic code
    - WAMSIM validated radiation/diffraction code for dynamic of floating structures from DHI
    - WAMSIM recode to HAWC2 dll-interface format
    - Ordinary HAWC2 turbine model
    - Ordinary WAMSIM model
    - Full system solved by HAWC2



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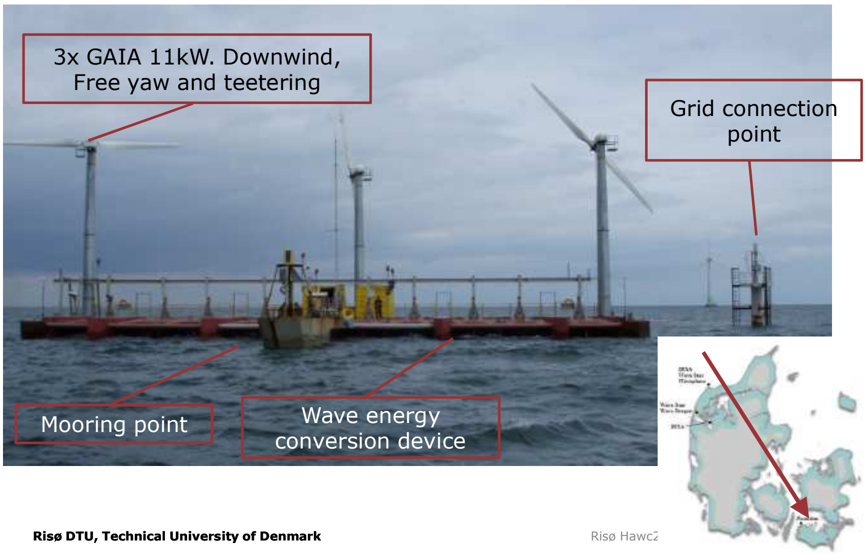
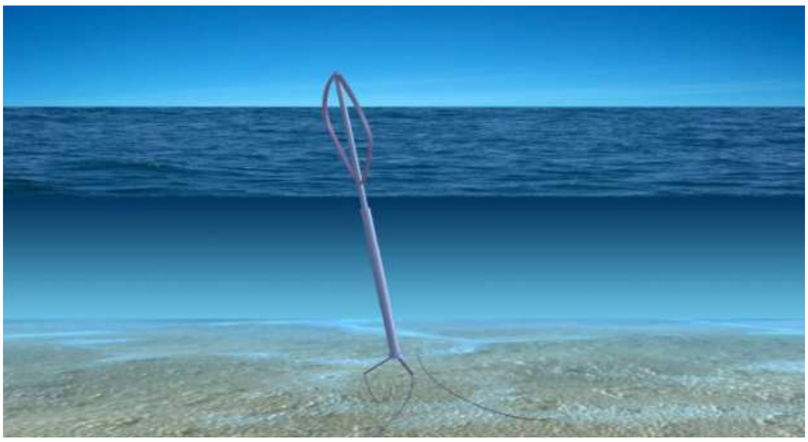
Poseidon: how it looks

PSO project, measurements and modeling: DONG, FPP, DHI and Risø DTU



DEEPWIND – New EU Funded Program

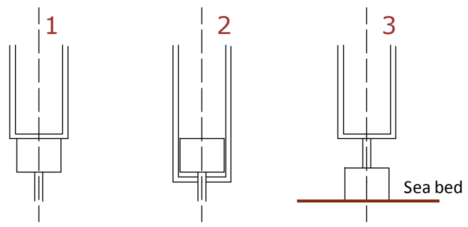


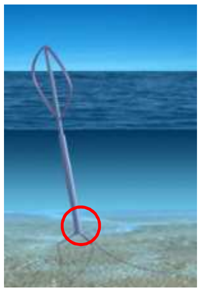
Vertical axis wind turbine
Bottom mounted generator for weight savings

DeepWind concept

Components - Generator configurations

- Several configuration are possible to convert energy in power
- Three selected to be investigated first:
  1. Generator fixed on the torque arms, shaft rotating with the tower
  2. Generator inside the structure and rotating with the tower. Shaft fixed to the torque arms
  3. Generator fixed on the sea bed and tower. The tower is fixed on the bottom (not floating).





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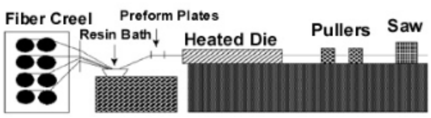
DeepWind Concept and project 9/21/2011

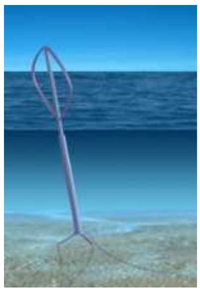
DeepWind concept

Components – Blades technology

- The blade geometry is constant along the blade length
- The blades can be produced in RPG
- Pultrusion technology:
  10 m chord, several 100 m long blade length



- Pultrusion technology could be performed at site on a ship
- Blades can be produced in modules



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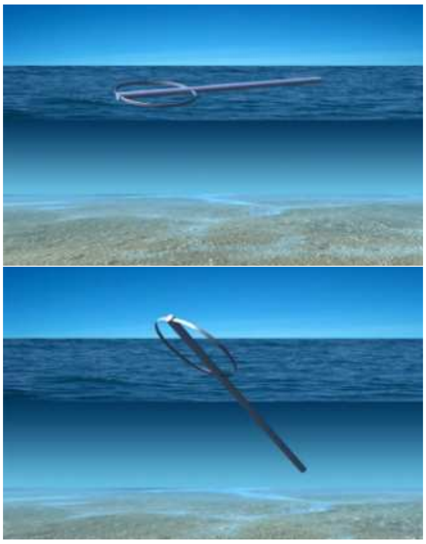
DeepWind Concept and project 9/21/2011

Deep Wind Concept
Installation, Operation and Maintenance

- INSTALLATION
  - ✓ Using a two bladed rotor, the turbine and the rotor can be towed to the site by a ship. The structure, without counterweight, can float horizontally in the water. Ballast can be gradually added to tilt up the turbine.



- O&M
  - ✓ Moving the counterweight in the bottom of the foundation is possible to tilt up the submerged part for service.
  - ✓ It is possible to place a lift inside the tubular structure.

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DeepWind Concept and project 9/21/2011

EUDP Walney Offshore Wind Farm Project

1. One Siemens 3.6MW machine instrumented with loads sensors
   1. Rotor Nacelle components
   2. Tower
   3. Foundation
2. Water depth 19m –28 m

3. Nacelle mounted LIDAR measuring wind speed at 2.5 rotor diameter in front of turbine.
4. Wave and current measurements near foundation
5. SCADA system data for the instrumented turbine and surrounding turbines.

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Project Setup

- Work Package 1 : Installation, measurement and maintenance of instrumentation on a Siemens (SWT) 3.6MW machine.
  - LIDAR acquisition, installation
  - Wave and current sensors testing and installation
  - Foundation instrumentation
  - Tower and nacelle instrumentation
  - SCADA systems

- Work Package 2: Maintenance of a loads data base, Data analyses and modeling for verification.
  - Existing Risø database server
  - Transfer data mechanisms
  - Data protection mechanisms
  - Loads modeling, simulation and verification.

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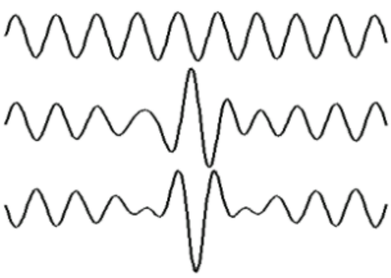
Analysis of Nonlinear Wave Effects

The structural responses of fixed offshore platforms is non-Gaussian because of:

- Morison drag term $u|u|$
- Wave Height effects (wave splash zone)
- Wave nonlinearity (sum frequencies)



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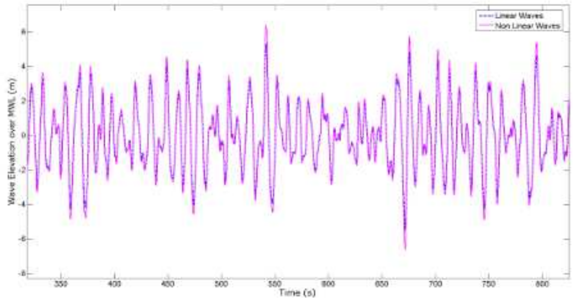
Implementing Non Linear Waves

- The Airy linear wave theory assumes the sea surface elevations can be neglected in comparison to the water depth – not true at 40m depth.
- 2nd order wave models results from interactions between any 2 wave frequency components producing frequency differences and sums.



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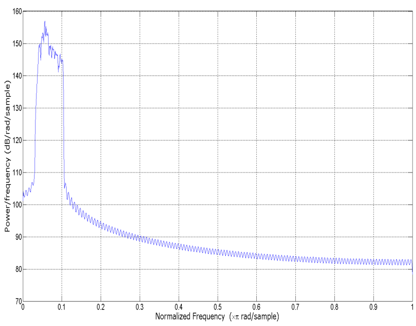
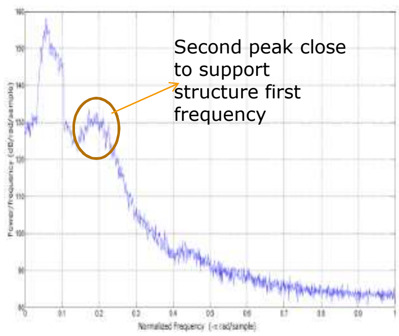
Mud Line Moment – Effect of Non linear Waves

1. 7.5 m high storm wave in 20m water depth at 24m/s mean wind speed. (Operational wind speed)
2. Second order non-linear theory applied.

Linear wave loading moment at mud line



Non Linear wave loading moment at mud line



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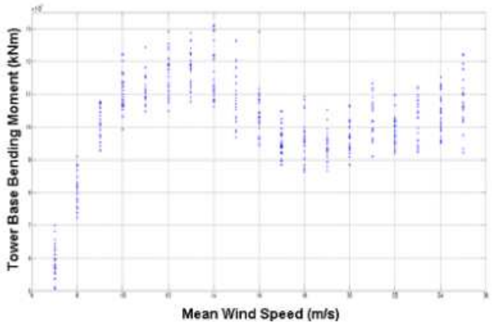
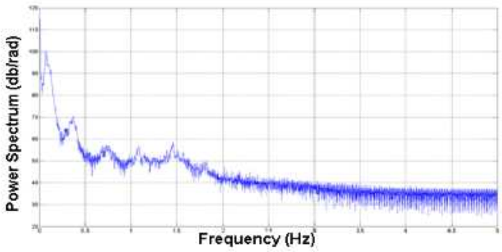
Impact of Soil Flexibility





- Soil flexibility increases the mudline loads due to the lowered frequency of the support structure.
- The tower design must be performed with the knowledge of the soil stiffness.
- Non linear nature of waves implies that the wave “sum” frequency affects the support structure more with soil flexibility

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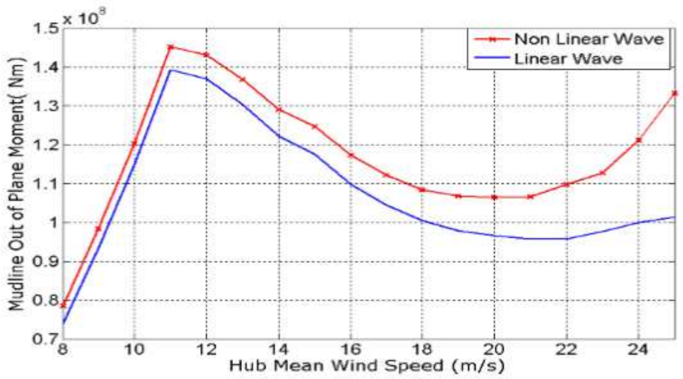
50 year Extreme Mud Line Moment – Non Linear Waves

1. 5MW turbine at 20 m water depth on a monopile foundation
2. 50 year wave significant height is used in combination with the rotor nacelle loads.
3. 8% higher overall out of plane mud line moment at rated wind speed.
4. Wave loading steadily increases and is more than 20% higher than the linear model at 24m/s.



Risø DTU, Technical University of Denmark

Market oriented Evaluation and Development of Offshore Foundations for OWECs

Kai Irschik
Jürgen Reimers
AREVA Wind GmbH

AREVA

M5000 technology tailor-made for offshore

- A leading-edge 5 MW offshore wind turbine:
  - Hybrid drive-train solution
  - Light weight
  - High output
  - Corrosion protection through air filtering
  - Simplified maintenance
- 4 turbines installed in Bremerhaven for first operating experience:
  - 2 first turbines in 2004 & 2006
  - 2 additional in 2008
- 6 turbines installed offshore in Alpha-Ventus project in summer 2009
- Next projects: installation of 80 turbines at Global Tech I and 40 turbines at Borkum West II

Offshore Foundations

AREVA

Bremerhaven: 1st hub to service North Sea

Offshore Foundations

AREVA

Stade: Rotor Blades

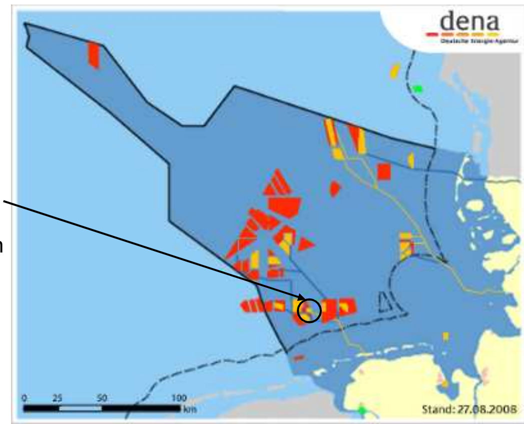
- Carbon fibre girders
- GRP Structure
- T-bolt root connection
- Consequently integrated lightning protection

Offshore Foundations

AREVA

Alpha Ventus: Germany's pilot project

- Location: 40 km from Borkum
- No. of turbines: 6
- Hub height max. 90 m
- Total height max. 148 m
- Customer: DOTI
- Water depth: 28 m
- Foundation Type: Tripod
- Scope of delivery: Foundation
  Turbine
  Installation

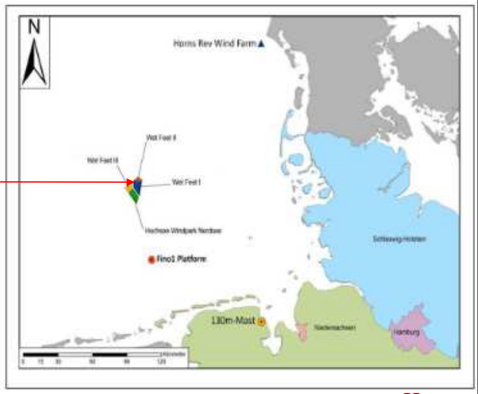


Offshore Foundations

AREVA

Global Tech I Project in North German Sea

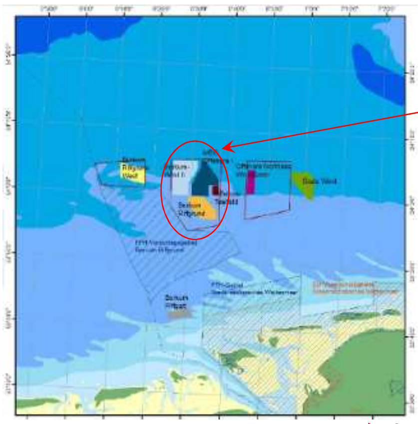
- Location: North Sea
- No. of turbines: 80
- Distance to coast: 90 km
- WTG connection: 30 kV
- Water depth: 35 - 42 m

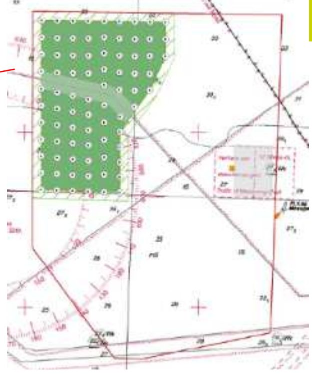


Offshore Foundations

AREVA

Borkum West II





OFFSHORE

Project

40 turbines 200MW

Borkum West II

▶ Location:	North Sea
▶ No. of turbines:	40
▶ Distance to coast:	40 km
▶ Grid connection:	155 kV
▶ Water depth:	25 – 28 m

Offshore Foundations

AREVA

Offshore Tripod

Type:	Steel, welded
Foundation:	Concrete piles
Height:	43 m
Distance pile sleeves:	24,3 m
Weight:	approx. 750 t

Offshore Foundations

AREVA

Offshore Support Structure

- **Support Structure is customer-supplied (current stage) :**
  loads are exchanged
- **Support Structure is developed in tender cooperation (starting this stage):**
  increasing amount of exchange of data and knowledge
- **Development of our own Support Structure (near future) :**

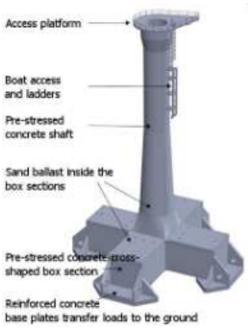
  → **What are the market requirements?**

  → **Bankability**

Offshore Foundations

AREVA

New Foundation & Logistic Concepts



Offshore Foundations

AREVA

Why we are here

- We are not yet capable to give answers to all problems that will arise in the next few years.
- We want to ask the right questions.
- We want to get into contact with companys and people that can help us answer them.

We know what we need

- We need cheaper foundation solutions
- We need solutions for higher water depths
- We need solutions for hard soil conditions

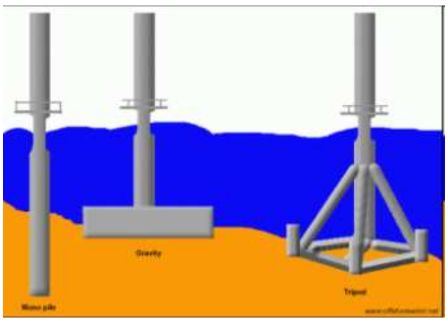
Offshore Foundations

AREVA

Possible future markets for substructure development

To decide which sub-structures need to be developed with which priority, we need more information about current and future markets

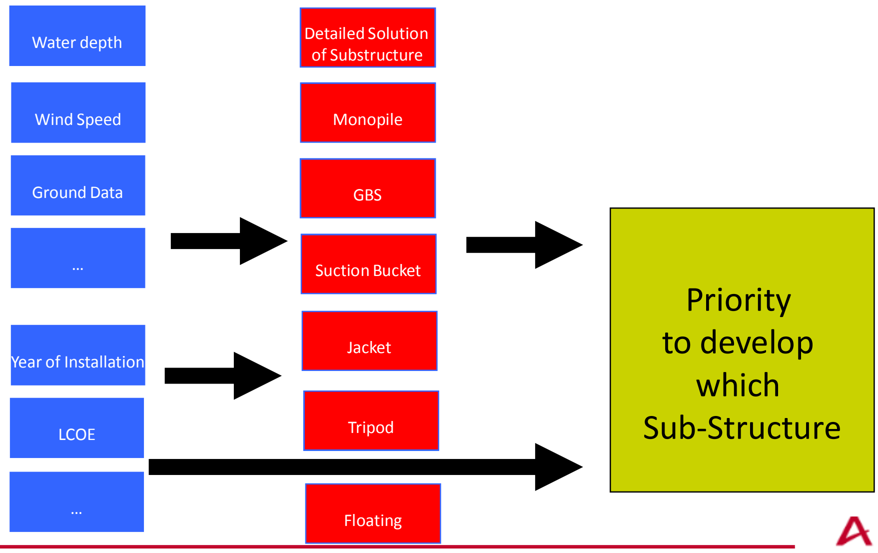
- Where are they?
- What are the requirements?
  - Soil condition (soft – medium – hard)
  - Water depths
  - Wind states
  - Current /Tides
  - Labour Costs
  - …
- What is the timeline?



Offshore Foundations

AREVA

Data Requirements for Sub-Structure Development



Offshore Foundations

AREVA

More detailed data to predict capex and opex

- **At the moment, the decision about installation is often done based on AEP and installation cost.**
- **With additional expert knowledge, and hydrodynamic simulations, e.g. the cost of service over lifetime can be easier accessed**
- **Example: Boat landing of service vessels**
  - **Monopile, Tripod and GBS provide some protection against waves in the boat landing operation, compared to Jacket foundation**
  - **The service window is much higher using the same service vessels**
  - **Smaller vessels could be feasable, thus decreasing costs for purchase, leasing, fuel consumption**
  - **Over 20 years lifetime, costs for maintenance vessels can add up to a considerable number**

Offshore Foundations

AREVA

Offshore Foundations

AREVA

Thank you for your attention!

Offshore Foundations

AREVA

Topical Expert Meeting # 66: Offshore Foundation Technology and Knowledge for shallow, middle and deep water

Esbjerg 20/21 September 2011

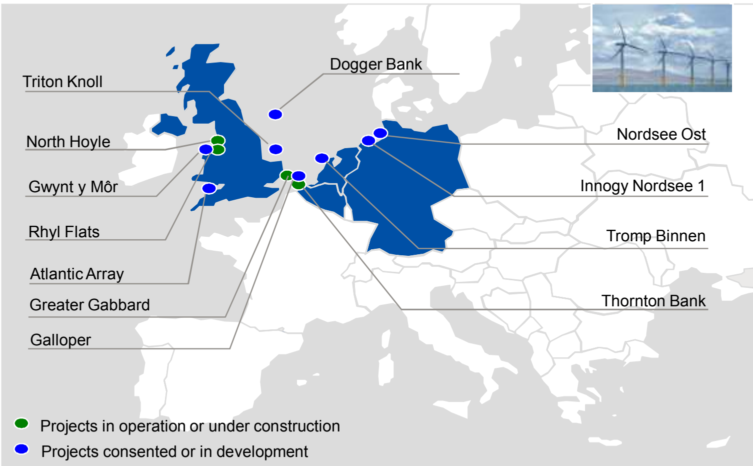
RWE
The energy to lead

1. **RWE Innogy offshore wind**
2. Applied foundation structures
3. Experiences made
4. Challenges / requirements

RWE
The energy to lead

PAGE 2

Overview Offshore Projects



RWE
The energy to lead

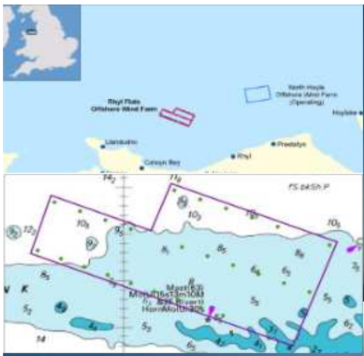
PAGE 3

North Hoyle

- West Coast UK (Irish Sea)
- Capacity: 60 MW
  30 turbines Vestas V80
- Foundations: Monopiles
- Distance from shore: 9 km
  Area: 10 km^2
  Water depth: 5 – 12 m
- UK Round 1, first commercial offshore project in the UK
- Year of construction 2003
- More than 7 years of operational experience

RWE
The energy to lead

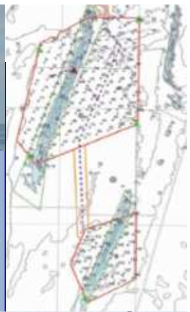
Rhyl Flats




- West Coast UK (Irish Sea)
- Capacity: 90 MW
  25 turbines
  Siemens SWT 3.6-107
- Foundations: Monopiles
- Distance from shore: 10 km
  Area: 10 km^2
  Water depth: 4 to 15 m
- UK Round 1
- Completion in 2009

RWE
The energy to lead

Greater Gabbard


- East Coast UK
  (River Thames Estuary)
- Capacity: 504 MW
- 140 turbines
  Siemens SWT 3.6-107
- Foundations: Monopiles
- Distance from shore: 35 km
  Area: 146 km^2
  Water depth: 24 to 34 m
- UK Round 2
- Under construction
  since 2009
- Joint Venture between SSE Renewables (50% share) and RWE Npower Renewables (50% share)

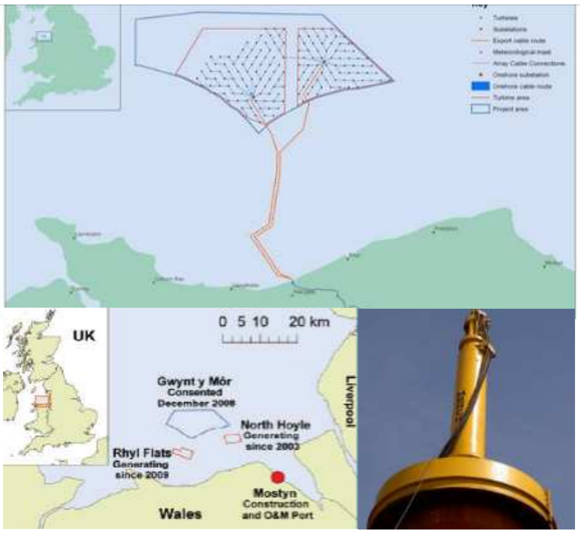
RWE
The energy to lead

Thornton Bank

- English Channel, Belgium
- Capacity: 325 MW
- Gravity base foundations and pre-piled jackets
- Installation in 3 phases
  - Phase 1 (6x Repower 5M) completed in 2009
  - Start construction phase 2 & 3 (48x 6MW) in April 2011
- Distance from shore: 30 km
  Water depth: 12 to 27,5 m
- Project company C-Power (RWE share: 26,7%)

RWE
The energy to lead

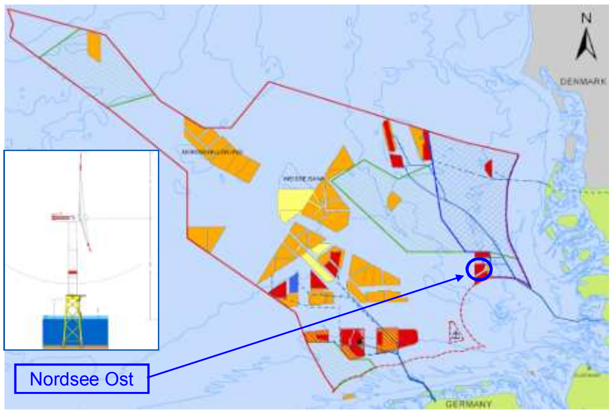
Gwynt y Môr



- West Coast UK (Irish Sea)
- Capacity: 576 MW
  160 turbines
  Siemens SWT 3.6
- Foundations: Monopiles
- Distance from shore: 18 km
  Area: 125 km²
  Water depth: 12 - 28 m
- UK Round 2
- Construction in two phases currently preparing for installation
- Joint Venture with Stadtwerke München and Siemens (RWE share: 60%)

RWE
The energy to lead

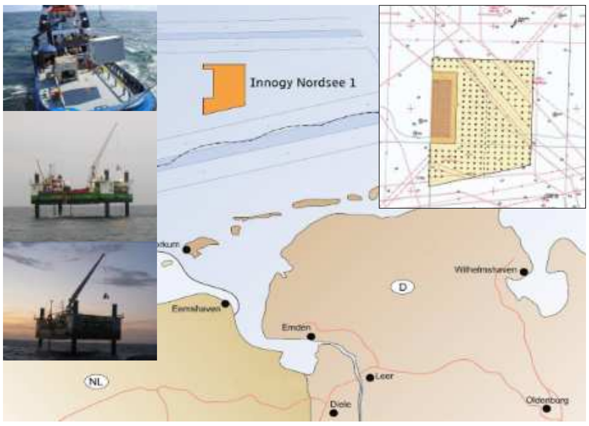
Nordsee Ost



- North Sea (Germany)
- Capacity: 295 MW
  48 turbines
  Repower 6.15 MW
- Foundations: Jackets
- Distance from shore:
  35 km north of Helgoland and
  40 km west of Amrum
  Area: 36 km²
  Water depth: 22 to 26 m
- Currently preparing installation

RWE
The energy to lead

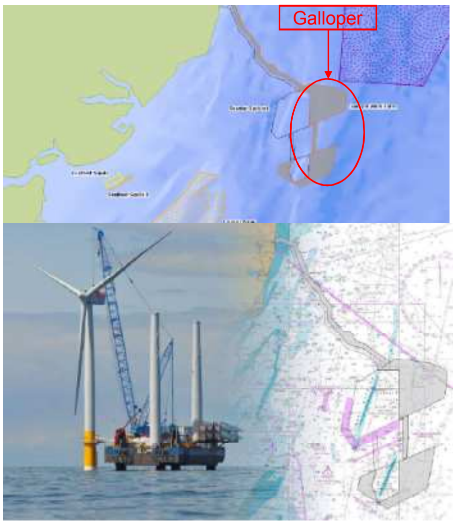
Innogy Nordsee 1



- North Sea (Germany)
- Capacity: approx. 1000 MW
  162 turbines of 6MW class
- Distance from shore:
  40 km north of Juist
  Water depth: 26 – 34 m
  Area: 146 km²
- Soil investigation in 2009
- Construction in 3 phases

RWE
The energy to lead

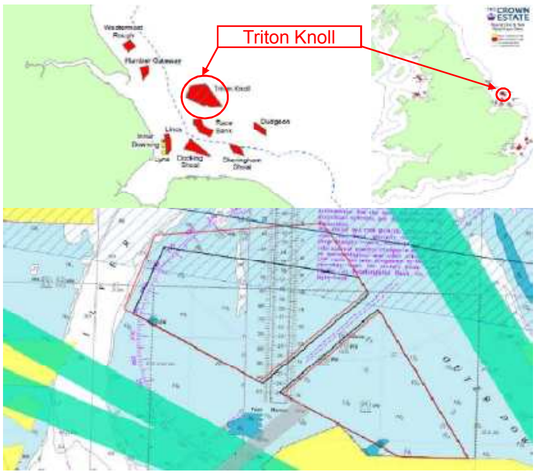
Galloper



- West cost of the UK (River Thames Estuary)
- Capacity: 504 MW up to 140 Turbines
- Distance from shore: 39 km
  Area: 180 km^2
  Water depth: 30 to 40 m
- UK Round 2.5
  Extension of Greater Gabbard
- Joint Venture between SSE Renewables (50% share) and RWE Npower Renewables (50% share)

RWE
The energy to lead

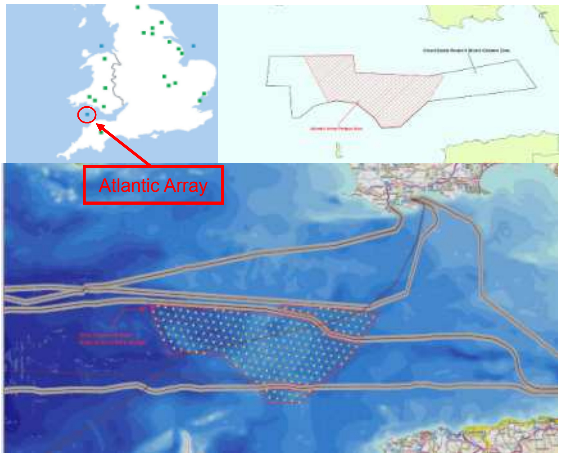
Triton Knoll



- North Sea UK
- Up to 1,200 MW
  150 turbines (8 MW) up to 333 turbines (3.6 MW)
- Distance from shore:
  33 km off the coast of Lincolnshire
  46 km off the coats of North Norfolk
  Area: 195 km^2
  Water depth: 8 - 28 m
- UK Round 2
- Fully consented 2010
- Environmental Impact Assessment (EIA) completed

RWE
The energy to lead

Atlantic Array (Bristol Channel Zone)



- West Coast UK (Bristol Channel)
- Capacity: 1500 MW
  250 turbines (6 MW)
- Distance from shore:
  14 km from North Devon
  18 km from South Wales
  Area: 492 km²
  Water depth: 23 to 56 m
- UK Round 3
- Start of offshore construction depending on RWE project pipeline

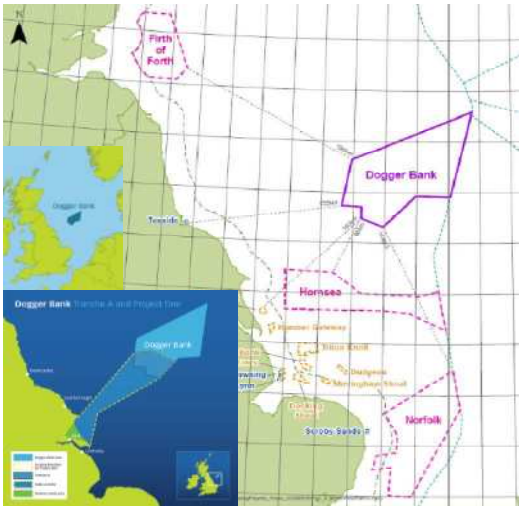
RWE
The energy to lead

Tromp Binnen

- North Sea (the Netherlands)
- Planned Capacity: 295 MW
  up to 59 turbines (5 – 6 MW)
- Distance from shore: 76 km
  Area: 33 km²
  Water depth: 23 - 28 m
- Potential capacity of entire Tromp area: 2 GW

RWE
The energy to lead

Dogger Bank



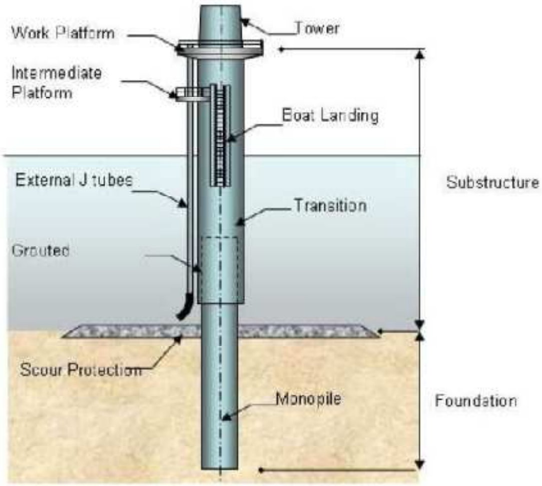
- North Sea (UK)
- Capacity: 9,000 MW
  Potential: 13,000 MW
  (equals 1500 turbines of 6 MW)
- Zone development plan:
  4 tranches (A-D) comprising
  3 - 4 projects each
- Distance from shore: 125 - 290 km
  Area: 8660 km^2
  Water depth: 18 - 63 m
- UK Round 3
  Development of Forewind Consortium
  [RWE Innogy, SSE, Statoil and
  Statkraft; (25% each)]
  Largest Offshore Wind Project

RWE The energy to lead

1. RWE Innogy offshore wind
2. **Applied foundation structures**
3. Experiences made
4. Challenges / requirements

RWE The energy to lead

> Monopiles

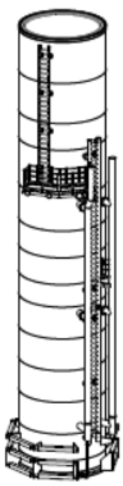


Used on projects:

- North Hoyle
- Rhyl Flats
- Greater Gabbard
- Gwynt y Môr

RWE
The energy to lead

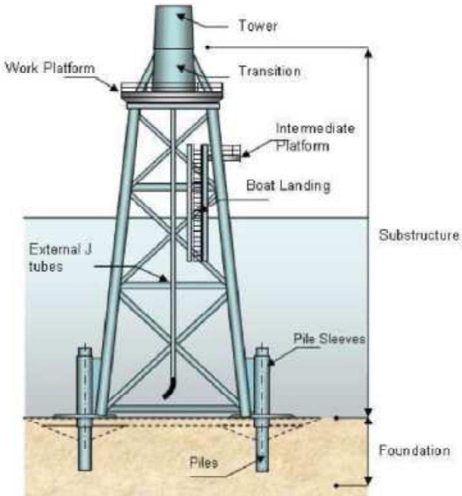
Criterion for Monopiles



- Light turbine
- Shallow water
- Appropriate soil properties
- Fabrication facilities for design
- No piling restricitions
- Used on North Hoyle, Rhyl Flats, Gwynt y Môr

RWE
The energy to lead

> Jackets

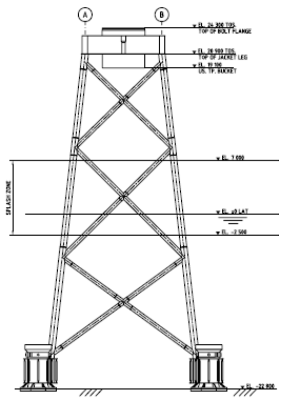


Used on projects:

- Thorton Bank Phase 2 & 3
- Nordsee Ost
- Innogy Nordsee 1

RWE
The energy to lead

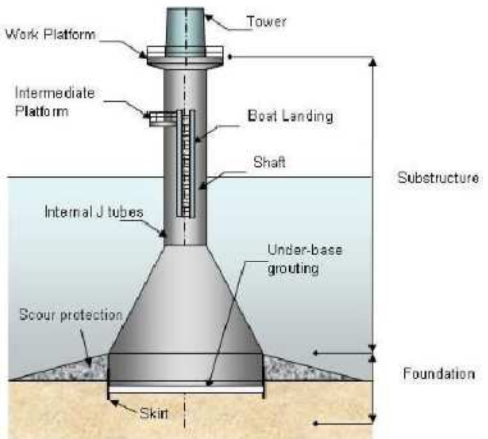
Criterion for Jacket



- Large Turbine
- Water depth 20m - 50m
- Demanding soil conditions – if piled
- Strong currents
- No piling restrictions
- No heavy lift vessel
- Used on Thorton Bank Phase 2 & 3, Nordsee Ost, Innogy Nordsee I (phase 1)

RWE
The energy to lead

> Gravity Based Structures



Used on projects:

- Thorton Bank Phase 1

RWE
The energy to lead

Criterion for GBS

- Large turbine
- Middle water depth
- Noise restrictions
- Solid uniform soil profile
- No strong currents requiring
- Economics
- Heavy lift vessel available or alternative installation method
- Used on Thornton Bank phase I

RWE
The energy to lead

> Criterion for novel foundation concepts

- Safe and cost effective construction and installation
- Robust installation methodology
- Minimum maintenance through life
- Proven technology
- Environmental impact
- Safe and efficient vessel access
- efficient cable pulling
- Safe cable protection

RWE
The energy to lead

RWE Innogy GmbH 21.09.2011 Seite 23

1. RWE Innogy offshore wind
2. Applied foundation structures
3. **Experiences made**
4. Challenges / requirements

RWE
The energy to lead

Experiences made with monopile Foundations

- Many details affecting cost effectivity
- Problems with grouted connections
- Cable installation and protection challenging

Experiences made with Jacket Foundations

- The details devil has many faces
- High fabrication requirements – qualified workmanship
- Relative little number of WTG specific jacket designs, yet
- Demanding installation – max inclination

1. RWE Innogy offshore wind
2. Applied foundation structures
3. Experiences made
4. **Challenges / requirements**

RWE
The energy to lead

General Experiences

- Different statutory regulations affecting design
- Flatness and roundness of flanges is a challenge
- Installation tolerances are challenging
- Offshore wind specific pile design standard required

RWE
The energy to lead


Thanks for your attention!
RWE
The energy to lead

Testing and Optimization of Support Structures for Offshore Wind Turbines

The Support Structures project group formed at Fraunhofer IWES

Martin Kohlmeier, Holger Huhn
Raimund Rolfes, Peter Schaumann

TEM #66, September 20-21, 2011, Esbjerg, Denmark

AGENDA

- The Fraunhofer Institute for Wind Energy and Energy System Technology
- Motivation and Aims
- The Planned Support Structure Testing Center in Hannover
  - Location and Dimensions
  - Planned Specifications of the Testing Equipment
  - Scenarios and Objectives of Testing
- Potential Benefits of Accompanying Research in Fields as
  - Load Analysis
  - Numerical Simulation
  - Material Modeling

Fraunhofer Institute for Wind Energy and Energy System Technology (IWES)

Bremerhaven and Kassel
Advancing Wind Energy and Energy System Technology

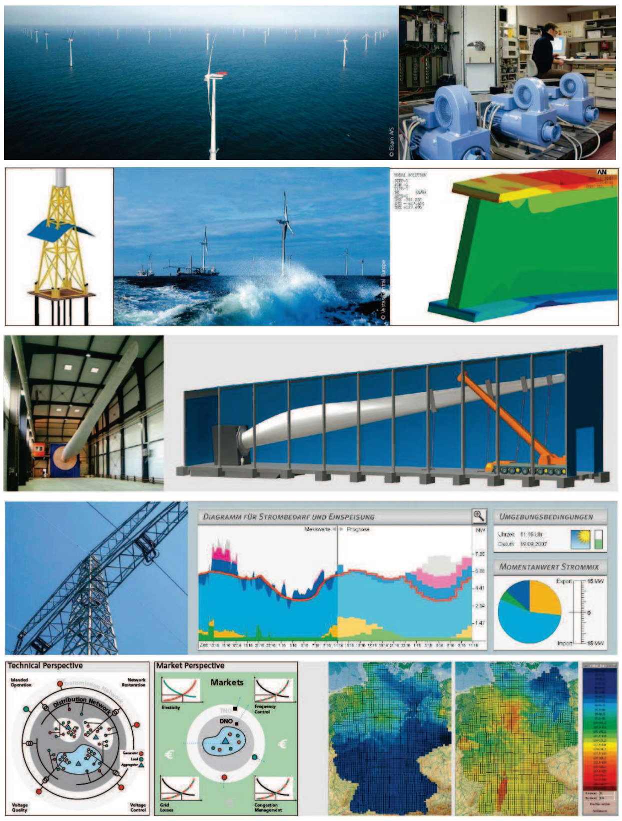
Foundation: 1.1. 2009

Directors: Prof. Dr. Andreas Reuter (Bremerhaven)
Prof. Dr. Jürgen Schmid (Kassel)

Research Spectrum:

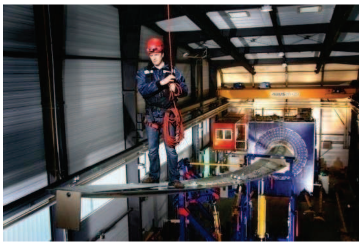
- Wind Energy from Material Development to Grid Optimization
- Energy System Technology for All Kinds of Renewable Sources

IWES Business Fields

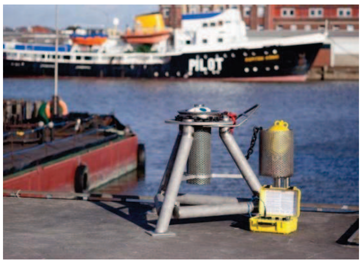


- Wind energy technology and operating management
- Dynamics of wind turbines and components
- Component development of rotors, drive trains and foundations
- Test and evaluation methods for wind turbines and components
- Environmental analysis of wind, sea and seabed for the utilization of wind and marine energy
- Control and system integration of decentralized converters
- Energy management and grid operation
- Energy supply structures and systems analysis

Core Competencies

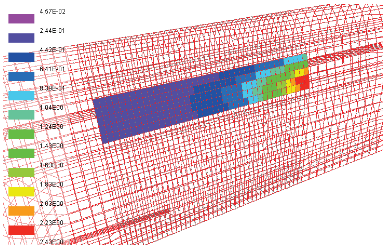


- Competence Center Rotor Blade



- Energy Meteorology and Systems Integration

- Technical Reliability



- Turbine Simulation and Assessment

- DyNaLab (Dynamic Nacelle Laboratory)

- Support Structures

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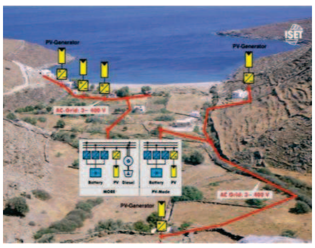
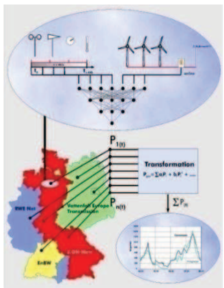
Core Competencies

- Electromobility and Smart Grids

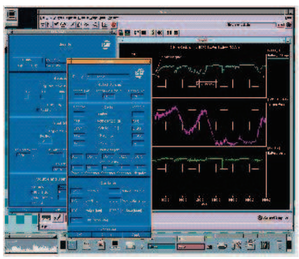
- Bioenergy System Technology



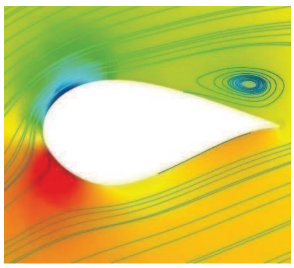
- Energy Economy and Grid Operation



- Systems Technology



- Control Engineering and Energy Storage Systems



- Fluid and System Dynamics

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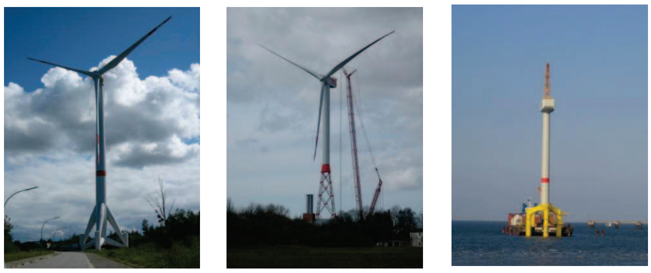
Motivation and Aims

- Multi-axial, Realistic, Quasi-static und Dynamic Tests with Loading According to Offshore Environment
- Testing of Large and Full Scale Specimen
- Large Scale Models of Support Structures



- Components of the Support Structure in Full Scale

▶ **Support Structure Testing Center in Hannover,** to be built by the Leibniz Universität Hannover and operated by Fraunhofer IWES

ForWind Center for Wind Energy Research | Leibniz Universität Hannover | Fraunhofer IWES

Planned Test Site Location

In the northern part of

Hannover, Germany

Next to the well known

Large Wave Flume (GWK) at the Coastal Research Center (FZK)

www.fzk-nth.de

Source: Franzius-Institute for Hydraulic, Waterways and Coastal Engineering. Arndt Hildebrandt, 2010.

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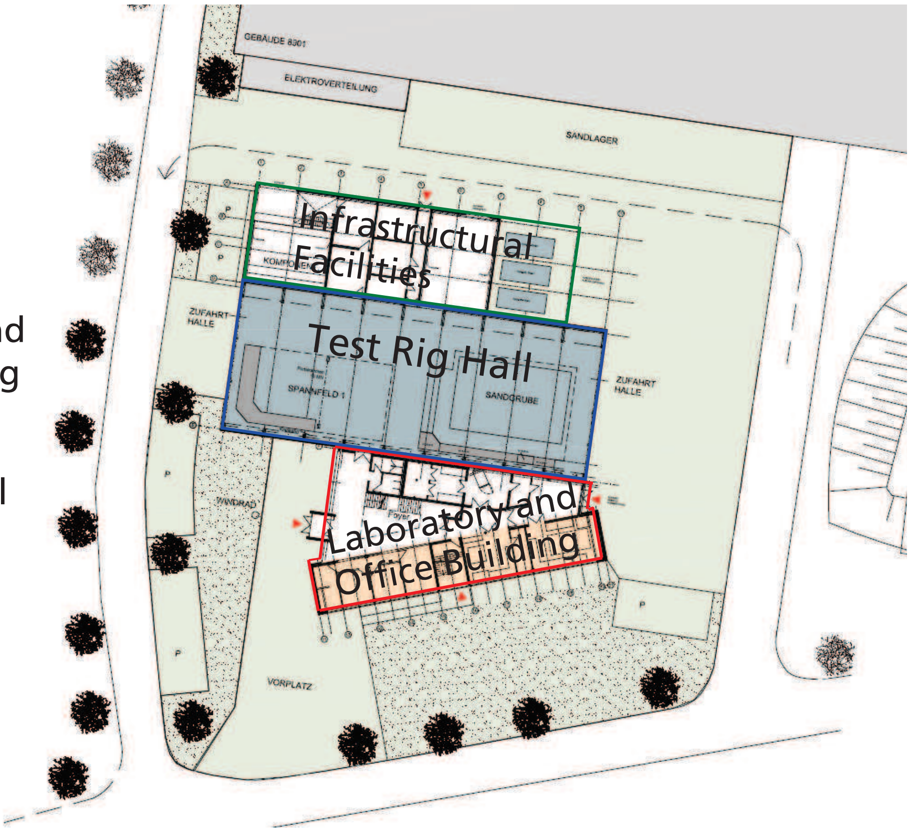
Planned Test Site Buildings

- Hall for Testing Rigs
- Laboratory and Office Building
- Infrastructural Facilities



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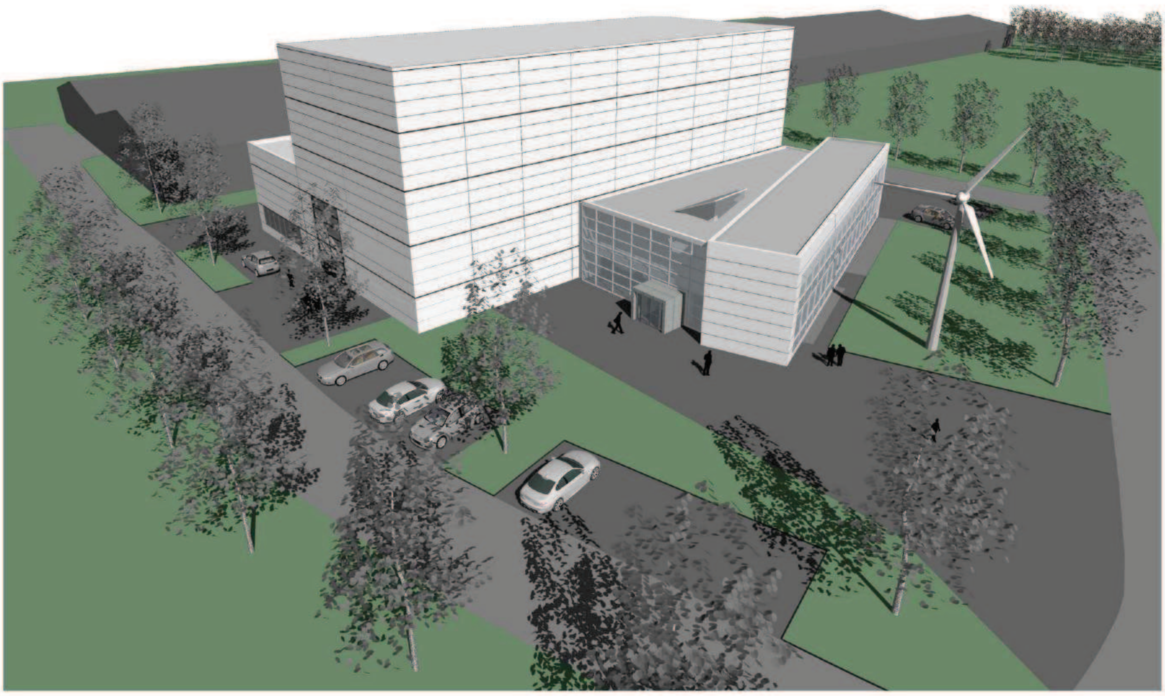
Hall with Laboratory and Office Building – Visualization



Staatliches Baumanagement Hannover
Celler Str. 7
30161 Hannover

ENTWURF - PERSPEKTIVE
17.09.2010

LEIBNIZ UNIVERSITÄT HANNOVER
TESTZENTRUM TRAGSTRUKTUREN

STRICKER ARCHITEKTEN
BÖHMERSTR. 28 - 30173 HANNOVER
TEL. 0511/410 48 03 FAX. 0511/410 48 05
e-mail: planung@stricker-architekten.de

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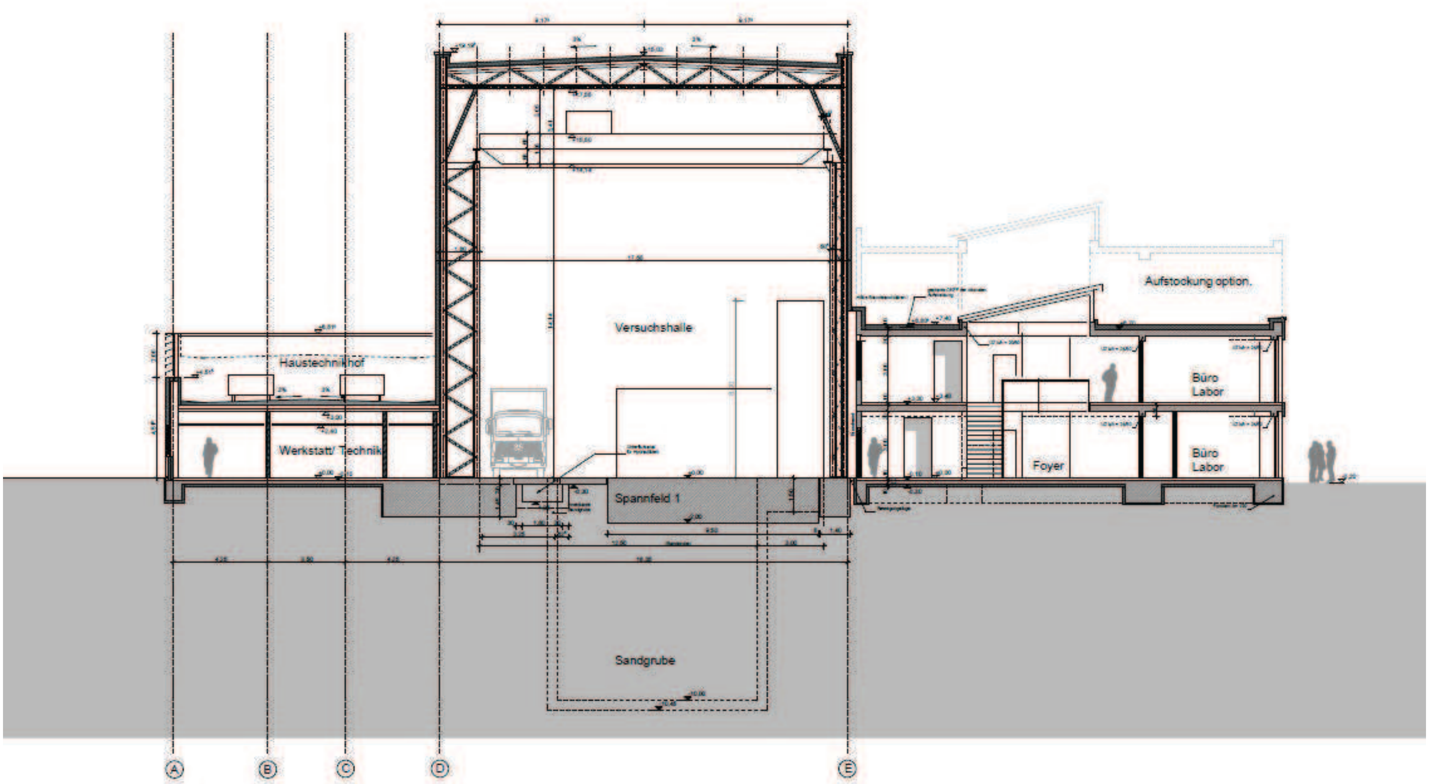
Hall with Laboratory and Office Building – Visualization

Hall with Laboratory and Office Building, Vertical Section

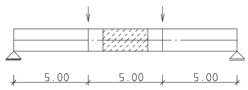


Scenarios and Objectives of Planned Testing

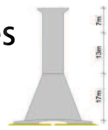
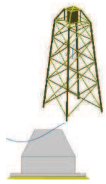
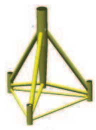
- Scenarios
  - Standard tests on large scale support structures and foundations
  - Detailed multi-axial fatigue tests on large/full scale support structure components like structural nodes, grouted joints and other welded or hybrid connections
  - Investigation of the soil structure interaction of foundations in water saturated soils
  - Large scale tests of horizontally and vertically loaded single piles
  - Testing of novel installation techniques and foundation concepts
- Objectives
  - Validation of numerical simulations and upscaling methods
  - Optimization of design, manufacturing and installation procedures
  - Improvement of guidelines and recommendations

Target Specifications of the Testing Equipment



- Length Scales
  - Full scale
    - for joints / grouted joint / hybrid connections / screws
  - Large scale (1:10 – 1:5)
    - jacket, tripod or tripile structures
    - concrete support structures
    - piles (up to 1:3,5) or suction buckets

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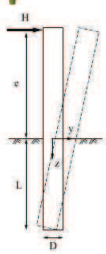
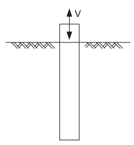

- Hydraulic Testing Rigs
  - Frequencies: up to 5Hz
  - Loading (multi-axial): force of up to 2MN
    bending moments up to 15MNm
- Resonant Testing Machines
  - Frequencies: up to 120Hz
  - Loading (axial): force of more than 1MN

Planning Status of Testing Facilities

Planning Status

Ground Floor

STRICKER ARCHITEKTEN
BÖHMERSTR. 28 - 30173 HANNOVER
TEL. 0511/410 48 03 FAX. 0511/410 48 05

LEIBNIZ UNIVERSITÄT HANNOVER
TESTZENTRUM TRAGSTRUKTUREN
GRUNDRISS EG M 1:200 23.11.2010

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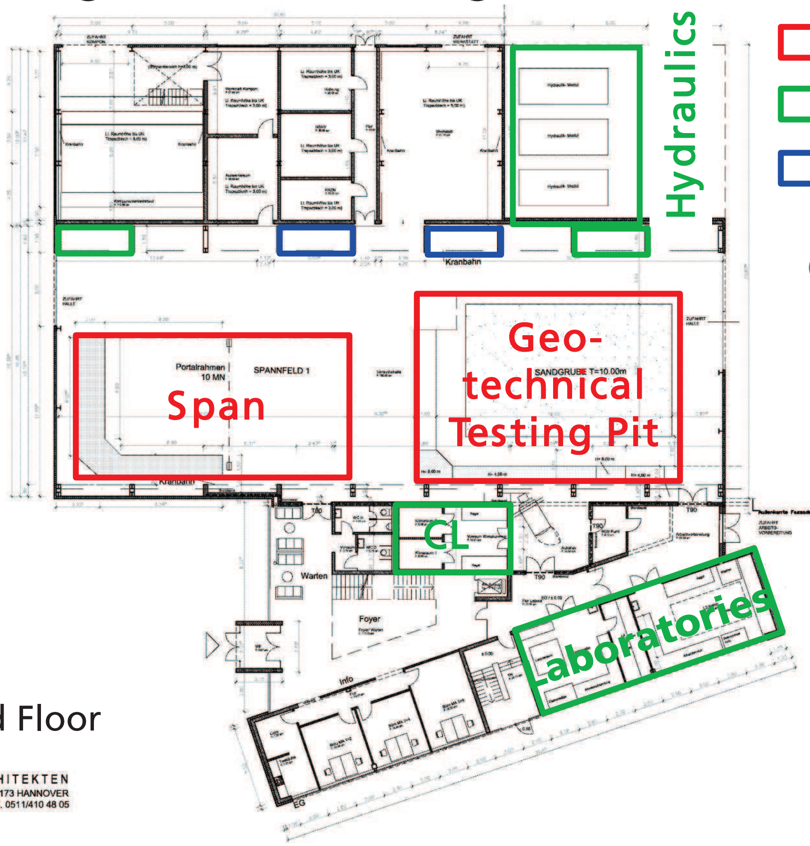
Planning Status of Testing Facilities



Giant Equipment
Testing Infrastructure
Testing Machines

CL: Climate Testing Laboratory

Planning Status

Ground Floor

STRICKER ARCHITEKTEN
BÖHMERSTR. 28 - 30173 HANNOVER
TEL. 0511/410 48 03 FAX. 0511/410 48 05

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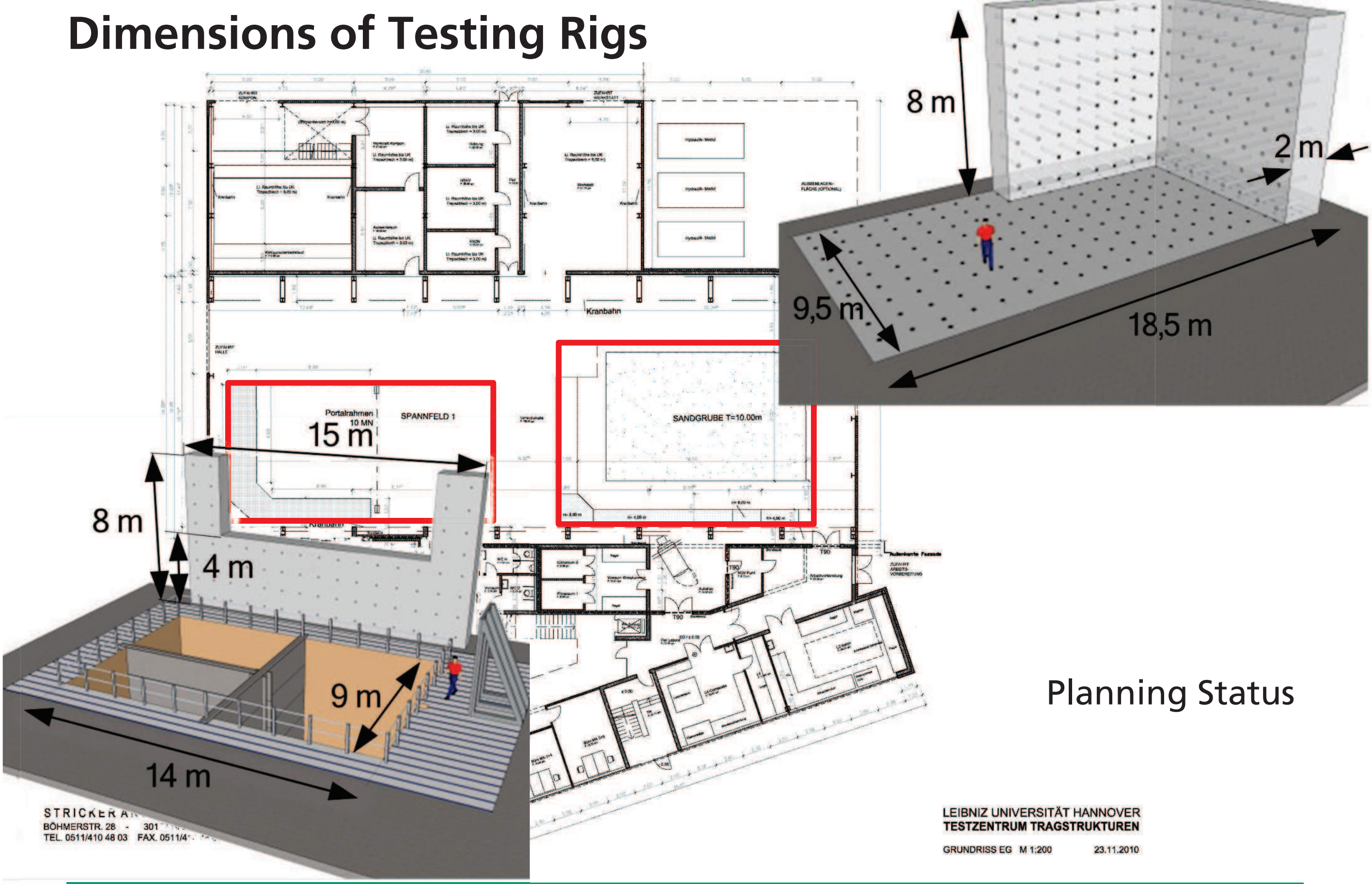
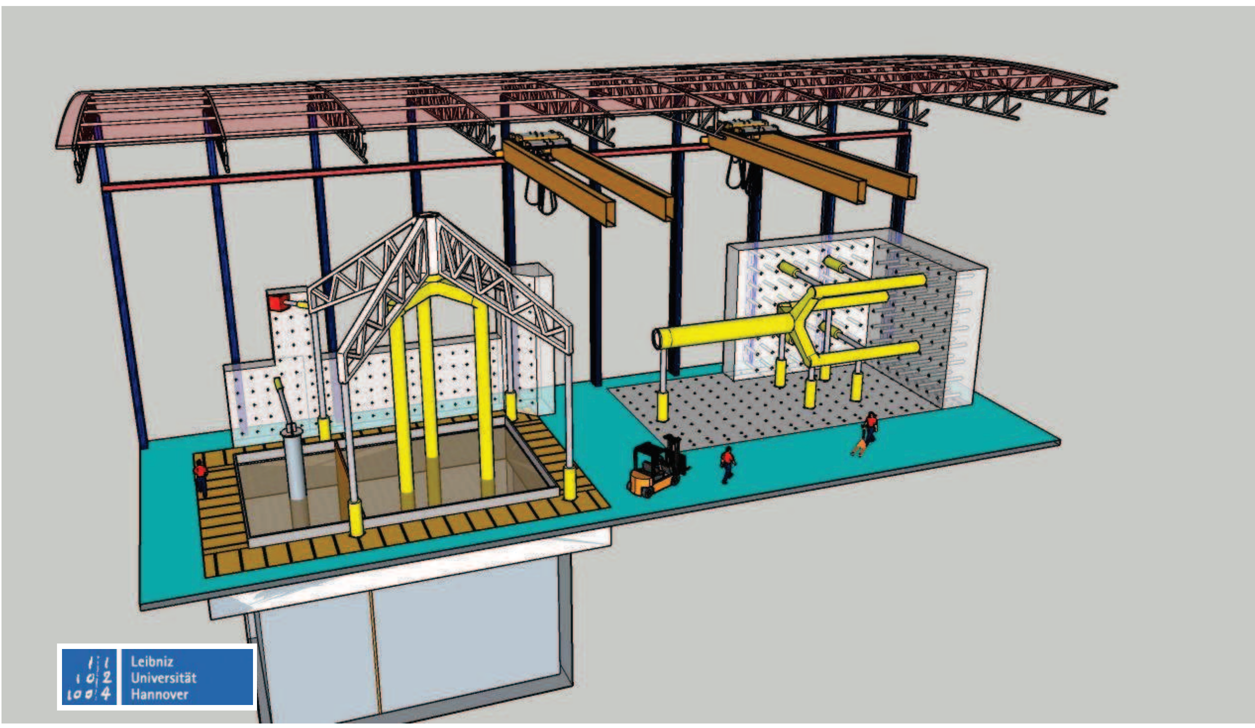
Dimensions of Testing Rigs



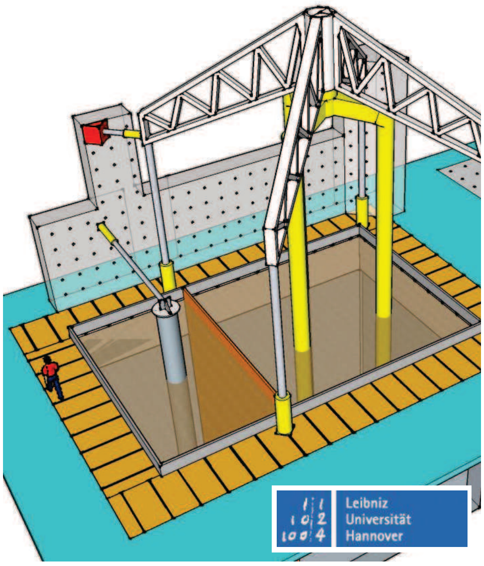
Planning Status

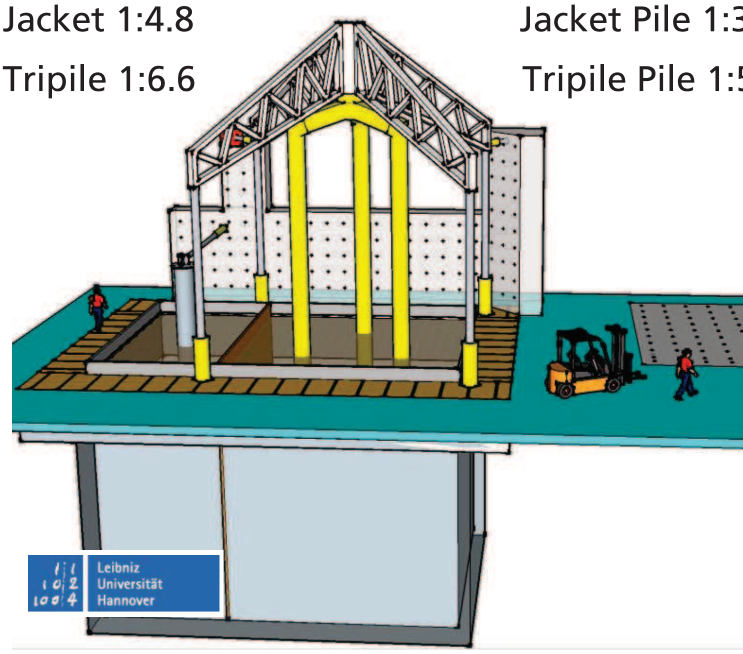
Testing Pit of 10 m Depth to be Filled with Sand and Water (left) and Span (right) with Support Walls



Testing Pit

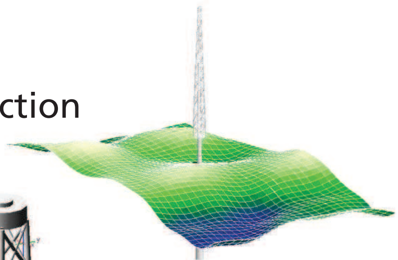
- Scales of Support Structures and Piles of Interest
  - Monopile 1:5.4
  - Tripod 1:5.8 — Tripod Pile 1:3.6
  - Jacket 1:4.8 — Jacket Pile 1:3.8
  - Tripile 1:6.6 — Tripile Pile 1:5.8

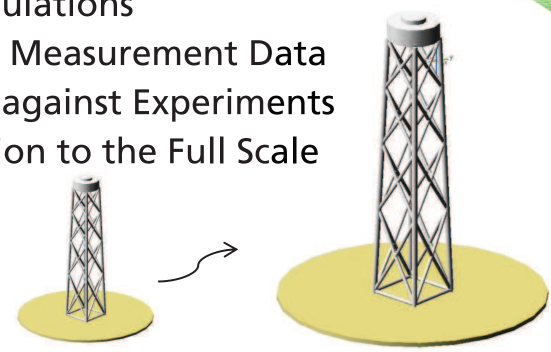




Accompanying Research

- Load Analysis
  - Wave Loading and Structural Interaction
- Numerical Simulations
  - Analysis of Measurement Data
  - Validation against Experiments
  - Extrapolation to the Full Scale





  - Analysis of Structural Joints and Hybrid Connections
  - Assessment of Different Types of Support Structures
- Material Modeling
  - Soil Structure Interaction
  - Behavior of Saturated Media in Cyclic Loading

Acknowledgements

Members of the Advisory Council:

Acknowledgements

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  - Senatorin für Bildung und Wissenschaft
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- Federal State of Lower Saxony

  and Federal Republic of Germany
- BMU Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
- BMBF Bundesministerium für Bildung und Forschung

  with support of the
- European Regional Development Fund ERDF

Thank you for your attention!

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Karlsruher Institut für Technologie

Physical and numerical modelling of the high cycle fatigue loading of offshore wind turbine foundations – some research results

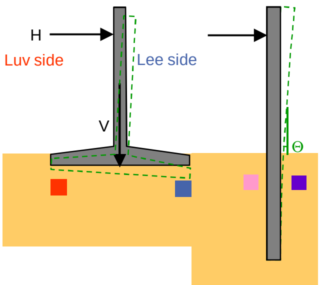
Dr.-Ing. Peter Kudella
Institute for Soil and Rock Mechanics, KIT Karlsruhe

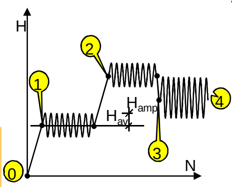
KIT-ZENTRUM ENERGIE

Research Idea

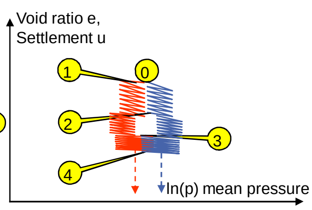
1. Accumulation of settlement, rotation

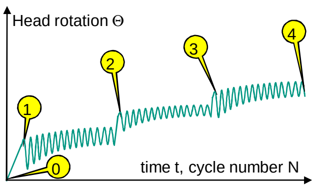
Two soil elements of similar initial state under arbitrary cyclic load packages





Load profile





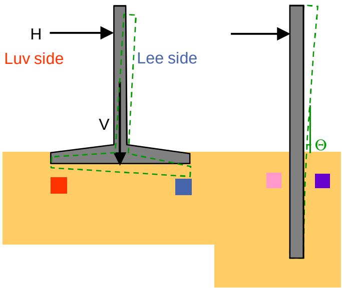
Soil densifies (dependent on density, load amplitude, mean value and direction), consequences:

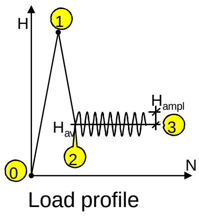
- Asymmetric settlement
- Densification and settlement accumulation

Research Idea

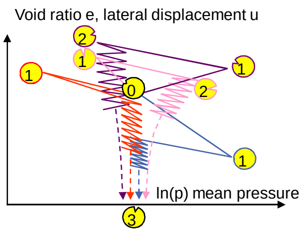
2. Partial system „self-recovery“, back rotation

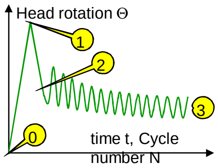
Two soil elements of similar initial state under small cycles after extreme load





Load profile





Gravity foundation:

Smaller leeward cyclic soil compression

- back rotation due to gravity

Pile:

Leeward side loosened, luvward interlocking

- back rotation due to elastic pile stiffness

Research Project

„Geotechnical Robustness and Self–Recovery of the Offshore Wind Power Generation Turbines“ (2007-2011)

WP 1:
„Fatigue and self-recovery of the subsoil through cyclic long-term loading of gravity foundations for offshore wind turbines“

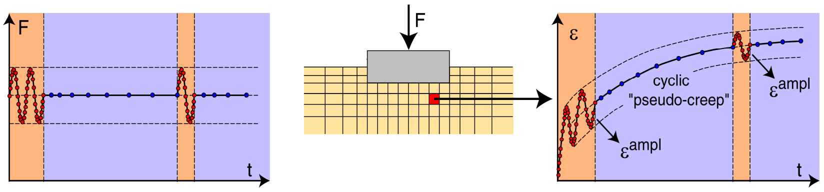
WP 2:
„Serviceability of monopile foundations for offshore wind turbines under consideration of high-cycle loading “

Objectives:

- 1. Development of a constitutive law for the polycyclic behaviour of sandy soils based on cyclic elementary tests allowing variable loading histories.
- 2. Implementation of the derived constitutive relation in a finite element code and calibration of the parameters with numerical element tests.
- 3. Performance of model tests with gravity footings and monopiles under controlled material and geometrical boundary conditions and loads as a first confidence stage for the validation of the proposed numerical model.
- 4. In the latest stage performance of full scale tests validation and predictions of the structural behaviour as a basis for design recommendations.

Accumulation Model

Calculation strategy: coupled „implicit" + „explicit" calculation steps



- Only a few cycles are calculated incrementally using a $\dot{\sigma}$-$\dot{\varepsilon}$-model (implicit)
- Larger packages of cycles ΔN in between are treated like creep deformations under constant load (explicit)
- input of the accumulation model: strain amplitudes ε^{ampl} from implicit cycles
- advantages: 1) no limitations in regard of possible cycle numbers
  2) much smaller number of increments → numerical errors minimized

Accumulation Model

$$\dot{\sigma} = \mathsf{E} : (\dot{\varepsilon} - \dot{\varepsilon}^{acc} - \dot{\varepsilon}^{pl})$$

- $\dot{\sigma}$ Stress rate
- E Elastic stiffness (pressure dependent)
- $\dot{\varepsilon}$ Strain rate
- $\dot{\varepsilon}^{acc}$ Accumulation rate (given)
- $\dot{\varepsilon}^{pl}$ Plastic strain rate (for strain paths touching the yield surface)

$$\dot{\varepsilon}^{acc} = \dot{\varepsilon}^{acc} \mathbf{m}$$

- $\mathbf{m}$ Direction of strain accumulation (unit tensor) → Flow direction of MCC-Model
- $\dot{\varepsilon}^{acc}$ intensity of strain accumulation (scalar)

$$\dot{\varepsilon}^{acc} = f_{ampl} \dot{f}_N f_p f_Y f_e f_\pi$$

Amplitude definition for multidimensional loops

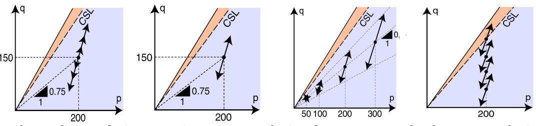
Functions (with material constants) consider:

- f_{ampl} Strain amplitude (C_{ampl})
- $\dot{f}_N$ Cyclic preload (C_{N1},C_{N2},C_{N3})
- f_p, f_Y Mean stress (C_p, C_Y)
- f_e Void ratio (C_e)
- f_π Polarization changes ($C_{\pi 1}$, $C_{\pi 2}$)

Cyclic laboratory testing

Parameter determination based on:

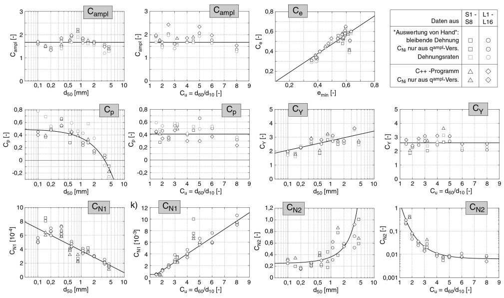
1. At least 11 drained cyclic triaxial tests



2. Estimation of C_{ampl}, C_e, C_p und C_Y from correlations and C_{N1}, C_{N2}, C_{N3} from only 1 test

$$f_N = C_{N1}\left[\ln(1 + C_{N2} N) + C_{N3} N\right]$$

3. Estimation of all parameters by correlations with d_{50}, C_u und e_{min}



Cyclic laboratory testing

Objective: Improvement of the accumulation model

- Very large cycle numbers $N > 10^8$
- Changing load cycle direction
- Changing mean effective pressures
- Stiffness parameter E from K and ν

$$\dot{\sigma} = \mathsf{E} : (\dot{\varepsilon} - \dot{\varepsilon}^{acc} - \dot{\varepsilon}^{pl})$$

$$K = A\ F(e)\ {p_{atm}}^{1-n}\ p^n\ F(\eta)$$

- Influence of density and stress anisotropy on K
- Simplified calibration methods for K and ν
- Extension of calibration towards fine grains and shell lime
- Very small stresses

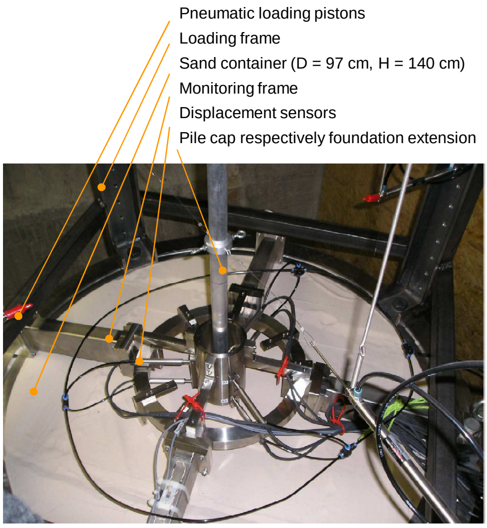
P. Kudella – Physical and numerical modeling of the high cycle fatigue loading of offshore wind turbine foundations – some research results
IEA R&D Wind, Task XI
TEM #66, Esbjerg 20.-21.09.2011

Model Testing – Test Setup

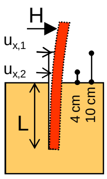

Steel drum


Sand densification

- Monopile 1:50, length 80 – 100 cm, inserted by driving
- Pile stiffness and loads scaled to model laws, pile diameter not
- Dry quartz sand, d_{50} = 0.14 mm, C_u = 1.5, densificated in layers to I_{d0} > 92 %
- Gravity foundation model 1:100



Model Testing – Measuring and Loading

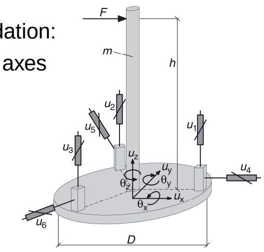


Monitoring quantities - Monopile:

- Lateral pile head displacement
- Maximal u^{max}
- Residual u^{av}
- Accumulated u^{acc}

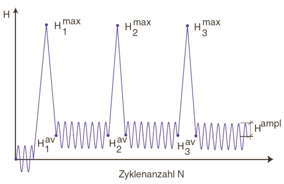
Plate foundation:

- Using 6 axes

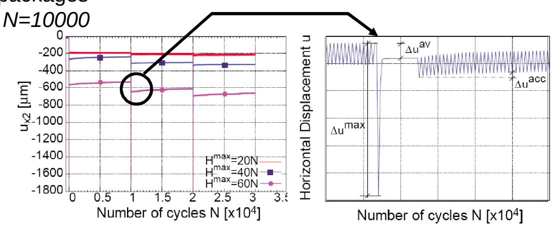


Loading scheme:

- 500 Precycles $H^{av}=0, H^{ampl}$
- Monotonic load H^{max}, H^{av} } 3 packages of $N=10000$
- Cyclic load $H^{av} \neq 0, H^{ampl}$

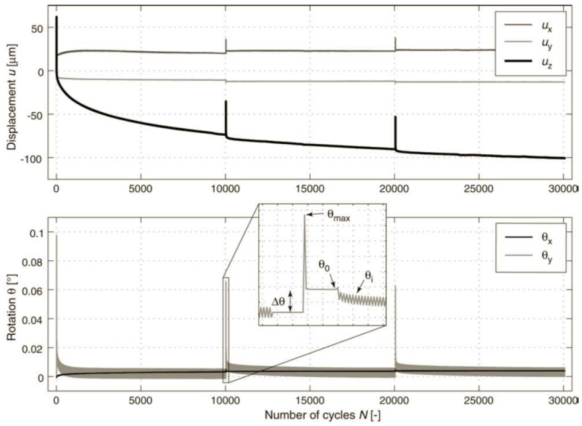


Typical displacement record:



Experimental results for plate foundations

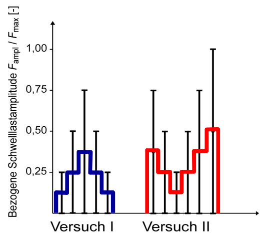
- H_{max} causes base gap and residual rotation θ_{max}
- following cycles with $0.1 < H_{ampl}/H_{max} < 0.9$ cause significant back rotation
- 2. and 3. package: soil stiffenes, back rotation reaches almost 100%
- back rotation faster for symmetric cycles ($H_{av} = 0$)
- Settlements double under changes of load direction
- Self-recovery is a special accumulation effect in differential settlement



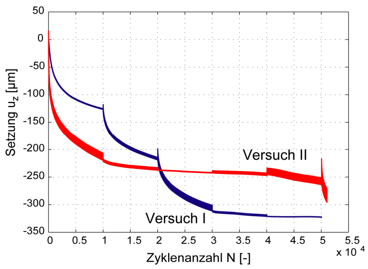
Displacement and (back) rotation due to symmetric cycles after maximum loading

Experimental results for plate foundations

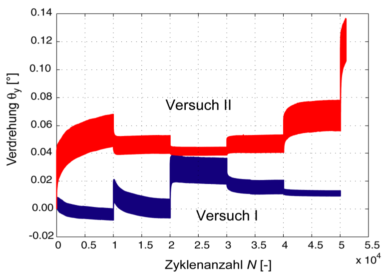
- Stepwise cyclic loading
- Settlements increase with load always, rotation increases with load only after base gap ($e > 0,125\ D_{Plate}$)
- Avoid base gap and/or use additional skirts !



Loading history (mean values, cyclic amplitude)



Mean settlements due to stepwise cyclic loading

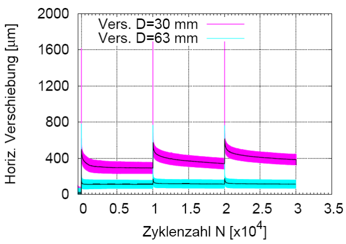


Rotation due to stepwise cyclic loading

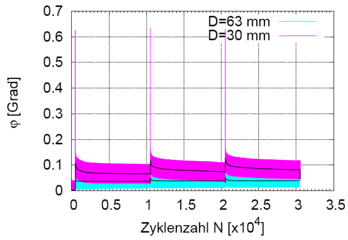
Experimental results for monopiles

- Model test with H^{max}=60 N, H^{av}=4 N, H^{ampl}=6,1 N, I_{D0}=90 %, L=80 cm, D=30 mm resp. D=63 mm, N=3x10⁴: Example for results demonstration

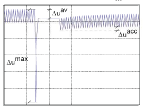
Overall lateral displacement

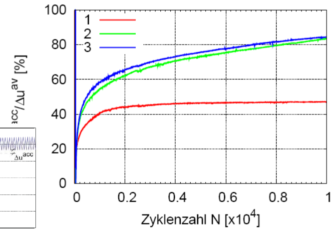


Overall rotation

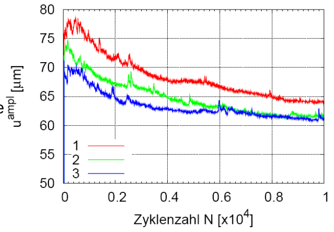


Back rotation normalized with residual rotation after unloading H^{max} → H^{av}





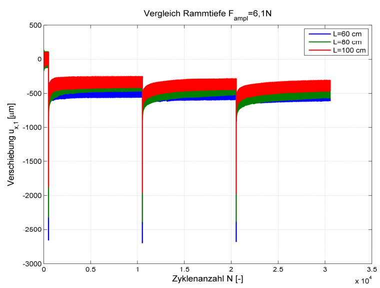
Cyclic lateral displacement amplitude per cycle package



Experimental results for monopiles

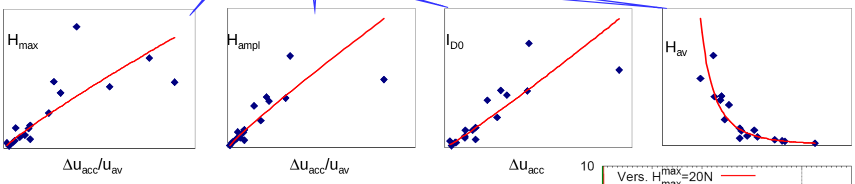
- Lateral displacements u_{av} (resp. pile rotations) increase with the number of cycles
- Residual displacements after maximum loads decrease with smaller cycles. This back-rotation accelerates for larger cyclic amplitudes.
- 2. and 3. load package: increasing soil stiffness (back rotation growing from 47% to 80%). The soil has not relaxed completely after restraint.
- A pile of adequate design length (here: L = 80 cm) meets the „vertical tangent" criterium (API, DNV).
- A longer pile shows smaller deformation (L = 100 cm relates to „zero toe kick").
- A pile too short (L = 60 cm) cannot store enough elastic energy, back-rotation capacity lost →
- with larger pile diameter D (30 – 63 mm), displacements decrease, normalized back rotation develops faster with similar magnitude
- Changes in loading direction result in a temporary acceleration of accumulation.

Overall lateral displacement for different pile lengths

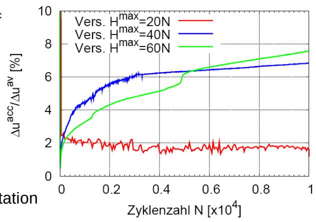


Experimental results for monopiles

- Accumulated displacements resp. back-rotation $\Delta u_{acc}/u_{av}$ increases
  with maximum load H_{max},
  with cyclic amplitude H_{ampl}
  and with density I_{D0}.
  They decrease with the mean load level H_{av}.



- Since back-rotation is a restraint-relaxation effect, it disappears for too „flexible" piles (EI small) as well as for too small H_{max}.



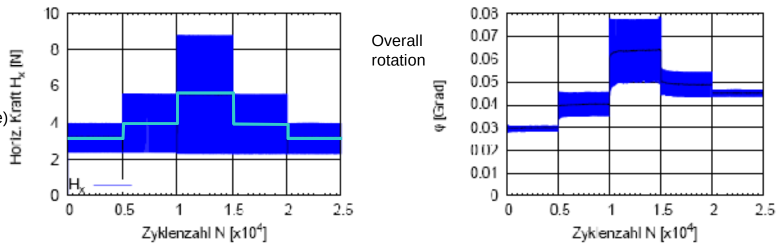
Normalized back rotation

Experimental results for monopiles

Stepwise cyclic loading (without previous extreme load):

Loading history (mean values, cyclic amplitude)

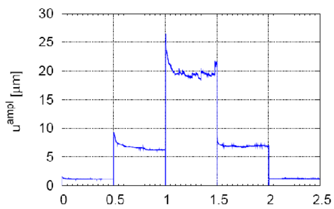
Overall rotation



- Accumulation for rising mean values H^{av}
- Back rotation for falling H^{av}
- Cyclic amplitude seems independent of loading history

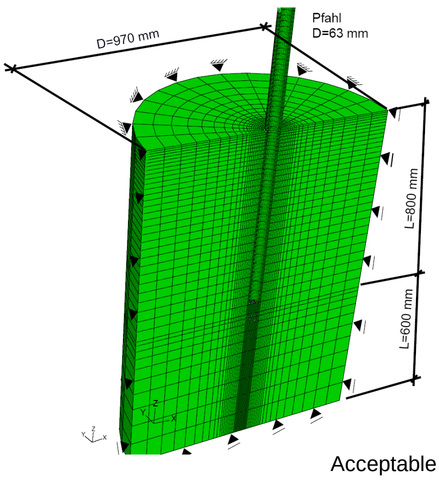
→ No design code describes that!

Cyclic lateral displace-ment amplitude

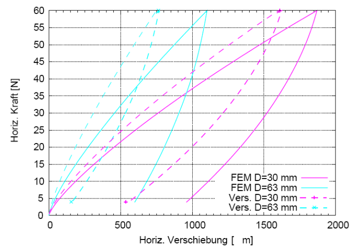


Numerical Model for monopile

Reference mesh



- FE code ABAQUS
- 12.800 C3D8R elements (reduced integration to minimize calculation time, locking and numerical self-restrain effects
- Monotonic (extreme) load and following 3 cycles using hypoplasticity
- Cyclic loading using the HCA model



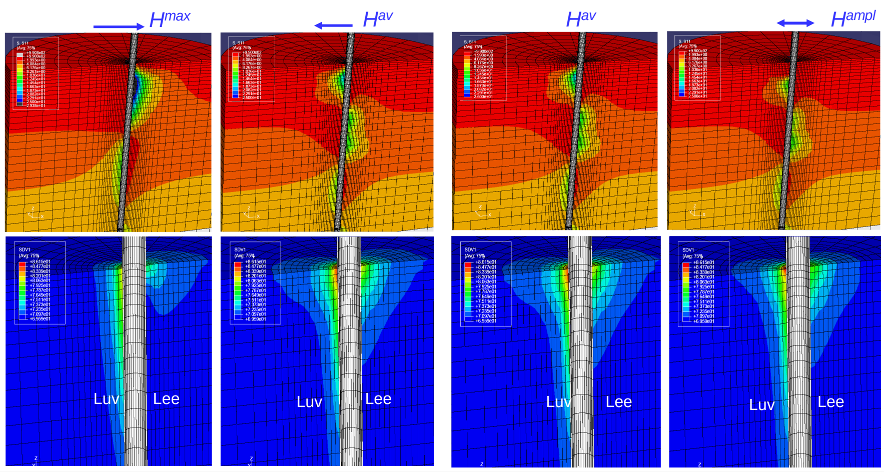
Acceptable modelling of the monotonous maximum loading

17 P. Kudella – Physical and numerical modeling of the high cycle fatigue loading of offshore wind turbine foundations – some research results IEA R&D Wind, Task XI TEM #66, Esbjerg 20.-21.09.2011

Numerical Model for monopile

Distribution of lateral stress (top) and void ratio (bottom) during monotonous loading: Residual restraint and loosening of Luv side

Distribution of lateral stress (top) and void ratio (bottom) during cyclic loading: Relaxation and redensification



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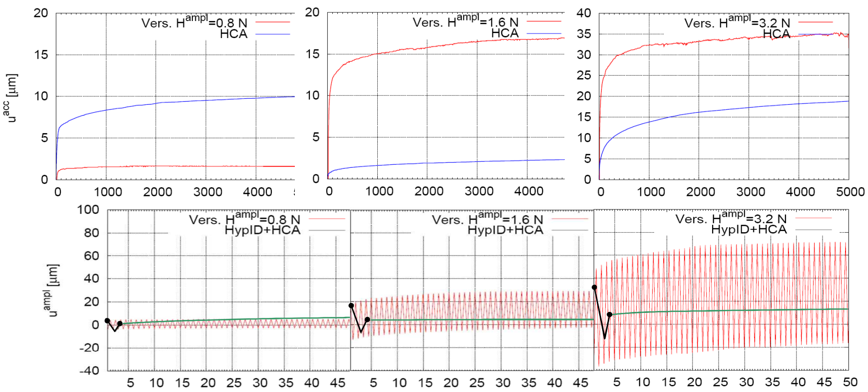
Numerical Model for monopile

Simulation of stepwise loading with variation of H^{av} and H^{ampl}



- Calculation of initial amplitudes using hypoplasticity (+ intergranular strain)
- Over-/underestimation of accumulation through unrealistic initial amplitudes

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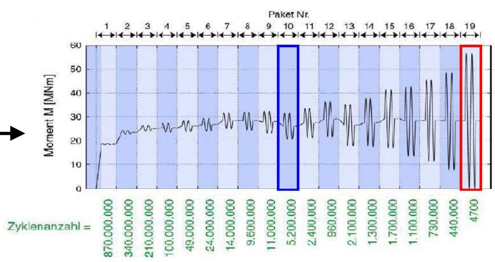
Results summarized

- Accumulations of displacement and rotation under polycyclic loads including back rotation effects are experimentally evident
- Dependencies on foundation geometry, soil density and load history are basically understood
- Physical models can be back-calculated, the phenomenonogical effects and dependencies be reproduced qualitatively using numerical models
- Numerical validations in small-scale still have shortcomings (lack of parameters for small-stress, self-restrain effects, transition beween different constitutive relations, general overestimation of system stiffness)
- Accumulations depend on the complete (cyclic) loading history
- Design/Prediction models based on the interchangeability of load packages must fail → („Miner's rule" holds only for elementary tests, if at all)



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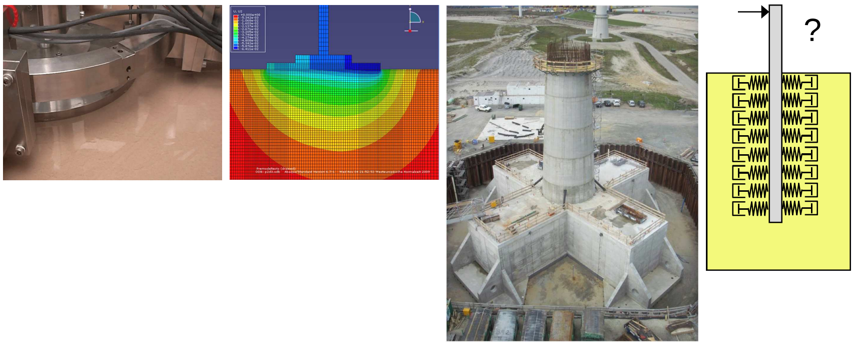
Further plans

- Physical small-scale model tests with water saturation
- Numerical models including saturation (pore water overpressure effects), gravity foundations and overcoming various numerical problems
- Interpretation of a full-scale onshore test, validation of numerical prediction model
- Simplified design procedures representing a realistic accumulation history



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IEA R&D Wind Task XI – TEM #66
Offshore Foundation Technology and Knowledge
For Shallow, Middle and Deep Water
September 20, 2011 – Esbjerg, Denmark

Improvements to Soil-Structure Interaction and Foundation Modeling

www.ntnu.no | Effects of Foundation Modeling Methodology | Eric Van Buren, PhD Offshore Wind

2

Personal Background

- Eric Van Buren; Houston, Texas
- BSc in Civil Engineering from Texas A&M University (2008)
- MSc in Structural Engineering from Texas A&M University (2009)
- Develop cost-effective foundation systems for bottom-fixed offshore wind turbines in intermediate water depth (30m-70m)
- Planned project completion in September 2012
- Part of NOWITECH, WP 3: Novel Substructures for Offshore Wind Turbines since August 2009

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Norwegian Research Centre for Offshore Wind Technology
The objective of NOWITECH is pre-competitive research laying a foundation for industrial value creation and cost-effective offshore wind farms. Emphasis is on "deep-sea" (+30 m) including bottom-fixed and floating wind turbines. Work is focused on technical challenges including a strong PhD and post doc programme:
• Integrated numerical design tools for novel offshore wind energy concepts.
• Energy conversion systems using new materials for blades and generators.
• Novel substructures (bottom-fixed and floaters) for offshore wind turbines.
• Grid connection and system integration of large offshore wind farms.
• Operation and maintenance strategies and technologies.
• Assessment of novel concepts by numerical tools and physical experiments.
• Total budget (2009-2016) is MNOK 320, M€ 38, MUSD 49
Established by the Research Council of Norway
Contact:
NOWITECH Director John O.G. Tande
john.tande@sintef.no
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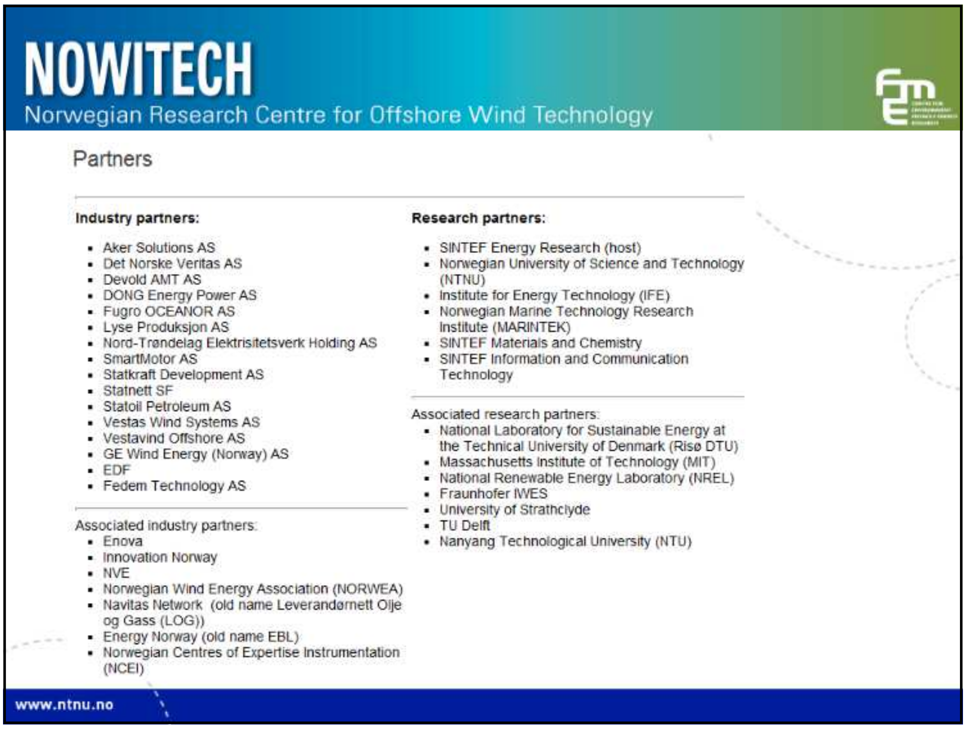
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• Statoil Petroleum AS
• Vestas Wind Systems AS
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• GE Wind Energy (Norway) AS
• EDF
• Fedem Technology AS
Associated industry partners:
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• Innovation Norway
• NVE
• Norwegian Wind Energy Association (NORWEA)
• Navitas Network (old name Leverandørnett Olje og Gass (LOG))
• Energy Norway (old name EBL)
• Norwegian Centres of Expertise Instrumentation (NCEI)
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• Norwegian University of Science and Technology (NTNU)
• Institute for Energy Technology (IFE)
• Norwegian Marine Technology Research Institute (MARINTEK)
• SINTEF Materials and Chemistry
• SINTEF Information and Communication Technology
Associated research partners:
• National Laboratory for Sustainable Energy at the Technical University of Denmark (Risø DTU)
• Massachusetts Institute of Technology (MIT)
• National Renewable Energy Laboratory (NREL)
• Fraunhofer IWES
• University of Strathclyde
• TU Delft
• Nanyang Technological University (NTU)
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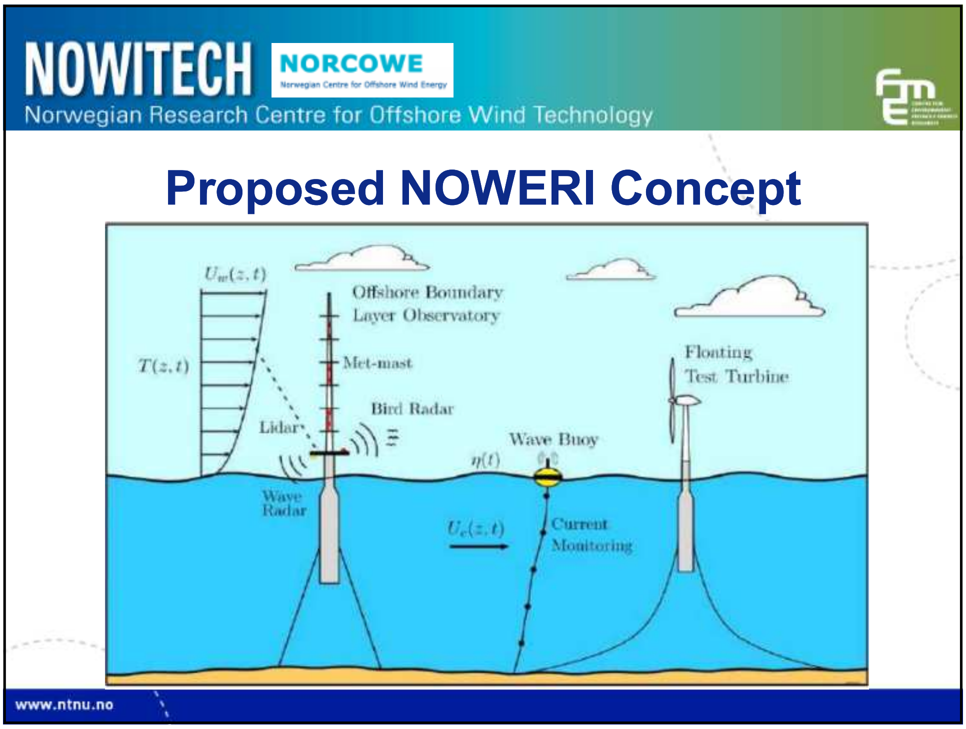
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Proposed NOWERI Concept
$U_w(z,t)$
Offshore Boundary Layer Observatory
$T(z,t)$
Met-mast
Floating Test Turbine
Bird Radar
Lidar
Wave Buoy
$\eta(t)$
Wave Radar
$U_c(z,t)$
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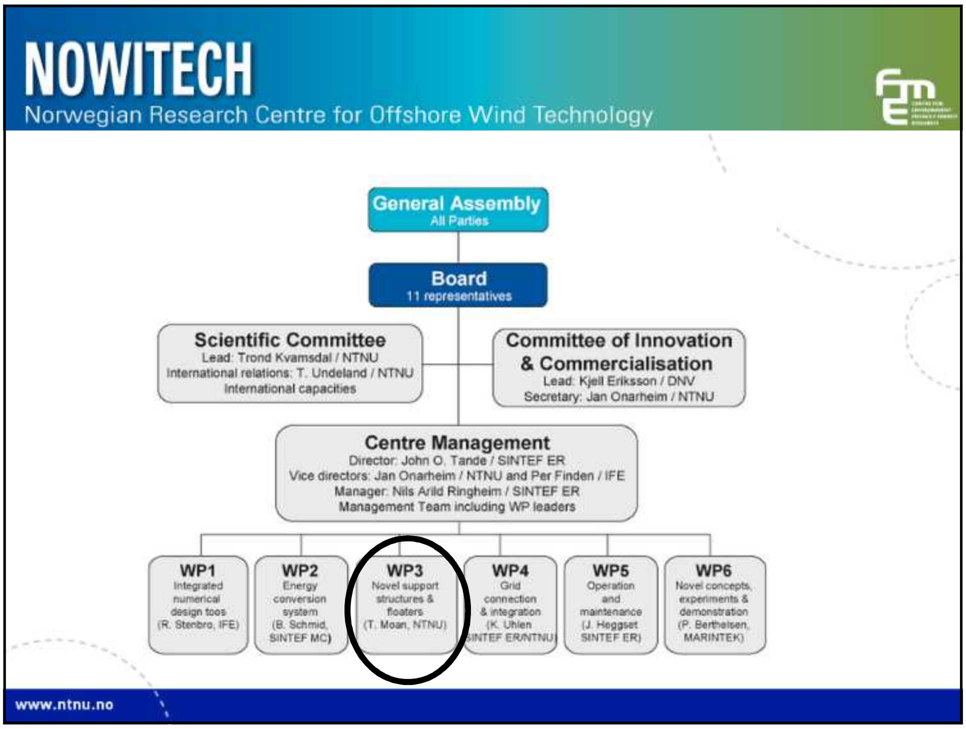
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International relations: T. Undeland / NTNU
International capacities
Committee of Innovation & Commercialisation
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Director: John O. Tande / SINTEF ER
Vice directors: Jan Onarheim / NTNU and Per Finden / IFE
Manager: Nils Arild Ringheim / SINTEF ER
Management Team including WP leaders
WP1 Integrated numerical design toos (R. Stenbro, IFE)
WP2 Energy conversion system (B. Schmid, SINTEF MC)
WP3 Novel support structures & floaters (T. Moan, NTNU)
WP4 Grid connection & integration (K. Uhlen SINTEF ER/NTNU)
WP5 Operation and maintenance (J. Heggset SINTEF ER)
WP6 Novel concepts, experiments & demonstration (P. Berthelsen, MARINTEK)
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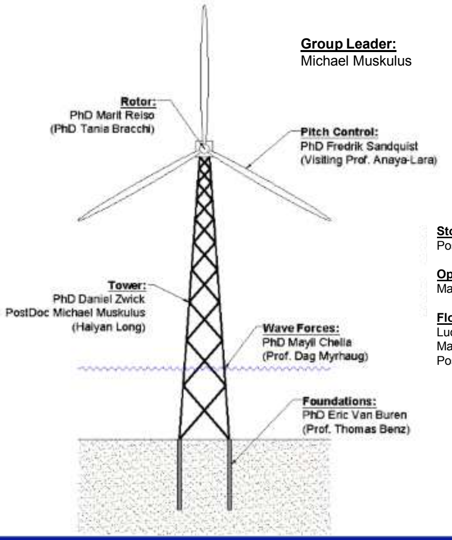
WP Activity 3.1: Bottom-fixed Support Structures

Group Leader:
Michael Muskulus



Stochastic Modeling:
PostDoc Paul Thomassen

Operations and Maintenance:
Matti Scheu

Floating Support Structures:
Ludwig Krause
Matthias Brommundt
PostDoc Karl Merz

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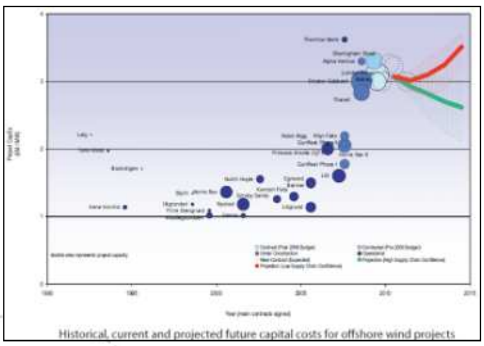
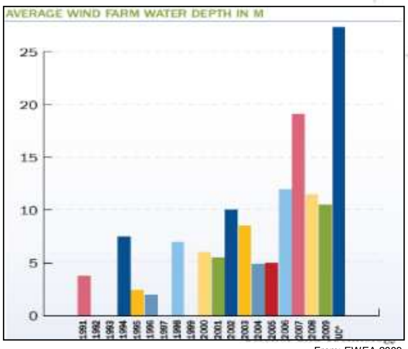
Motivations for Research

- Costs of offshore wind energy are **rising** as water depth and distance to shore increases – largely from increasing support structure costs
- Foundation modeling techniques are outdated and do not fully describe the dynamics of the system, e.g., damping in the foundation is largely ignored
- Uncertainty in foundation performance leads to overdesign and increased costs



Historical, current and projected future capital costs for offshore wind projects

From: GL-Garrad Hassan 2009



From: EWEA 2009

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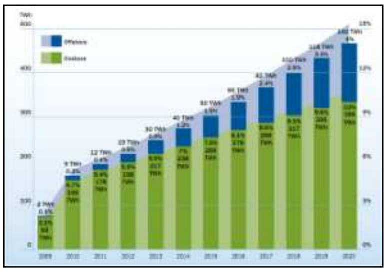
Offshore vs. Onshore costs

- Offshore turbine support structures typically cost 2.5 times more than a comparable onshore turbine support structure
- Support structures make up a much higher percentage of the total CAPEX for offshore turbines compared to land based turbines.



Courtesy: EWEA 2010

Contribution to Total Cost		
Component	**Onshore**	**Offshore**
Turbines (excluding works)	68-84%	49%
Support Structure	**1-9%**	**21%**
Grid Connection	2-10%	16%
Consultancy	2-8%	9%
Electric Installation	1-9%	5%
Other	2-10%	1%

From: Wind Energy - The Facts

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Reducing the costs...

- Efficiently designed support structures and foundations
  - Specifically engineer foundations for loads and site conditions at each offshore wind turbine
  - Develop computer software tools specifically produced for offshore wind turbine foundation design
- Mass production of offshore wind turbine support structures
  - Towers and foundations must be designed in a way that is economical to mass-produce
  - Efficient use of materials, manufacturing facilities, and manpower
  - Purpose built offshore wind support structure manufacturing facilities will be needed
- Improved installation techniques and equipment
  - New foundation technology which is easier and quicker to install
  - Purpose-built installation vessels to install wind turbines in a cost effective manner

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Pile Foundations Models

CERTAINTY & COST

- Fully coupled finite element model simulation
  - Most comprehensive modeling technique, includes many additional non linear effects
  - Includes interactions between soil layers (vertical) and between adjacent piles (horizontal)
  - Very time consuming and expensive, requires extensive soil lab testing
- Sequential analysis with finite element simulations
  - Combines the capabilities of the multiple non-linear spring model with finite element simulations
  - Allows for dynamic FE simulations of the foundation without the need for a fully coupled model
- Multiple non-linear spring representation (p-y curves)
  - Foundation modeled with springs distributed along length of pile
  - Dependant on accurate soil profile and characteristic parameters
- Single non-linear spring representation
  - Entire foundation modeled with single springs at mudline for each DOF
  - Does not account for pile flexibility or soil profile non-homogeneity
- Model with an equivalent fixity depth (Apparent Fixity Length)
  - Very simple and fast in computations, more representative than fixed condition
  - Does not capture any soil-structure interaction
- Assume fixed boundary conditions
  - Extremely simple, fast computations
  - Gross misrepresentation of stiffness of the foundation

SIMPLICITY & SPEED

Red: Models being developed in PhD (Coupled)
Blue: Existing models (Uncoupled)

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Research Question

Does assuming a fixed boundary condition for the foundation of an offshore wind turbine tower provide an accurate enough estimation of the dynamic characteristics of the tower to warrant its use for preliminary structural optimization procedures?

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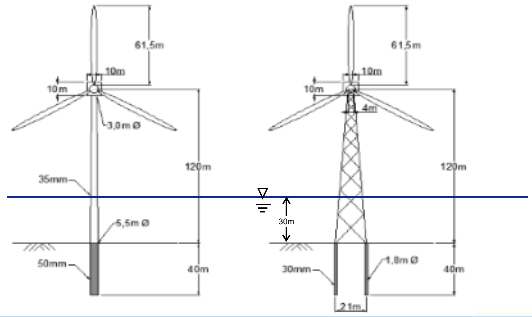
Support Structures

- Monotower
  - Up scaled model of NREL 5MW offshore reference turbine tower
  - 120m height, 35mm wall thickness, diameter tapering from 5.5m to 3m
  - Natural frequency of 0.197 Hz in 1st bending mode, 0.557 Hz in torsion
- Full-height lattice tower
  - Designed by former NTNU PhD student Haiyan Long
  - 120m height, 4 legs, 10 sections. 21 meters wide at base, 4 meters at nacelle
  - Natural frequency of 0.938 Hz in 1st bending mode, 2.42 Hz in torsion



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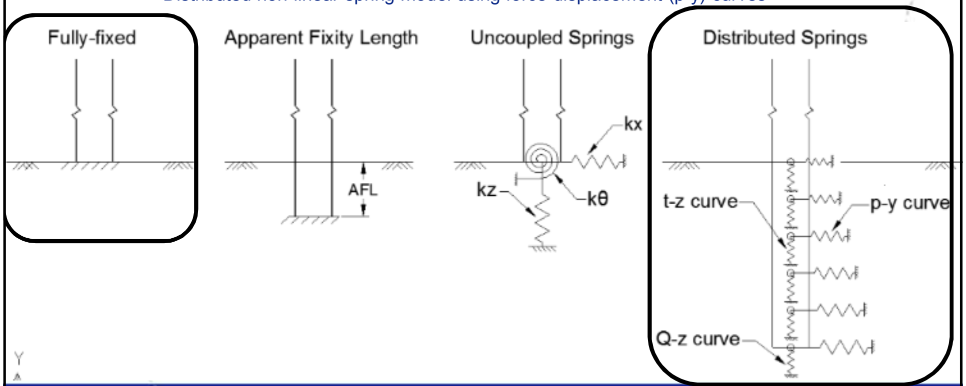
Uncoupled Foundation Models

- Four different foundation modeling techniques are considered
  - Fixed boundary conditions
  - Apparent Fixity Length (AFL)
  - Uncoupled Springs
  - Distributed non-linear spring model using force-displacement (p-y) curves



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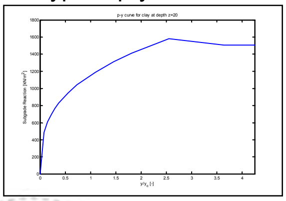
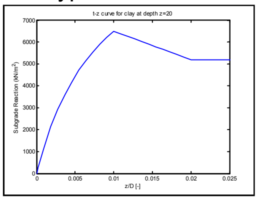
Distributed NL springs (p-y curves)

- Force displacement (p-y) curves found in the design standard are used for horizontal and vertical displacements
  - ISO 19902:2007(E) – Petroleum and natural gas industries – fixed steel offshore structures (Ch 17)
  - Dependant on undrained shear strength profile, friction angle, unit weight of soil, and pile diameter
  - Not really suitable to extremely large diameter piles (such as those used on monopile wind turbines)
- Hyperbolic force displacement relationship used for torsional stiffness
  - Method developed by Randolph and Guo *Torsional Piles in Non-homogenous Media* (1996)
  - Dependant on undrained shear strength profile, unit weight of soil, pile stiffness, pile diameter

Typical p-y curve



Typical t-z curve



Soil Characteristics

		Sand	Clay
Submerged Unit Weight	γ' [kN/m³]	10	11
Friction Angle	φ' [deg]	40	-
Proportionality Constant	k [kN/m³]	45000	-
Undrained Shear Strngth	c_u [kN/m²]	-	75

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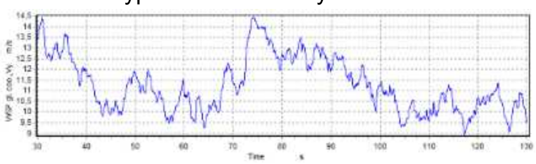
Model Setup

- Analyzed Using HAWC2
  - Multibody aero-servo-hydro-elastic asymmetric Newmark-Beta type solver
  - 130 second time series with first 30 seconds discarded to eliminate transients
  - 12 m/s average wind velocity, power-law wind shear profile
  - Mann type turbulence intensity of 10%, u,v,and w directional scaling
  - Tower aerodrag and hydro drag included only on main legs due
- Soil modeled as lookup table of displacement-force relationship
  - Lookup table developed using p-y curve equations executed in Matlab
  - Built-in HAWC2 soil module uses look-up table

Typical wind velocity time series



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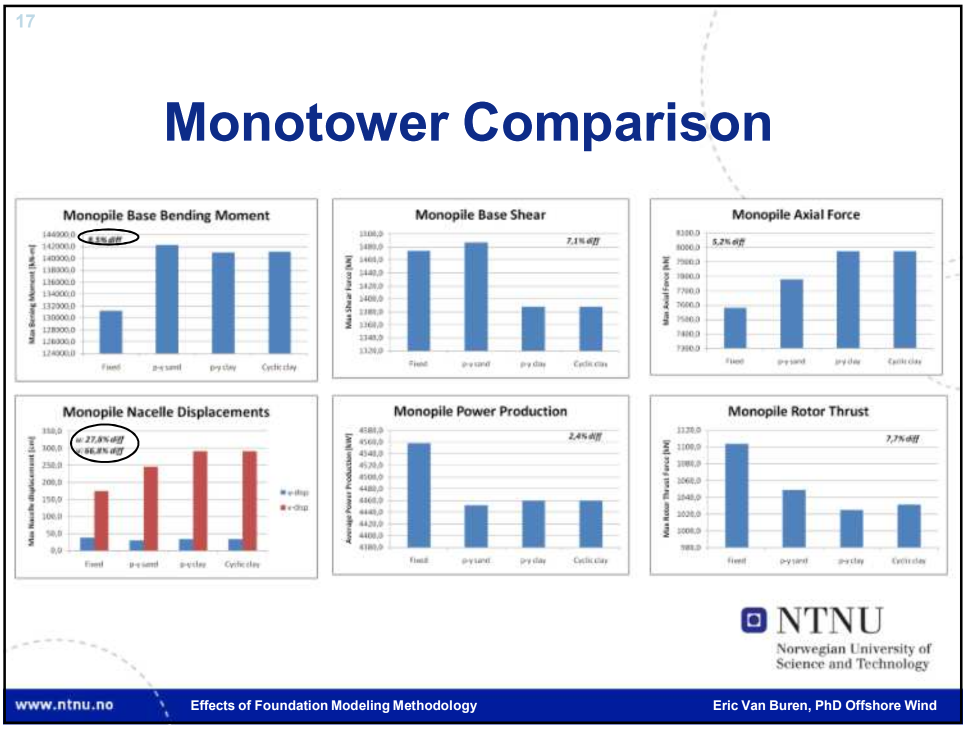
17
Monotower Comparison
Monopile Base Bending Moment
Monopile Base Shear
7,1% diff
Monopile Axial Force
5,2% diff
Monopile Nacelle Displacements
u: 27,8% diff
v: 66,8% diff
Monopile Power Production
2,4% diff
Monopile Rotor Thrust
7,7% diff
Fixed
p-y sand
p-y clay
Cyclic clay
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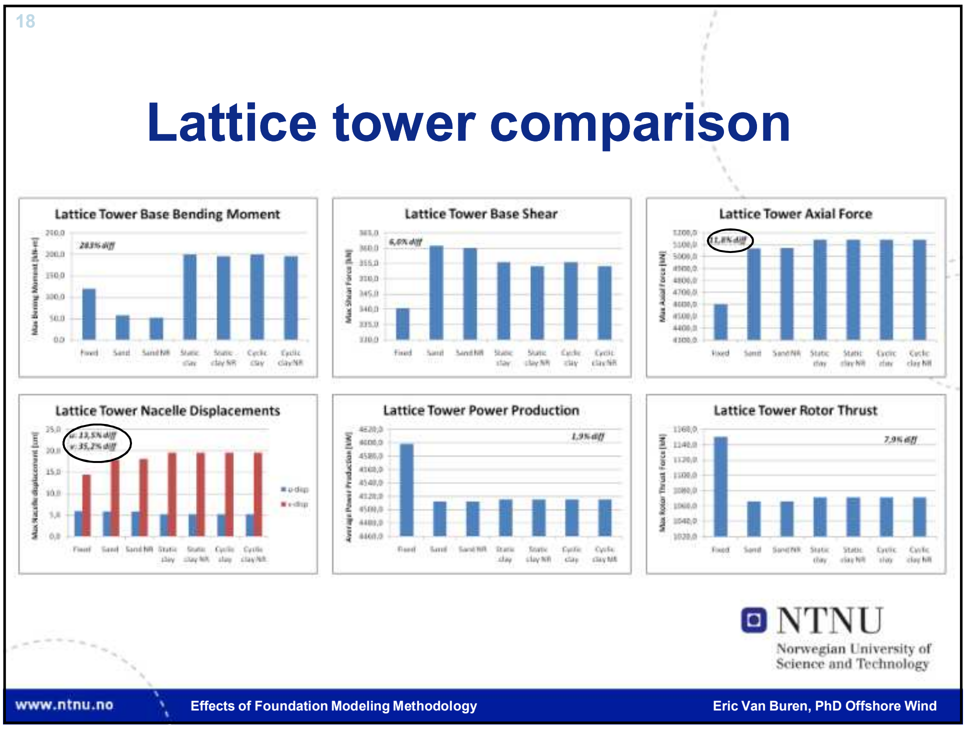
18
Lattice tower comparison
Lattice Tower Base Bending Moment
283% diff
Lattice Tower Base Shear
6,0% diff
Lattice Tower Axial Force
11,8% diff
Lattice Tower Nacelle Displacements
u: 13,5% diff
v: 35,2% diff
Lattice Tower Power Production
1,9% diff
Lattice Tower Rotor Thrust
7,9% diff
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Conclusions

- Significant discrepancies noted between the different foundation models
  - Models with more flexible p-y curve foundation experienced **higher** forces and larger displacements at the nacelle than the fixed models
  - Discrepancy significant enough to affect the outcome of structural optimization procedures
- Results agree with similar investigations
  - Erica Bush compared similar foundation models using FAST
  - Foundation models compared using several solvers as part of OC3 code comparison

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Shortcomings of the p-y model

- No interaction between soil layers
- No interaction between adjacent piles
- P-y curves assume slender pile behavior, monopiles are much more rigid
- P-y curves primarily developed for (static) lateral capacity calculations
- Damping levels are mostly a total guess
- Pile size effects likely to effect the results

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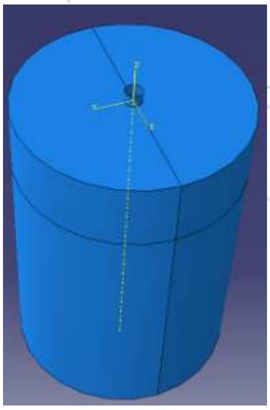
Finite element model of piles

- Allows for a more detailed description of the pile-soil interaction
- Provides the capability to measure time-history dependent damping due to pore pressure dissipation and other effects
- Includes capabilities to measure damping due to energy radiation through the soil
- Allows soil stiffness to be correctly predicted given history and dynamic effects
- Allows for small strain effects to be included



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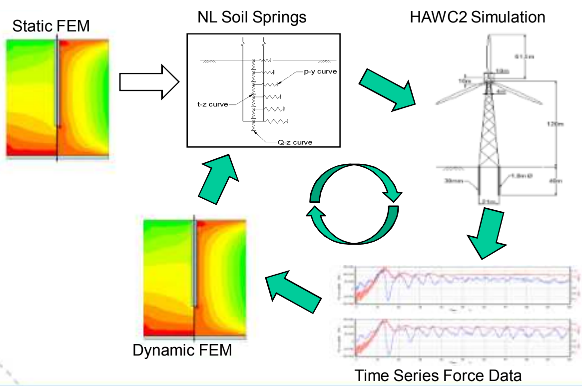
Coupled Foundation Models

Sequential Analysis FE Method

- Method used to investigate the response of a piled foundation to the loads experienced on an offshore wind turbine structure using the finite element method
- An iterative process of finite element simulations of the soil-pile structure and the wind turbine structure
- Does not allow data to feed into the aero-elastic code at each time step, only as initial conditions



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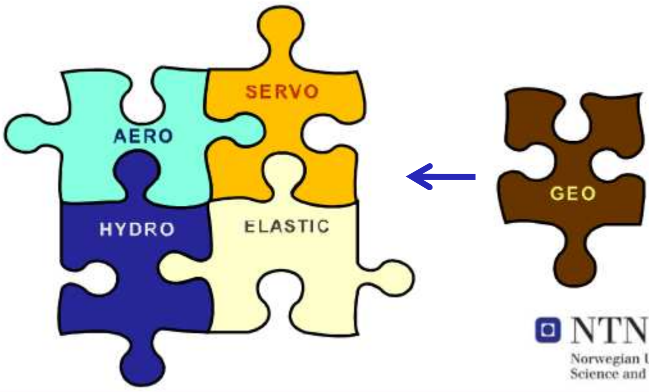
Coupled Foundation Models

Fully-Coupled FE Model

- Foundation, or 'Geo' module to be develop using open source FEM foundation code
- Geo Module then fully coupled with an Aero-Servo-Hydro-Elastic code (FAST, FLEX5, ADAMS, etc.)
- Adding an analysis tool for the foundation system is the last piece needed to provide a proper analysis of the entire wind turbine system



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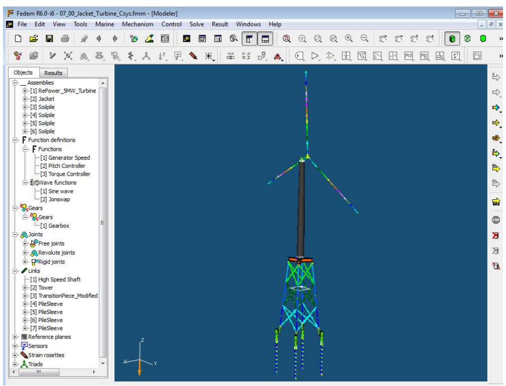
Cooperation with FEDEM

Flexible multibody solver

- Linked with AeroDyn for aeroelastic capabilities
- Internal hydrodynamic solver
- Used by Kværner Verdal (Aker Jacket Solutions) for Nordsee Ost Wind Park
- Research Partner with NOWITECH (as of 2011)



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Further Work

- Develop an improved soil model for foundation response which can be coupled to a Aero-Servo-Hydro-Elastic simulation (Aero-Servo-Hydro-**Geo**-Elastic)
  - Can be implemented and coupled with FEDEM and/or FAST/ADAMS or other open source code
  - Allows for a time domain analysis of the entire wind turbine system
- Extend investigations to suction caissons and other foundation solutions
  - Potential foundation concepts can be used in conjunction with a number of different tower concepts
- Investigate dynamic processes of scour and the impacts on soil stiffness and damping
  - Changes in soil properties can have significant impacts on the fatigue life of the structure
  - Impact will be more significant with shallow foundations such as suction caissons
- Validate numerical models with field data

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Questions?

Thank you for your attention

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Eric.vanburen@ntnu.no

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Modelling of transition piece of jacket substructures for offshore wind turbines

Elena Menéndez, Offshore subestructures, R&D Department
Alstom Wind

Esbjerg, September 20-21st 2011

POWER | ALSTOM

Introduction

ALSTOM

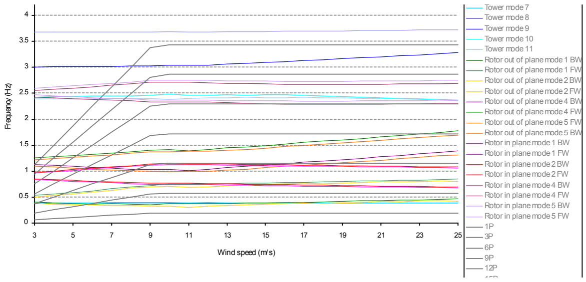
Alstom Wind is currently working in the installation of its first prototype for the new **Offshore**, **Haliade 150 6 MW wind turbine**. Even though the prototype is being installed *onshore*, a *jacket substructure* has been included. The objective has been to gain experience with this kind of susbstructure before “getting wet”.

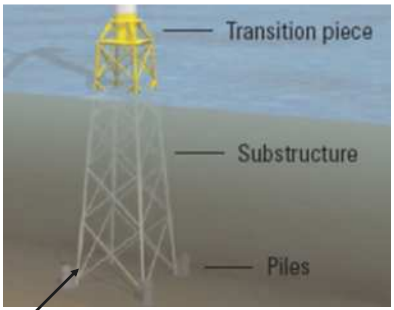
The fact that a jacket has been used has been a **challenge** in many ways. One of them was the **correct modelling** of this new component in Alstom’s aerolastic and structural codes.

Introduction

ALSTOM

•Wind turbine **dynamics** are key in the design and assessment of offshore (and onshore) WTG. A good modelisation of the wind turbine-tower-substructure set is fundamental for obtaining the right **design loads**.





•Offshore wind turbines include a “new” component, substructure, that has a great influence in the dynamic behaviour of the whole system.

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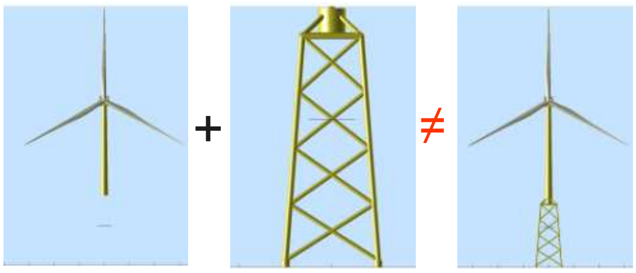
Introduction

ALSTOM

•An **integrated approach** is fundamental when assessing loads and performance of the wind turbine and the substructure. Treating them as separate items is clearly not the way to proceed.



•For jacket type substructures, the most complex part of the substructure itself (excluding the foundation) is probably the so called “**transition piece**”. This is the piece that transfers the loading from the wind turbine to the substructure.

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Introduction

ALSTOM

- Most aerolastic codes used nowedays have features capable of modelling a wind turbine jacket, using beam elements. However, more complex structural models are not available in all aerolastic software packages.
- A suggestion to overcome this shortage is presented next

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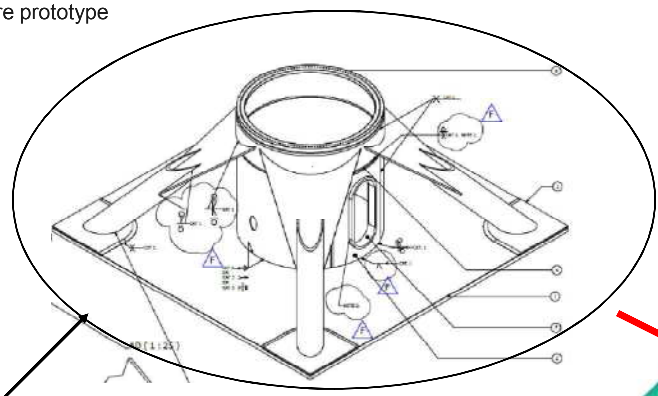
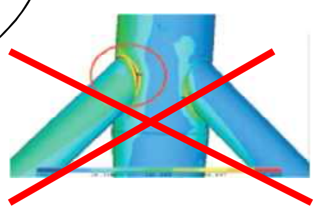
Description of transition piece

ALSTOM

The following transition piece is being used for Alstom's **Haliade 150 6 MW** wind turbine onshore prototype





This is by no means a simple beam structure!!!

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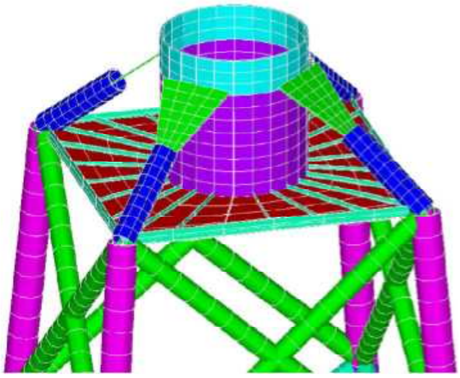
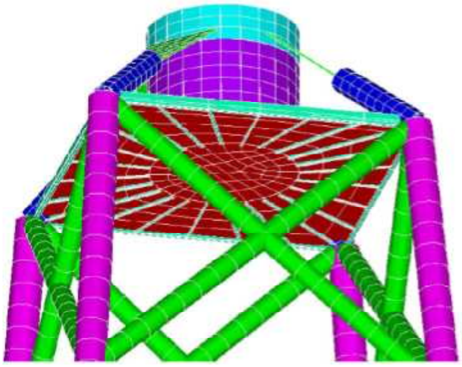
Detailed FEM model of transition piece

ALSTOM

A detailed FEM model of the transition piece, using a combination of beam and shell elements, is presented





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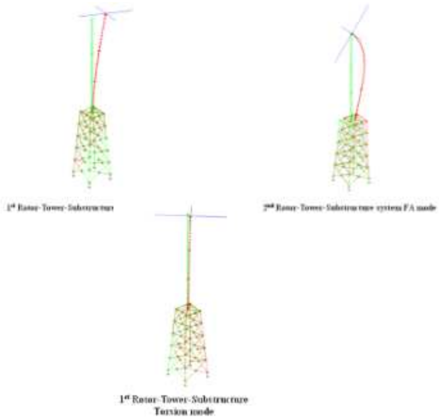
Detailed FEM model of transition piece

ALSTOM

Next is a table of the frecuencies of the first fundamental modes of the whole WTG-substructure system obtained with the detailed FEM model

Modeshape	Frequency (Hz)
1st FA	0.32
1st StS	0.33
Torsion	1.07
2nd FA	1.68
2nd StS	1.71



NOTE: The figures to the right do NOT correspond to the resulting frequencies of the tables of this document. Their use is only to show the approximate shape of the eigenmodes.

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Simplified FEM model of transition piece

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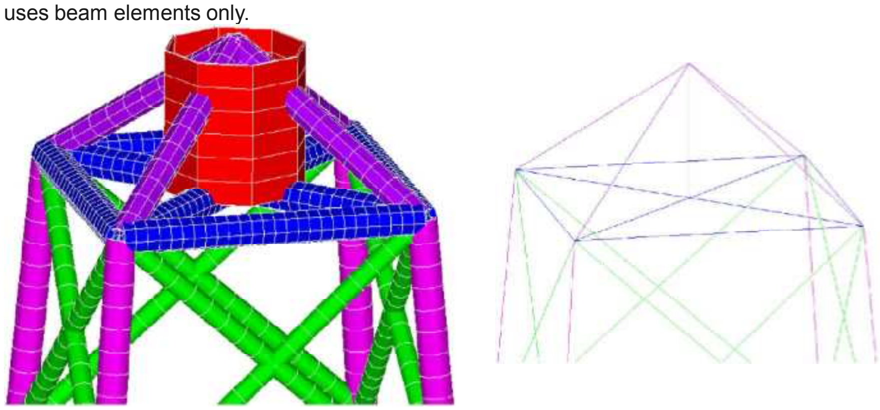
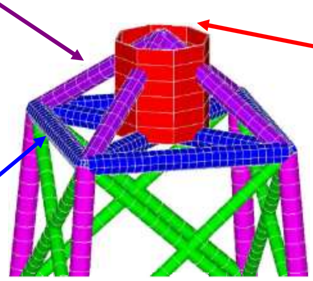
In order to create a model that can be implemented in our aerolastic software, a simplified FEM model was created, that matched the detailed model in terms of dynamic behaviour. This model uses beam elements only.



Simplified FEM model of transition piece

ALSTOM

The diagonals that merge into the trunk are modelled as beams that cross at the vertical axis of the tower. This results in a very high stiffness at that point. In order to solve this, the thickness of the beams was reduced (thus less rigidity) and the density assigned was increased in order to maintain the right mass.



The trunk of the transition piece is modelled according to its actual geometrical and material properties, excluding details like door, door frame and flange

- The diaphragm that forms the deck was modelled as a square and a cross formed by beams. In this case, the opposite was done: Thickness was increased in order to raise the stiffness of the section and in return, a lower density was applied to adjust the total mass

Simplified FEM model of transition piece

ALSTOM

Next is a table of the frecuencies of the first fundamental modes of the whole WTG-substructure system obtained with the simplified FEM model.

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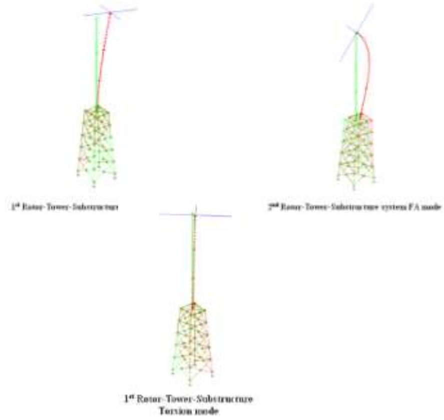

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Comparison of resulting frequencies

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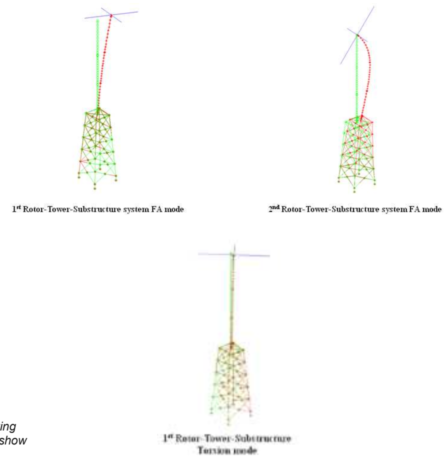
The differences in frequency for the most important fundamental modes are shown next.

Modeshape	Difference (%)
1st FA	0.09
1st StS	0.13
Torsion	0.46
2nd FA	0.15
2nd StS	0.03



NOTE: The figures to the right do NOT correspond to the resulting frequencies of the tables of this document. Their use is only to show the approximate shape of the eigenmodes.

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Conclusions

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- It is possible to translate a detailed FEM model into a more simplified beam FEM model with a good correlation of dynamic behaviour between both models.
- Care has to be taken in the translation so that mass, as well as stiffenesses are correctly represented.
- Stiffness has to be adjusted carefully to get a good match in all degrees of freedom.
- As long as the dynamic behaviour is correct, the simplified FEM model is considered valid for its use in an aerolastic code. The model can be subsequently used to evaluate loads and performance.

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Further work and studies

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- Correlate the calculated eigenfrequencies with values coming from measurements. This will help in identifying the uncertainties and assessing the goodness of the FEM and aerolastic models used in the design phase.
- Improve the beam model with some or all of these features:
  - Model joint-flexibility and joint offsets in the beam model
  - Modify properties according to measurements
  - Include, if necessary, redundant members that do not exist in real model but can give a good representation of mass and stiffness properties

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Acknowledgements: Manel Santiago, Design engineer,
Offshore substructures, R&D Department. Alstom Wind

www.power.alstom.com

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Geotechnical challenges for offshore wind farm developments

Dr. Paul Doherty

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Research Topics

- Site Investigation Methods
- Gravity Bases
- Monopile Design
- Jacket Pile Design
- Pile Driveability
- Dynamic Testing Methods

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Site Investigation Testing

- **SONIC CORING**

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Site Investigation Testing

- **Seismic Dilatometer**
  - Provides a shear wave velocity profile
  - Gives an indication of in-situ stress conditions
  - Can be used directly in foundation design
  - More research needed

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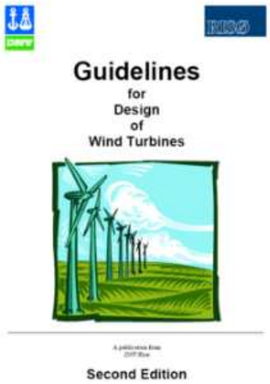
Gravity Bases

- **Shallow Footings**
  - Bearing capacity – overall stability, sliding & overturning
  - Degradation of soil strength caused by cyclic loading
  - Consolidation settlement



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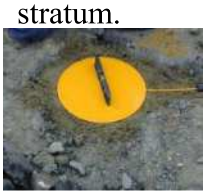
Gravity Bases

- **Snugborough Wind Farm**
- 11.5m x 11.5m RC spread footing.
- 3.0m founding depth in stiff clay stratum.





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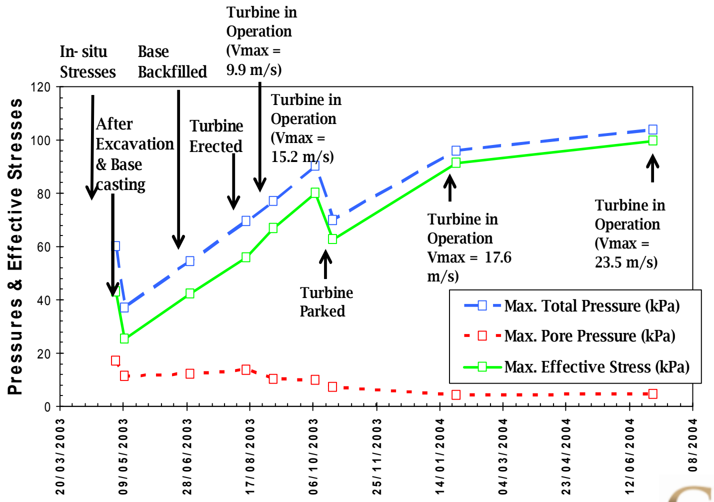
Snugborough Windfarm – Stresses over Foundation Lifetime



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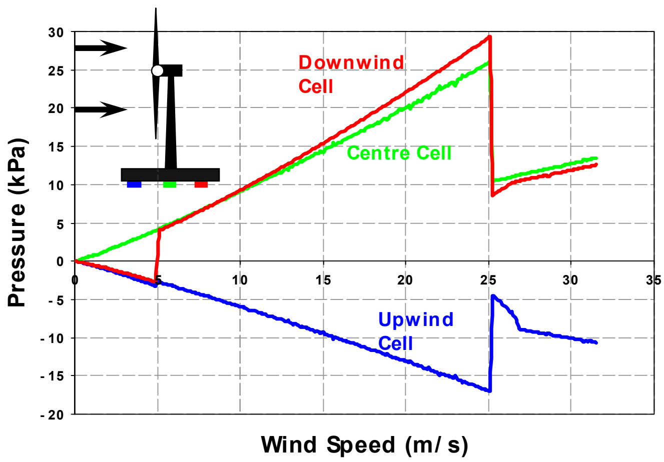
Snugborough Windfarm – Stresses Changes



$q_f = s_u N_c$

$= 75 \times 6.14$

$= 460$ kPa

$q_{all} = 460/3$

$= 153$ kPa

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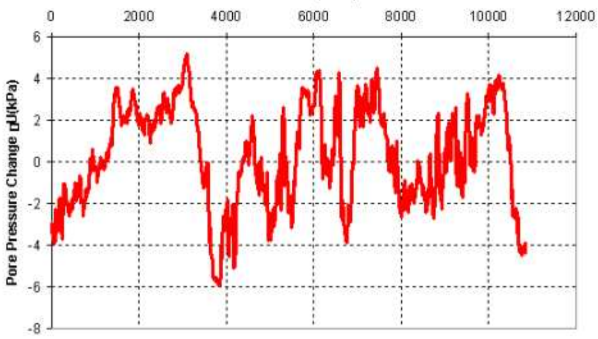
Snugborough Windfarm – Operational Pore Pressures



- Porewater pressure changes are immediate
- Much smaller than total stress changes
- Suggests that consolidation settlement is not an issue

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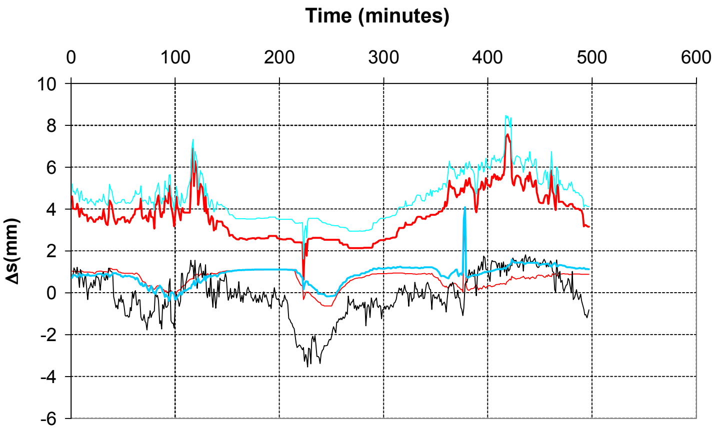
Snugborough Windfarm – Settlements



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What did we learn from the field tests?

- Applied stress levels are low
- The distribution of stress beneath the foundation is critically dependent on construction details
- Cut-Off mechanism was effective in minimising excess applied stress
- Minimal excess porewater pressure was set-up during loading of the footing on till
- No cyclic accumulation of settlement occurred

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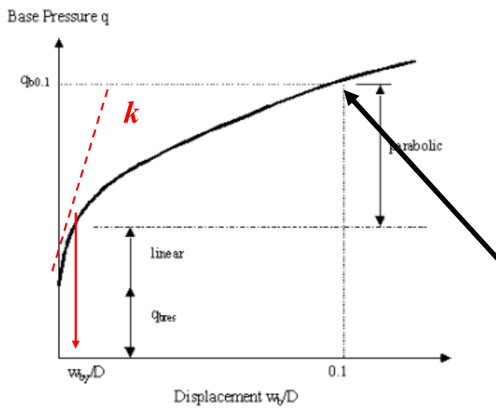
Developing models:
Predicting Mobilisation of Bearing Resistance



$q_b = [k\,(w_b/D)] + q_{bres}$

where

$k = (4/\pi)\,E_0/(1-\upsilon^2)$

for $w_b/D < w_{by}/D$

$q_{b0.1} = 0.2\,q_c$

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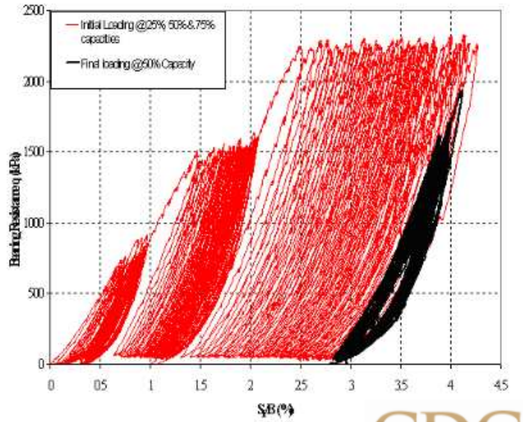
Other Effects Considered:

- Footing Shape
- Footing Scale
- Eccentric Loading
- Moment Loading
- Cyclic Loading



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Monopiles

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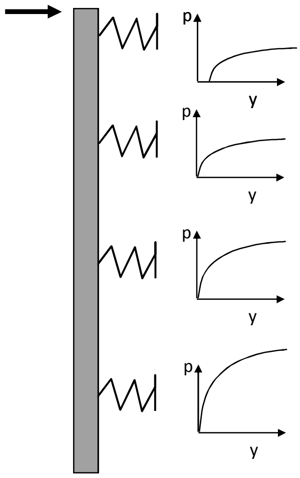
Monopile Design: p-y method

- The API-07 and DNV-07 codes recommend a p-y method of analysis
- The p-y approach is highly empirical and based on very limited test data from model scale (610mm diameter) on-shore pile tests
- Should these test results be extrapolated to the large diameter piles being used today?
- Is the current method overconservative?



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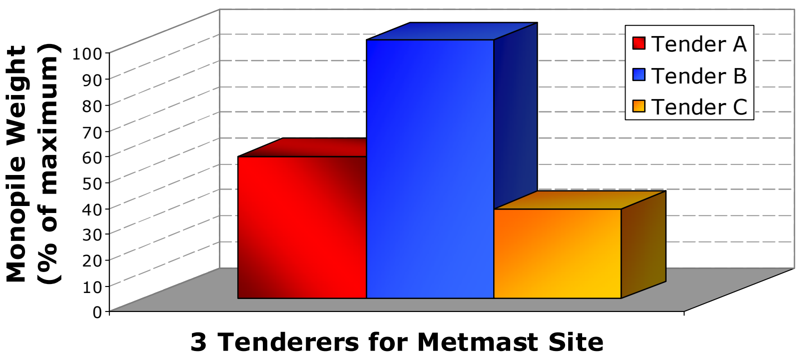
Industry uncertainty



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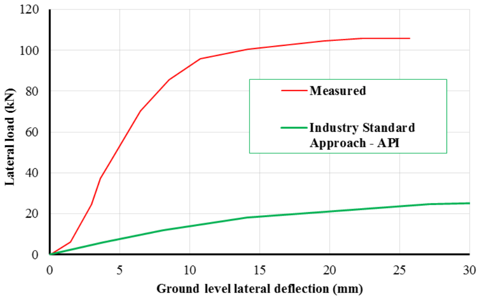
Monopile Design

- **2 Piles Installed at Blessington**
  - Both piles had an L/D of approx. 6
  - Both piles were very stiff (similar to industry scale monopiles)
  - Both piles were instrumented with strain gauges
  - One static test
  - One cyclic test

Monopile Design

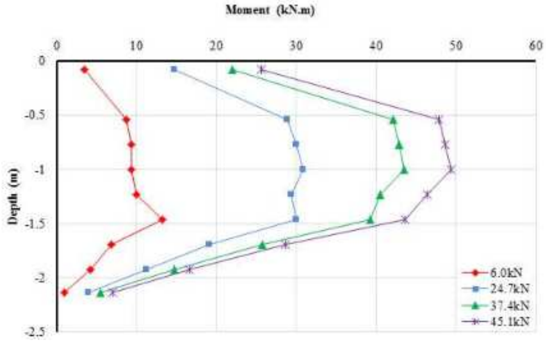
- **Static Load Test**
  - Pile Loaded Laterally
  - Capacity over100% higher than predicted using API method



  - Well predicted by in-house FEA modelling
  - Need to consider in-situ E, stress state, non-linearity

Monopile Design

- **Static Load Test**
  - Instrumentation worked well
  - Moment profile was measured during test



  - Developing new CPT based p-y curves for use by industry

Monopile Design

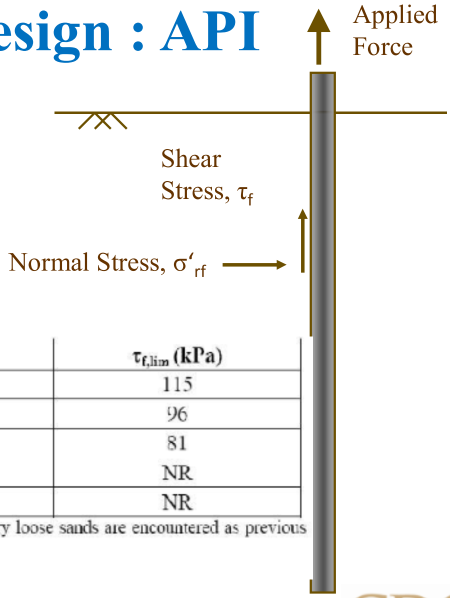
Cyclic Load Test

- Over 3000 cycles applied
- The displacements were smaller than API calculated
- The loading stiffness generally increased as the number of cycles increased

Jacket Pile Design : API

$$\tau_f = K_f \, \sigma'_v \tan\delta$$

$$\tau_f = \beta_s \, \sigma'_v$$



Density	$\beta_s{}^b = K_f \tan\delta$	$\tau_{f,lim}$ (kPa)
very dense	0.56	115
dense	0.46	96
medium dense	0.37	81
loose[a]	NR	NR
very loose[a]	NR	NR

[a] Designers are referred to CPT based methods if loose or very loose sands are encountered as previous recommendations are considered unconservative.
[b] β_s is assumed 25 percent higher for closed ended piles.

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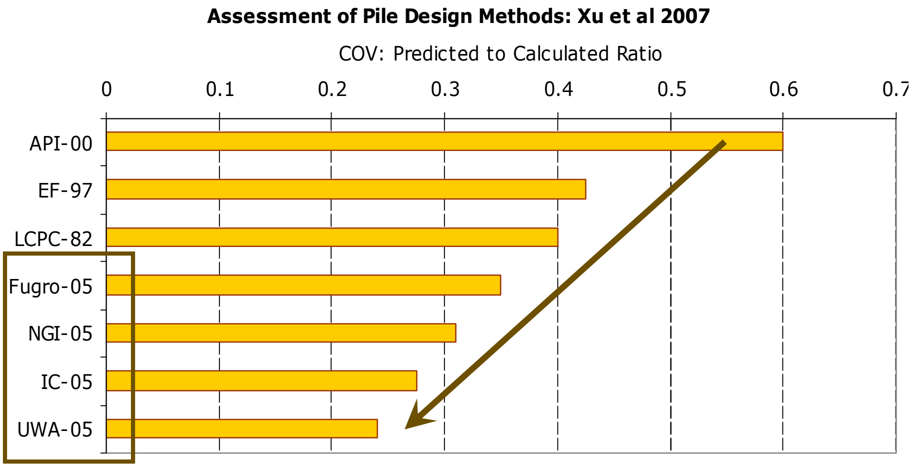
Uncertainty in Pile Design



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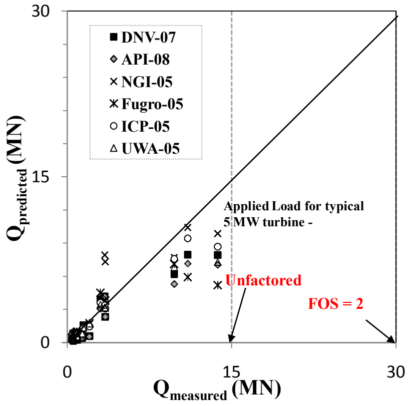
Assessment of performance



Open-ended piles Gavin et al. (2010)

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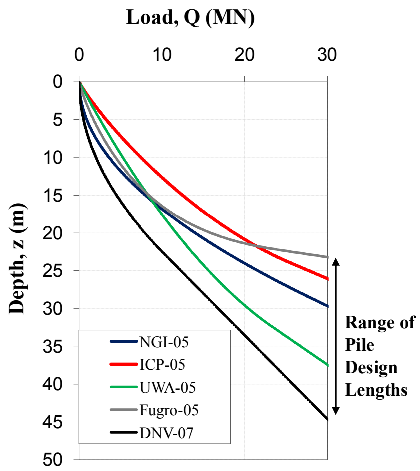
Jacket Pile Design



Assume :

Dense North Sea Sand,

q_c = 50 MPa, D = 2.5 m, t = 30 mm,
L/D = 10 to 22

Use methods in API (2007)

For a 2.5 m diameter pile:

Design Lengths:
FUGRO-05 = 23 m
ICP-05 = 26 m
NGI-05 = 30 m
UWA-05 = 37 m
DNV (API 00) = 45 m

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Jacket Pile Design Methods

Methods developed from carefully instrumented pile load tests performed on small relatively lightly loaded closed-ended piles have been extrapolated to offshore conditions, we should consider:

1. **Soil conditions**
2. **Difference between open and closed-end condition**
3. **Friction fatigue due to cyclic loading**

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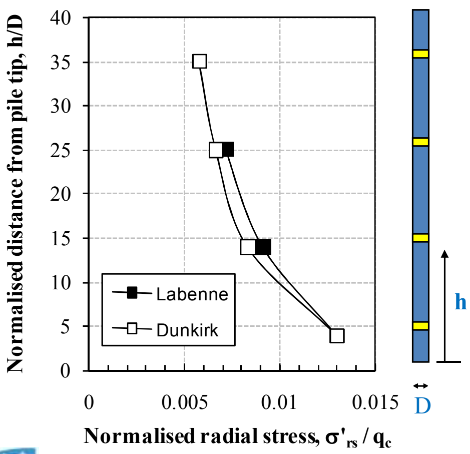
Tests using Imperial College Pile (ICP) Lehane (1992)



$$\tau_f = \sigma'_{rf} \tan \delta$$

$$\sigma'_{rf} = \sigma'_{rs} + \Delta\sigma'_{rd}$$

c

$$\sigma'_{rc} = 0.03\, q_c \left(\frac{h}{D}\right)^{-0.5}$$

a

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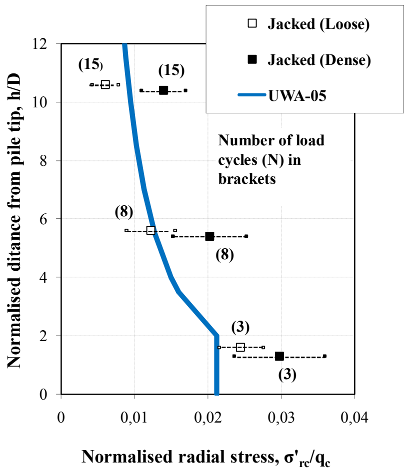
Normalised radial stress after installation



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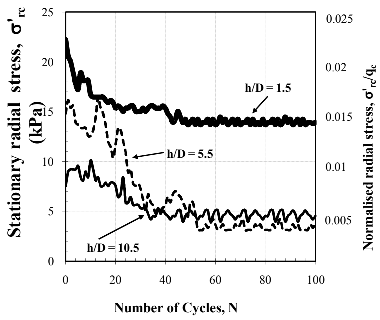
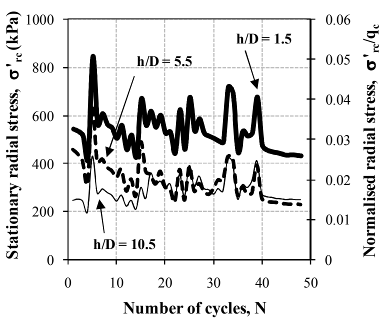
Effect of cyclic loading



Loose Sand



Dense Sand

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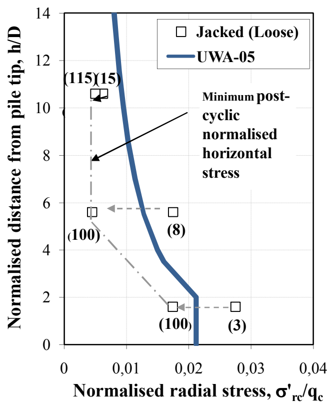
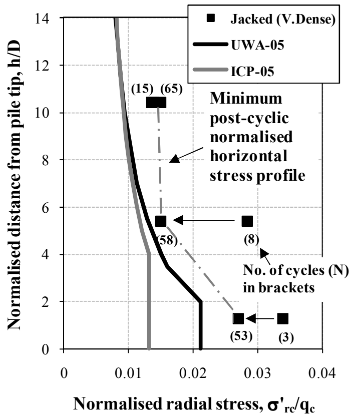
UCD Test Site and Instrumented Pile



Loose Sand



Dense Sand

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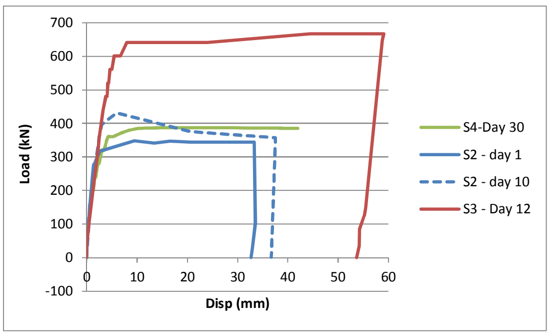
Jacket Pile Design

Axial Load Tests

- Large range in capacities observed



– Variation in resistance seems to result from a complex interrelationship between time related capacity increases and cyclic reductions in resistance.

Jacket Pile Design

Axial Load Tests

- Radial Stresses Measured Directly using flat earth pressure cells cast into the pile face
- Similar measurements were obtained from miniature cells embedded in steel piles
- Analysis is ongoing

Pile Driveability

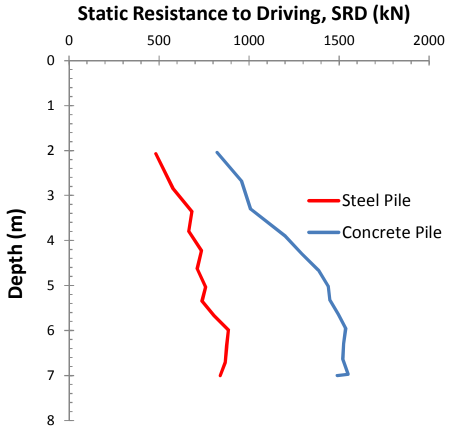
- Steel Piles & Concrete Piles Driven

Pile Driveability

- Dynamic Installation Resistance Measured using strain gauges & accelerometers
- Installation resistance of concrete & steel piles measured

Pile Driveability

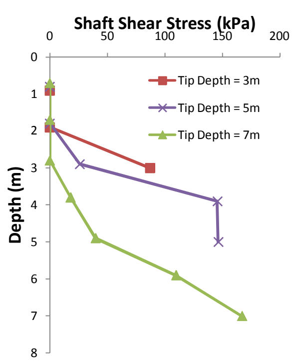
- Resistance of Concrete Pile greater than steel pile
- This is due to the higher base resistance
- Indicates plug behaviour is important
- Shallow increase in SRD suggests friction fatigue is evident



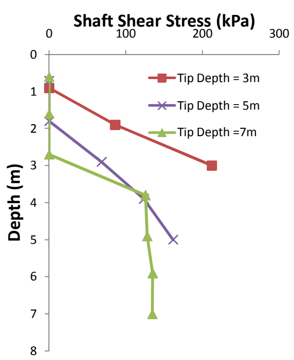
Dynamic Monitoring

- CAPWAP signal matching used to assess shear stress profiles

CONCRETE



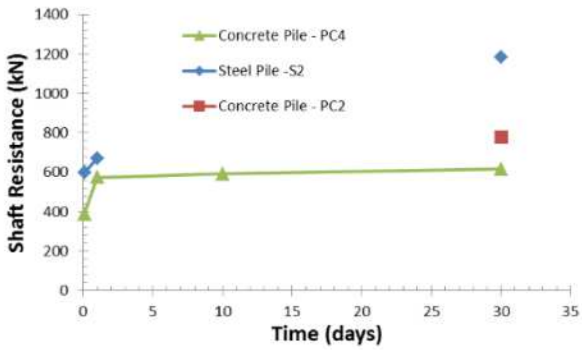
STEEL



- Similar Stresses on Concrete & Steel Piles
- Friction Fatigue is Significant on both piles

Dynamic Monitoring

- CAPWAP capacities used to assess ageing



- Ageing observed on steel pile
- Limitation - Hammer capacity can effect mobilisation of base resistance and effect ageing results

Hybrid / Novel Structures

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Keystone Twisted Jacket Instrumentation

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GDG GAVIN & DOHERTY GEO SOLUTIONS

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CONCLUSIONS

- Existing Design Procedures are empirically based and thus uncertainties exist
- More Sophisticated design procedures have been developed and validated using field tests
- Need industry to accept and use these advanced models

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Thanks for your time!
Acknowledgements

- Project sponsors: Science Foundation Ireland, Mainstream Renewable Power, IRCSET
- Roadstone for access to the test site
- Dr. David Igoe, Ali Tolooiyan, Lisa Louise Kirwan, Weichao Li, Tim Hennessey (ESBI)
- Piling by Bullivant Taranto Ltd.
- Nigel Dillon Lloyd Acoustics Pile Testing

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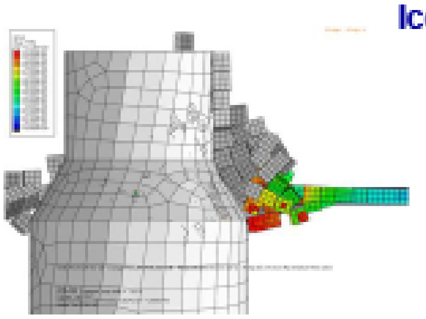
Business from technology



Ice loads and ice-induced vibrations in offshore wind turbines

Topical Expert Meeting #66
on
Offshore Foundation Technology and Knowledge,
for shallow, middle and deep water
Esbjerg, Denmark
20.-21.9.2011

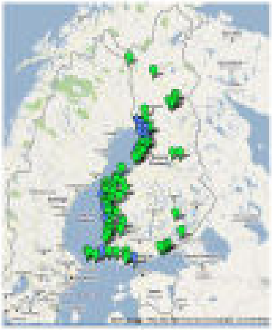
Jaakko Heinonen
VTT Technical Research Centre of Finland

Content

- Wind energy in Finland
- Sea ice conditions and ice loads
- Field measurements of ice loads
- Examples of numerical simulation of ice-structure interaction
- Introduction of ice loads in overall simulation of offshore wind turbines
- Pilot offshore wind turbines in Finland

Wind energy in Finland

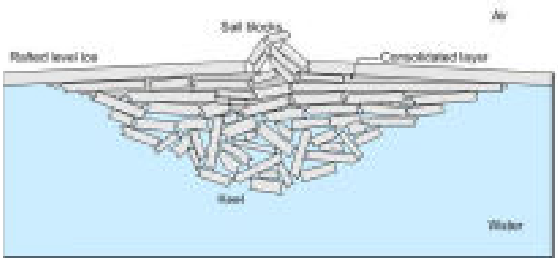
- The total capacity of wind turbines in Finland is 197 MW (May 2011).
- The production of wind energy covers 0.3% of total consumption of electric energy in Finland.
- The government of Finland has defined to increase the total capacity over 2000 MW by 2020.
  - most of new wind turbines will be installed at see, mainly due to better wind conditions
  - Feed-in tariff from 2010 (83.5 €/MWh)
- Large capacities for offshore wind farms in cold climate regions
  - high and constant wind velocities
- Offshore wind energy is not well established in northern countries
- Ice loads are a big uncertainty in WT support structure design



Wind power turbine installations in Finland: currently running and planned

Ice features - Sea ice

- First year ice
  - Level ice, pack ice
  - Ice ridges
  - Landfast ice
- Multi-year ice
- Icebergs



Ice ridges in Gulf of Bothnia, off-shore Hailuoto Finland:
- Sail height = 0.7 - 1.5 m
- Keel depth = 3 – 6 m
  - porosity = 30 - 40 %
- Ice block thickness = 20 cm and width = 0.5 – 1.3 m
- Consolidated layer
  - low porosity (~3 %)
  - thickness ~ 1.4 – 1.8 times level ice thickness

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Characteristics of sea ice loading

- Moving Sea-Ice Floe
  - Ice floe velocity, up to 1,2 m/s
- Driving Forces:
  - Wind
  - Sea current
  - Tidewater

- Ice load depends on
  - Floe thickness
  - Ice drift speed
  - Shape of the structure
  - Failure mode of ice
  - Crystal structure of ice
  - Flexibility of the structure at ice level
  - Etc.

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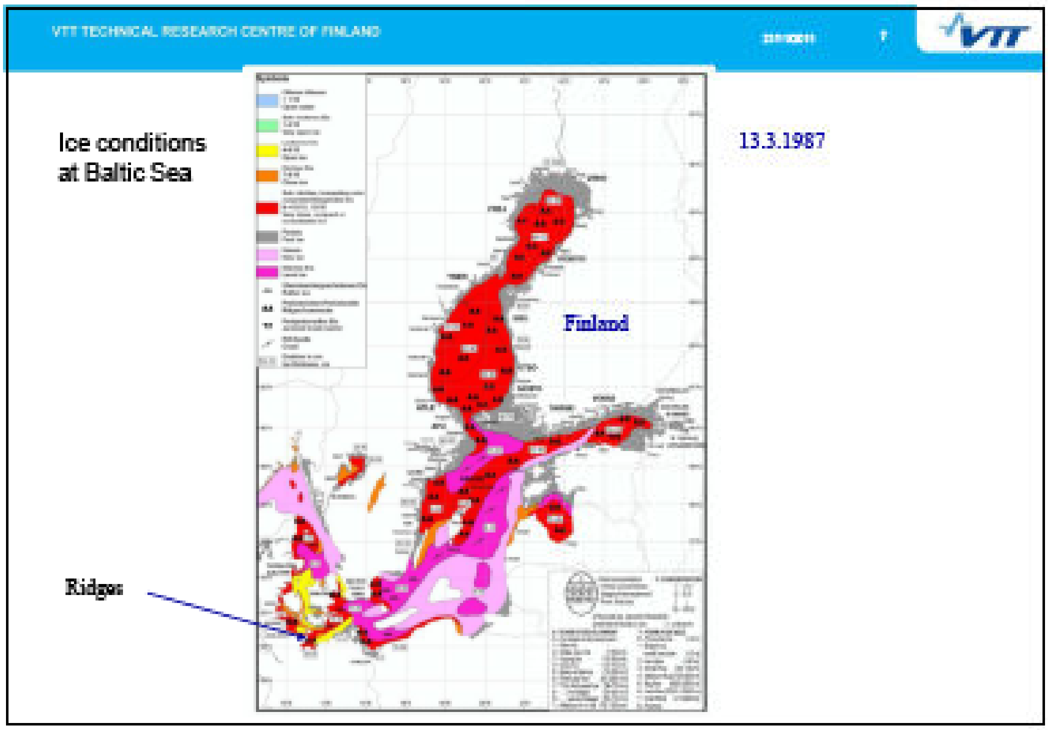
Other ice features

- Athmospheric icing
- Ice accretion on structures (blades)
- River ice, lake ice
- Glacier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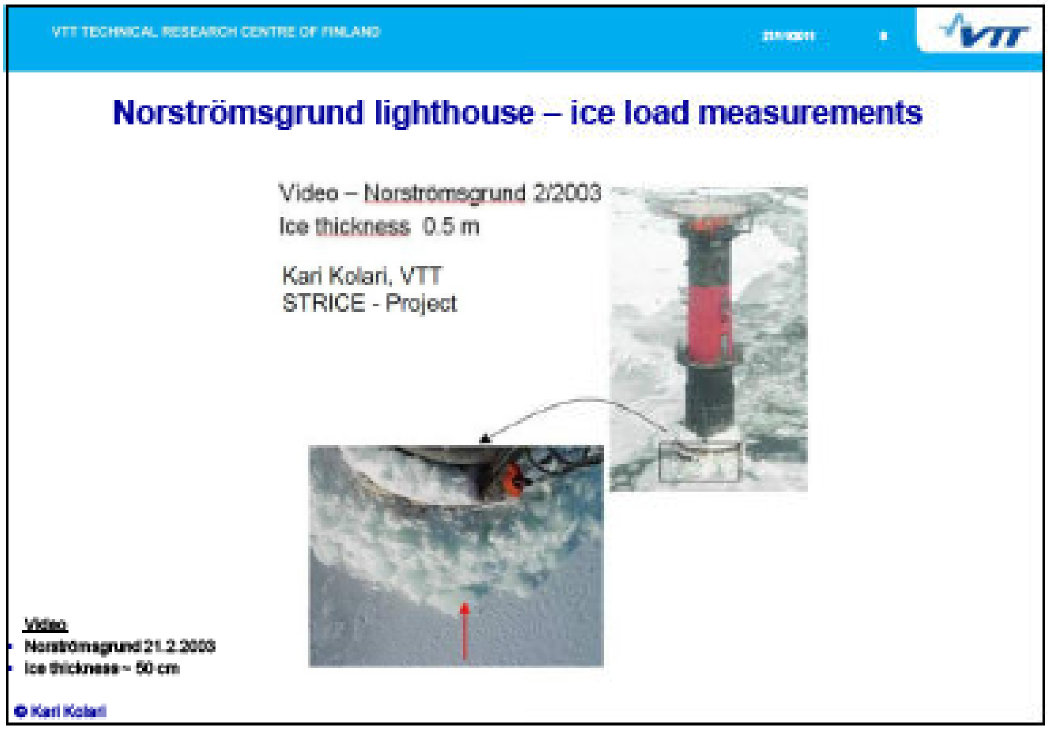
Ice conditions at Baltic Sea
13.3.1987
Finland
Ridges


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
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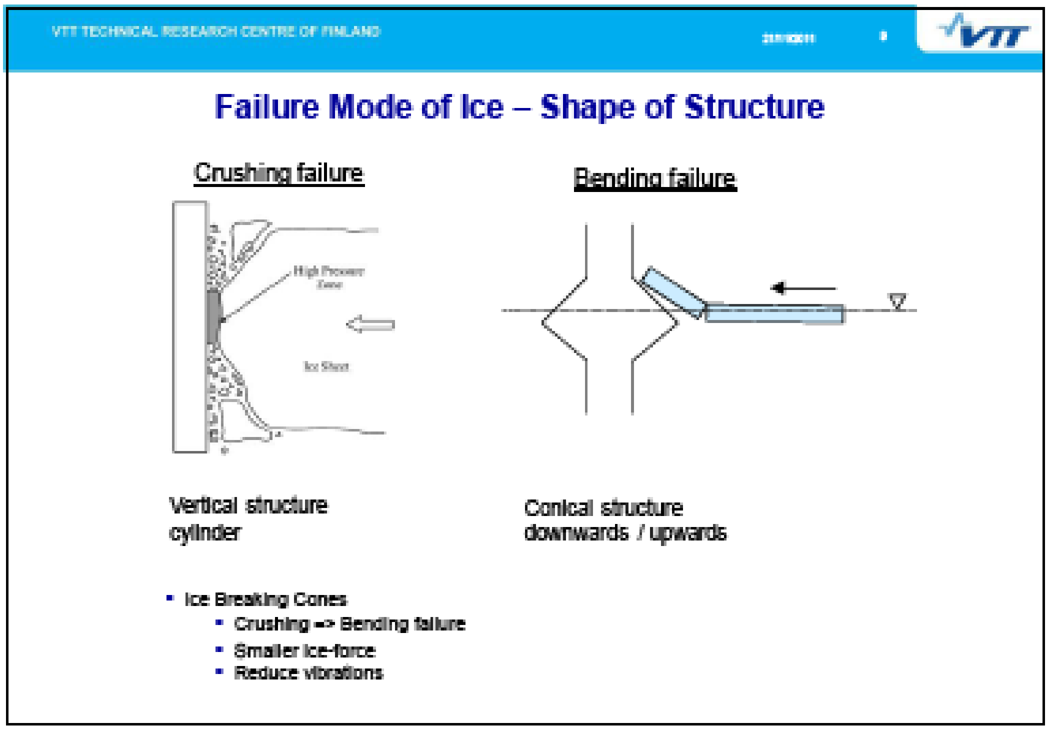
Norströmsgrund lighthouse – ice load measurements
Video – Norströmsgrund 2/2003
Ice thickness 0.5 m
Kari Kolari, VTT
STRICE - Project
Video
Norströmsgrund 21.2.2003
Ice thickness ~ 50 cm
© Kari Kolari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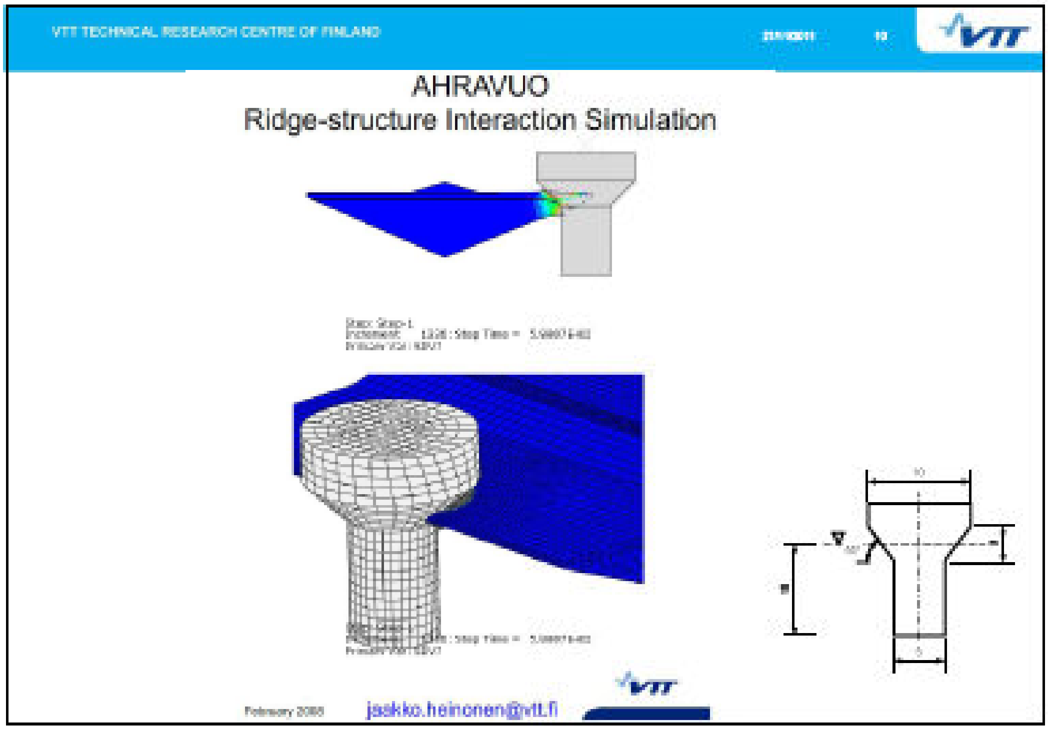
Failure Mode of Ice – Shape of Structure
Crushing failure
Bending failure
Vertical structure
cylinder
Conical structure
downwards / upwards
Ice Breaking Cones
Crushing => Bending failure
Smaller ice-force
Reduce vibrations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AHRAVUO
Ridge-structure Interaction Simulation
jaakko.heinonen@vtt.fi

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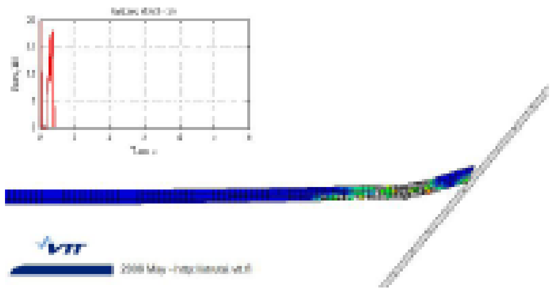
Bending failure of ice against inclined structure



- Ice thickness 30 cm, velocity 10 cm/s
- Inclined surface (α=50°)
- Contact between ice and structure
- Buoyancy with "soft contact" against water surface
- UMAT material model that describes flaking (cracks)
  - Wing Crack Damage (WCD) model

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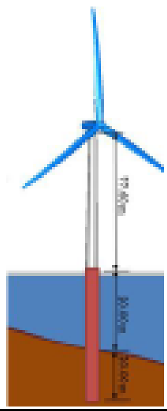
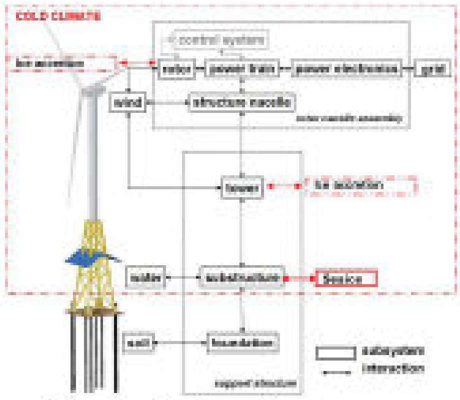
Introduction of ice loads in overall simulation of offshore wind turbines

- Collaboration with Fraunhofer IWES
  - Breaking the ice –project (BRICE)
- Implementation of ice load models into an overall wind turbine simulation platform OnWind
- Implementation of a self-excited ice-structure interaction model by Määttänen-Blenkarn into ABAQUS and OnWind
- Comparison and verification of the ice load models and structural behaviour
- Investigation of influence of ice velocity in ice structure interaction to a single-legged offshore wind turbine



OnWind
Overall simulation of offshore wind turbines

- Use of the OnWind software developed by Fraunhofer IWES for overall simulation of wind turbines
  - Object-oriented
  - based on open source modelling language Modelica
- Structural model for dynamic analysis including
  - all essential parts and loads
  - multibody dynamics and deformable parts
- Improve existing simulation software
  - including ice models
  - including low temperatures
- Simulation of ice-structure interaction
  - Ice induced vibrations
  - Fatigue loads
- Optimization of offshore foundations
  - Less conservative safety factors
  - Cost effective

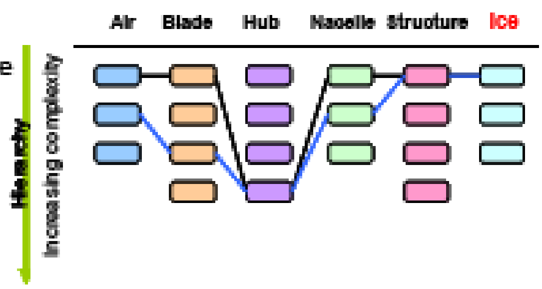


Wind turbine topology

Sebastian Hetmanczyk, Fraunhofer IWES

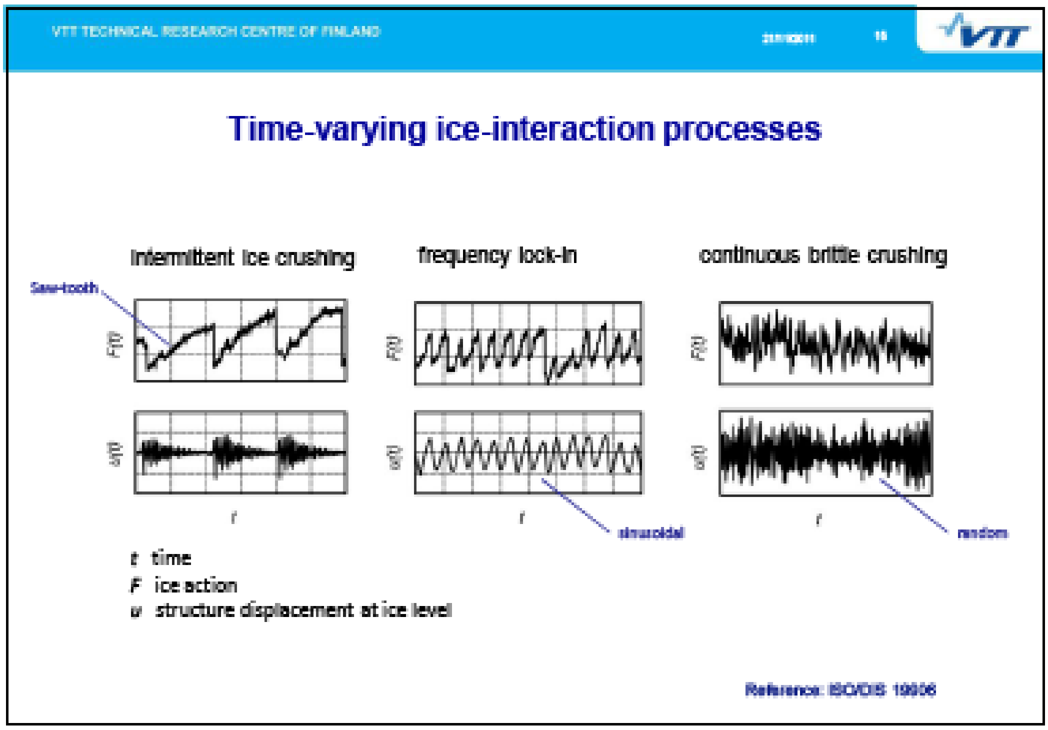
OnWind
Overall simulation of offshore wind turbines

- Hierarchical simulation structure
  - Rigid body models
  - Beam models
  - 3D FE-models



- Component based
  - Exchangeable / Reusability through object orientation
  - Variable models of wind turbines regarding topologies and structure

Sebastian Hetmanczyk, Fraunhofer IWES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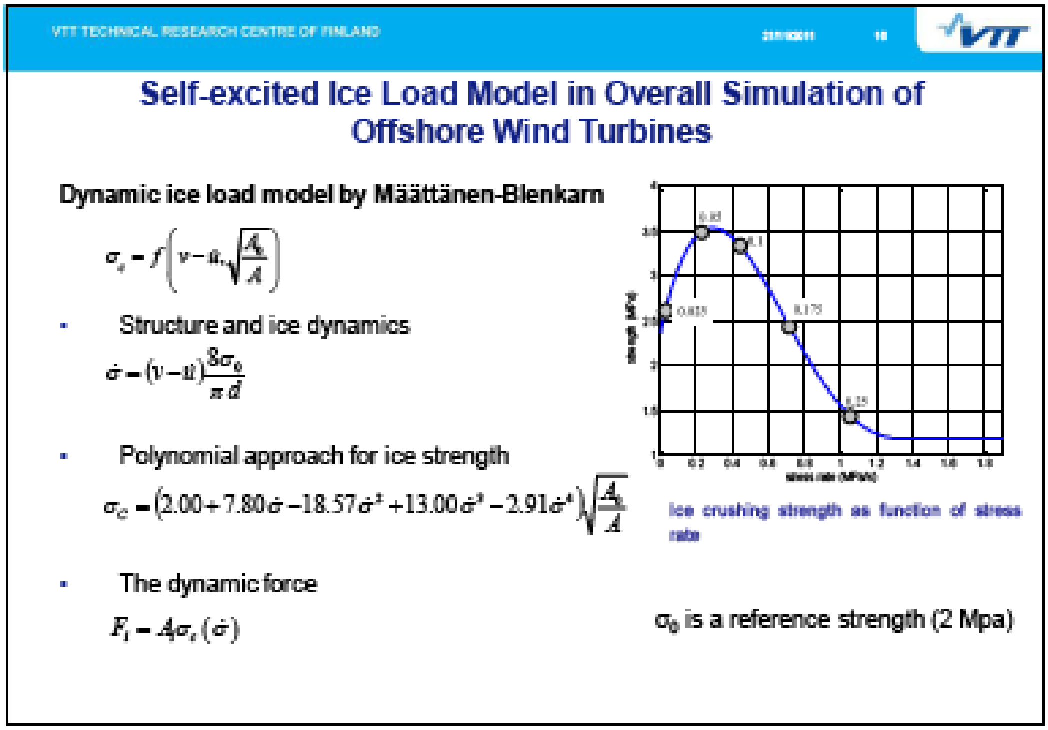
Time-varying ice-interaction processes
intermittent ice crushing
frequency lock-in
continuous brittle crushing
Saw-tooth
F(t)
u(t)
t
sinusoidal
random
t time
F ice action
u structure displacement at ice level
Reference: ISO/DIS 19906


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
VTT
Self-excited Ice Load Model in Overall Simulation of Offshore Wind Turbines
Dynamic ice load model by Määttänen-Blenkarn
$\sigma_c = f\left(v - \dot{u}, \sqrt{\frac{A_0}{A}}\right)$
Structure and ice dynamics
$\dot{\sigma} = (v - \dot{u})\frac{8\sigma_0}{\pi d}$
Polynomial approach for ice strength
$\sigma_C = (2.00 + 7.80\dot{\sigma} - 18.57\dot{\sigma}^2 + 13.00\dot{\sigma}^3 - 2.91\dot{\sigma}^4)\sqrt{\frac{A_0}{A}}$
The dynamic force
$F_i = A\sigma_c(\dot{\sigma})$
Ice crushing strength as function of stress rate
σ_0 is a reference strength (2 Mpa)

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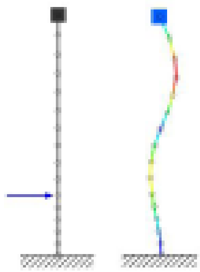
Numerical model

Numerical model

- NREL[1] offshore – 5 MW baseline wind turbine
- Two wind turbine configuration with different substructure length
- Dynamic ice model by Määttänen-Blenkarn
- Euler-Bernoulli beam for all structure components
- Rayleigh damping



Simulation

- The dynamic analyses in time domain
- Mixed explicit/implicit Euler solver in OnWind
- Hilber-Hughes-Taylor algorithm in Abaqus
- Simulation time period was set to 20 seconds

Simplifications

- No wave and wind loads
- No soil-structure interaction
- Simplified structure with dead mass on tower top

[1]NREL National Renewable Energy Laboratory

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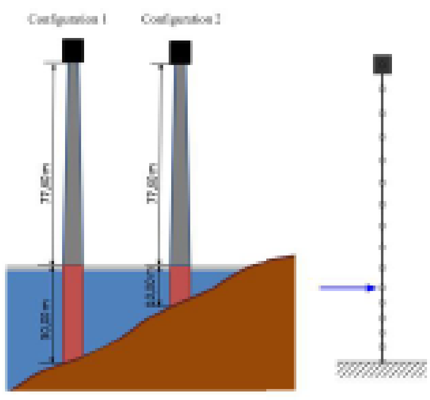
Structural configurations



Shape of the structure at the water level is cylindrical. Diameter = 6m.

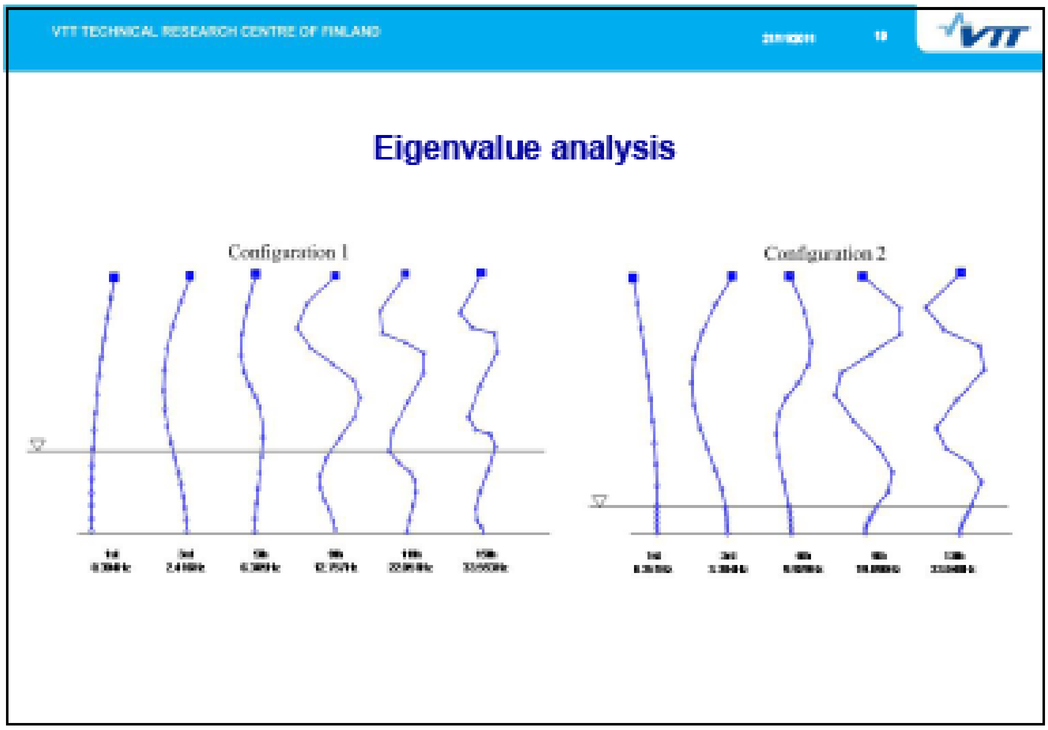
Various structural configurations

- Two different substructure length corresponding water depths 30 m and 10 m
- Ice thickness 0.6 m

	Configuration 1		Configuration 2	
	Height	Mass	Height	Mass
Substructure	30.00 m	285000 kg	10.00 m	95000 kg
Tower	77.60 m	228000 kg	77.60 m	228000 kg
Top mass		300000 kg		300000 kg
Sum	107.60 m	813000 kg	87.60 m	623000 kg

Varied parameters:

- Ice velocity


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
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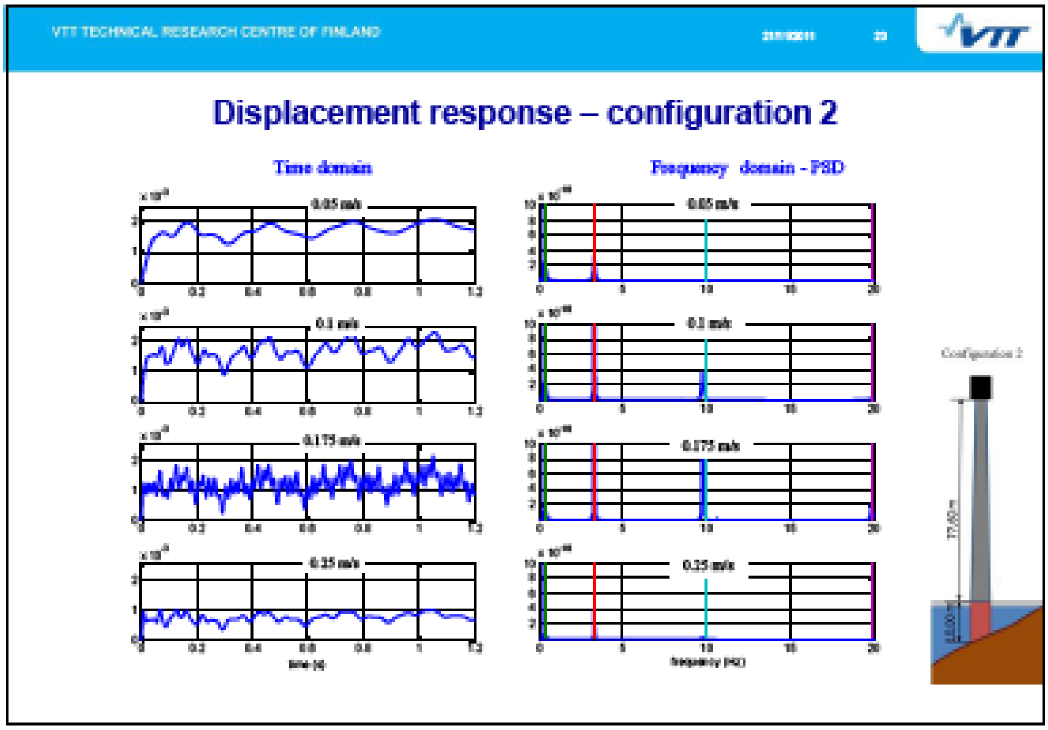
Eigenvalue analysis
Configuration 1
Configuration 2


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
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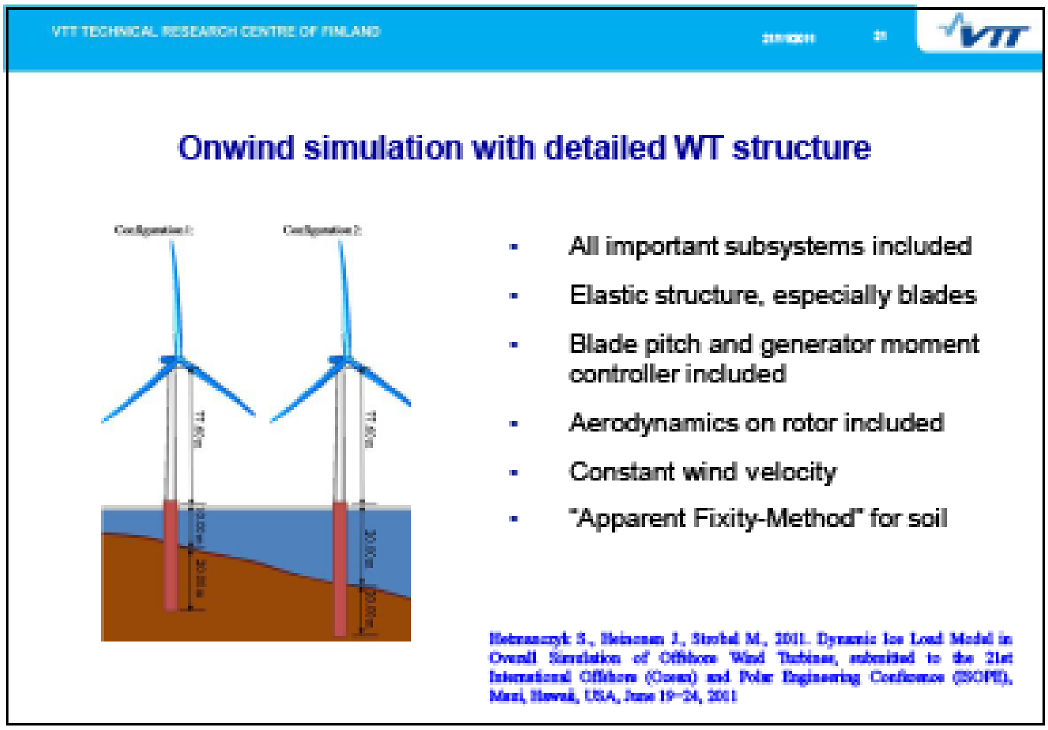
Displacement response – configuration 2
Time domain
Frequency domain - PSD
0.05 m/s
0.1 m/s
0.175 m/s
0.25 m/s


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
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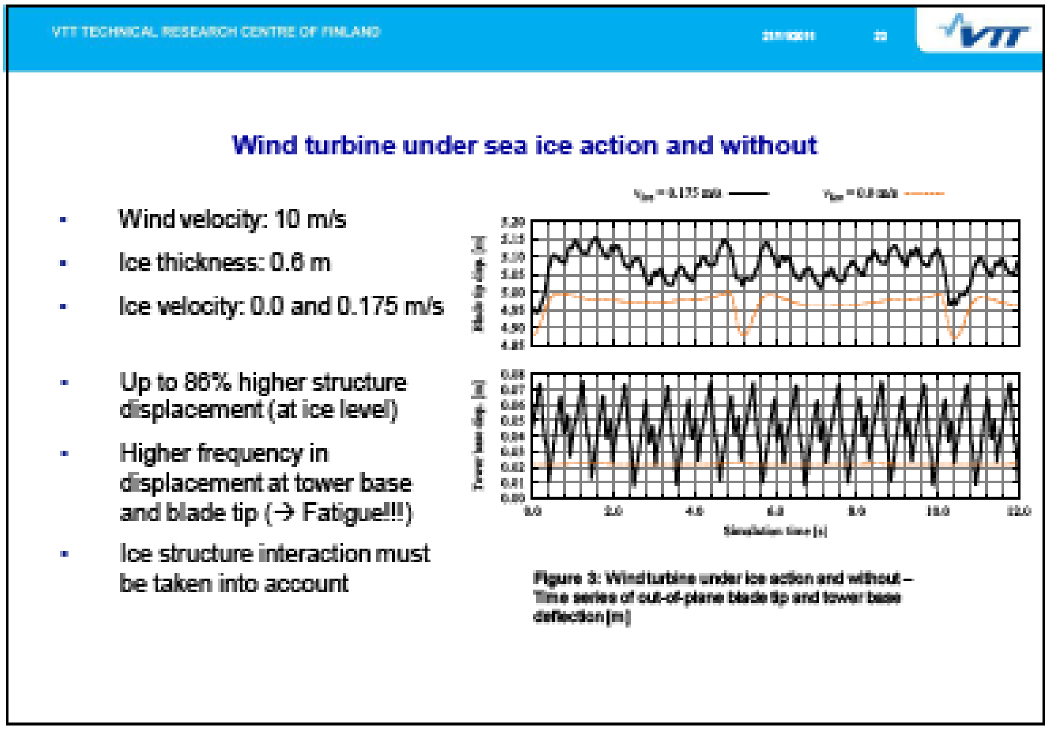
Onwind simulation with detailed WT structure
All important subsystems included
Elastic structure, especially blades
Blade pitch and generator moment controller included
Aerodynamics on rotor included
Constant wind velocity
"Apparent Fixity-Method" for soil
Hetmanczyk S., Heinonen J., Strobel M., 2011. Dynamic Ice Load Model in Overall Simulation of Offshore Wind Turbines, submitted to the 21st International Offshore (Ocean) and Polar Engineering Conference (ISOPE), Maui, Hawaii, USA, June 19–24, 2011


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
VTT
Wind turbine under sea ice action and without
Wind velocity: 10 m/s
Ice thickness: 0.6 m
Ice velocity: 0.0 and 0.175 m/s
Up to 86% higher structure displacement (at ice level)
Higher frequency in displacement at tower base and blade tip (→ Fatigue!!!)
Ice structure interaction must be taken into account
Figure 3: Wind turbine under ice action and without – Time series of out-of-plane blade tip and tower base deflection [m]

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Conclusions

- Various ice models will be implemented into overall wind turbine simulation platform
- The first implementation - Määttänen-Blenkarn model - was implemented successfully
  - A good agreement was found between Abaqus and OnWind
  - Simulations with OnWind software were carried out successfully creating a promising basis for future research
- Frequency lock-in vibration in both configurations
- Significant difference in structure displacement at ice level between configurations 1 and 2
- Implemented ice model has limited capability to describe various ice failure mechanism
  - Advanced models will be implemented during the BRICE-project

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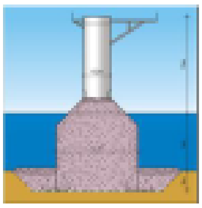
Pilot OWECs in Finland

- Demonstration turbine 3MW in Kemi (North part of west coast)
  - monopile (cylindrical structure)
  - ice loads
  - wave loads



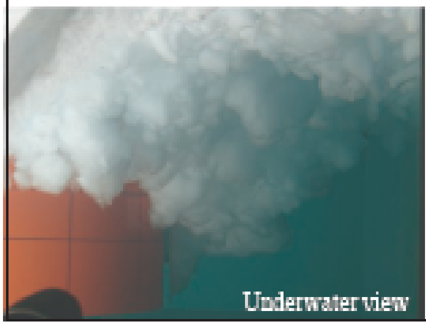
- Demonstration turbine 2.3 MW in Tahkoluoto Pori (west coast)
  - gravity based conical structure
  - ice loads
  - wave/wind loads
  - wind profile at sea in cold climate

VTT TECHNICAL RESEARCH CENTRE OF FINLAND

Ice Basin at Aker Arctic Research Center

- Experimental feasibility studies of an offshore structure
  - model tests
  - Ice loads, global and local forces to structures
  - different ice features
    - level ice, rafted ice, ridges
  - Intrumentation of forces, deformations, accelerations etc.
  - video observations above and below the ice
- Test carriage
  - speed range 0 – 3 m/s
  - 2nd carriage speed 0 – 1.5m/s


Model ice


Underwater view

Test basin:
length 75m
width 8m
depth 2.1m*
*can be adjusted


Ice tank

VTT creates business from technology

Fraunhofer IWES

Topical Expert Meeting #66

IWES
"Simulation and assessment of wind turbines"
Activities

Urs Wihlfahrt | September, 20th 2011 | Fraunhofer IWES

Agenda

- Fraunhofer – IWES
- Recent Projects
- Ongoing Projects

Fraunhofer IWES

Agenda

Fraunhofer – IWES
Fraunhofer-Gesellschaft
IWES
Simulation and assessment of wind turbines

Recent Projects
UpWind
OC3 / OC4

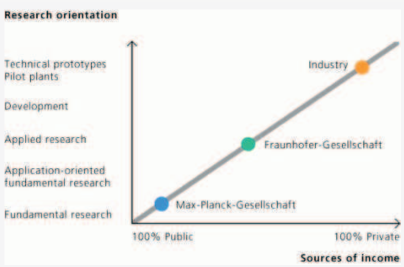
Ongoing Projects
OneWind
IDD – Engineer Design Data
BRICE – Breaking the Ice
WindBucket

Fraunhofer-Gesellschaft

- One of the worlds major research organizations
- Over 18,000 staff, mainly scientists and engineers
- 1.66 billion annual research budget in total
- 60 Institutes for applied / industry related research
- Research centers and representative offices in Europe, USA, Asia and in the Middle East

Funding

- Approx. 40% funding from public sector
- Approx 60% funding from contract research



Overview Fraunhofer Institute for Wind Energy and Energy System Technology

Advancing Wind Energy and Energy System Technology

Research spectrum:

- Energy system technology for all renewables
- Wind energy from material development to grid optimization

Personal:

approx. 250 (full-time: 160)

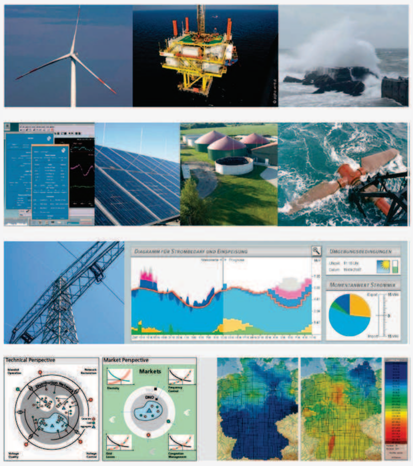
Formerly:

- Fraunhofer-Center for wind energy and marine technology CWMT
- Institut for solar energy supply systems ISET

Business fields - Bremerhaven

- Wind energy technology and operating management
- Elasticity and dynamics of turbines and components
- Competence center rotor blade
- Development of rotors, drive trains and foundations

Business fields - Kassel



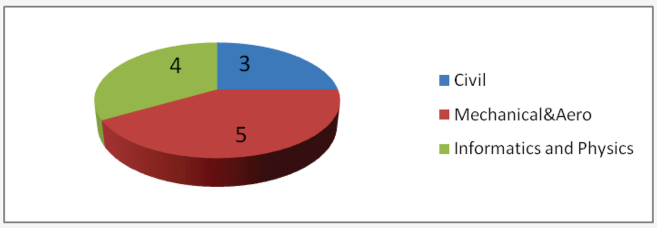
- Environmental analysis for wind and ocean energy
- Control and integration of decentralized converters
- Energy management and grid operation
- Energy supply structures and systems analysis

Department “Simulation and assessment of wind turbines”

Activities:

- **Model development** for the simulation of OWT
- **Consultancy** for
  - offshore projects and load assumptions
  - new materials and concepts

Members:



Agenda

Fraunhofer – IWES
- Fraunhofer-Gesellschaft
- IWES
- Simulation and assessment of wind turbines

Recent Projects
- UpWind
- OC3 / OC4

Ongoing Projects
- OneWind
- IDD – Engineer Design Data
- BRICE – Breaking the Ice
- WindBucket

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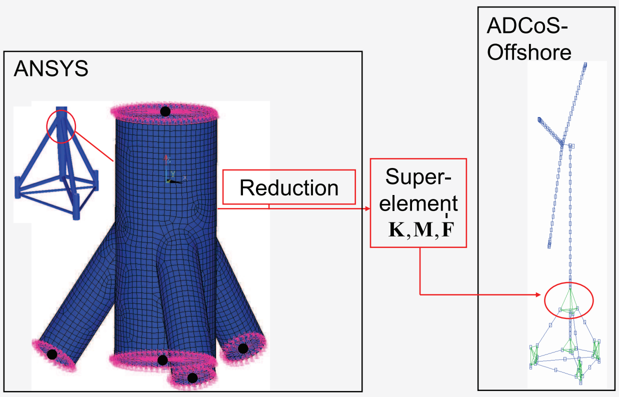
Upwind

Superelements

- Ruduce complexitivity with superelements
- Integration into ADCoS-Offshore



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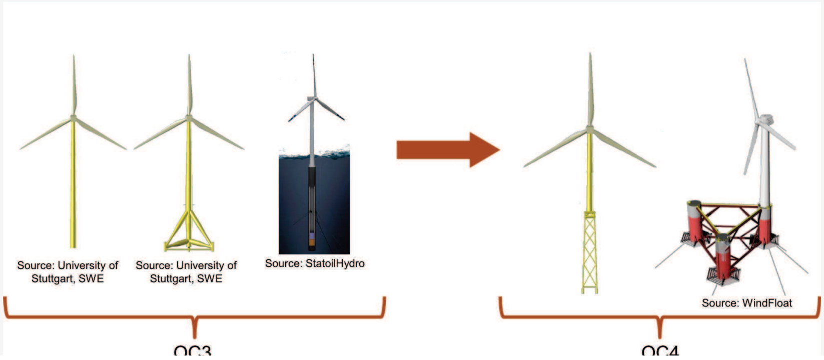
Seite 11 | Topical Expert Meeting #66 | Recent Projects | OC3 / OC4

From OC3 to OC4

- To benchmark and verify the codes in terms of their simulation capabilities of different sub-structures. The comparison is done in code-to-code manner
- New support structure types
- Local structural dynamics in jacket
- Complex hydrodynamics calculations for semi-submersible



Seite 12 | Topical Expert Meeting #66 | Ongoing Projects |

Agenda

Fraunhofer – IWES
- Fraunhofer-Gesellschaft
- IWES
- Simulation and assessment of wind turbines

Recent Projects
- UpWind
- OC3 / OC4

Ongoing Projects
- OneWind
- IDD – Engineer Design Data
- BRICE – Breaking the Ice
- WindBucket

OneWind Software

Develope a system that allows to combine

- *all* components of a wind park
- in *one* numerical model
- with *different* Levels of Detail

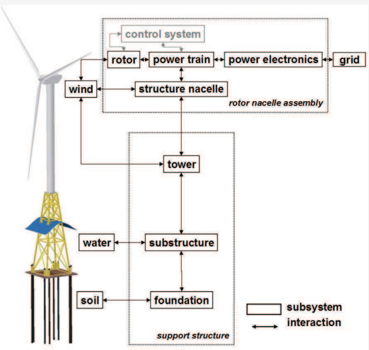
Implementation

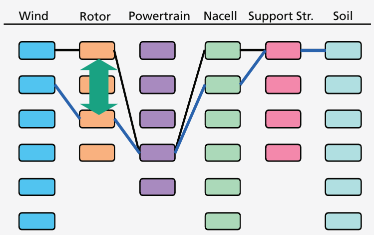
- Fully coupled or aero-servo-hydro-elastic simulation in time domain
- All important subsystems included
- Elastic structure, especially blades
- Blade pitch and generator moment controller included
- Aerodynamics on rotor included
- Ocean waves as load source included
- Dynamic interactions between subsystems at each time step

Environment

- Eclipse Framework
- Modelica Language
  - Object orientated / Component based
  - Equationbased

Components and Complexity of Components





Substructure IDD

IDD — Engineer Design Data

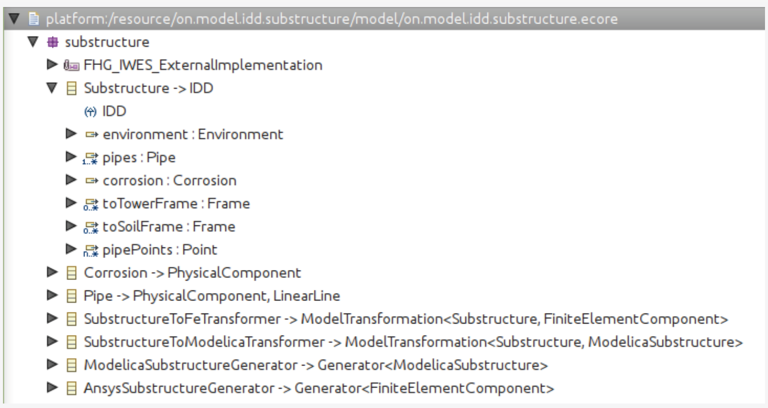
- tool-independent, parametrical description of physical components
- generators use IDD to produce input code for specific simulation tools
- implemented using Eclipse Modeling Framework and Java

Substructure IDD

- parametrical description of bottom-fixed branched offshore wind turbine substructures
- generators for producing
  - Modelica code
  - APDL code (ANSYS input)

Fraunhofer IWES

IDD as Eclipse Ecore



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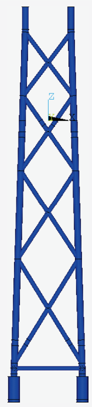
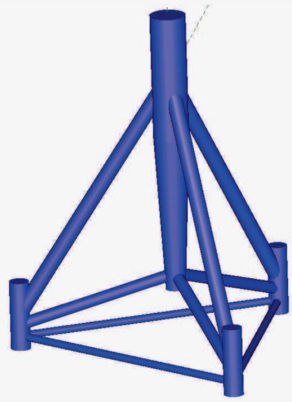
Seite 17 Topical Expert Meeting #66 | Ongoing Projects | IDD – Engineer Design Data

Examples for Models Generated Based on Substructure IDD

ANSYS model



Modelica model



- models have been verified with models that were created "the usual way"
- substructure IDD make the definition of any arbitrary branched structure and generating Modelica and ANSYS models possible

Fraunhofer IWES

Seite 18 Topical Expert Meeting #66 | Ongoing Projects | IDD – Engineer Design Data

Future Plans Regarding the Substructure IDD

- extending the amount of possible shapes for the structural members possible (e.g. introducing T-sections, I-beams, etc.)
- discretization with more element types (e.g. Timoshenko beam elements, shell elements, etc.)
- introducing mooring line models to extend the substructure IDD to floating substructures

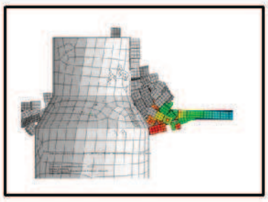
Fraunhofer IWES

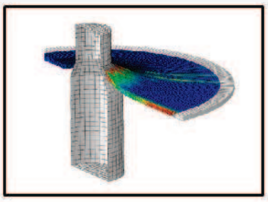
Breaking the Ice – BRICE

Breaking the Ice (BRICE) is a common 3 year project of Fraunhofer IWES, VTT – Technical Research Centre of Finland and Hamburgische Schiffbau-Versuchsanstalt (HSVA)

Motivation

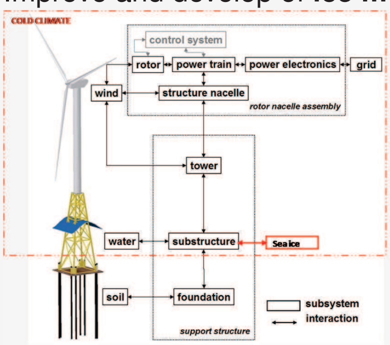
- Large capacities for offshore wind farms in cold climate regions (e.g. Baltic Sea, Great Lakes)
- Wind energy is not well established in northern countries
- Ice loads are a big unknown in WT support structure design . . .





Motivation

- We want to give the engineers a **better understanding** about the effects of the **ice-structure interaction** providing an overall simulation tool.
- Investigation of ice conditions in **Baltic Sea** area
- Improve existing **numerical WT** models
- Improve and develop of **ice models**



- **Simulation** and **experimental** tests of:
  - Ice structure interaction
- Main Focus on:
  - Ice induced vibrations
  - Fatigue loads
- **Optimization** of offshore foundations:
  - Less conservative safety factors
  - Cost effective

Fraunhofer IWES

WindBucket – Suction Bucket Foundations

WindBucket ia a common 2 year project of Fraunhofer IWES, Leibniz University Hannover and OVERDICK (Hamburg)

Motivation

Suction Bucket foundations for offshore windenergy

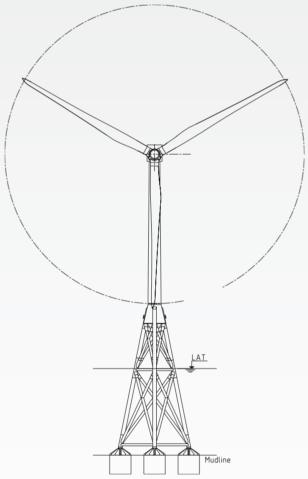
Suction buckets compare to pile driving

- reduction of noise emmission during building stage (BSH-Standard)
- faster installation
- easy removal
- less steal

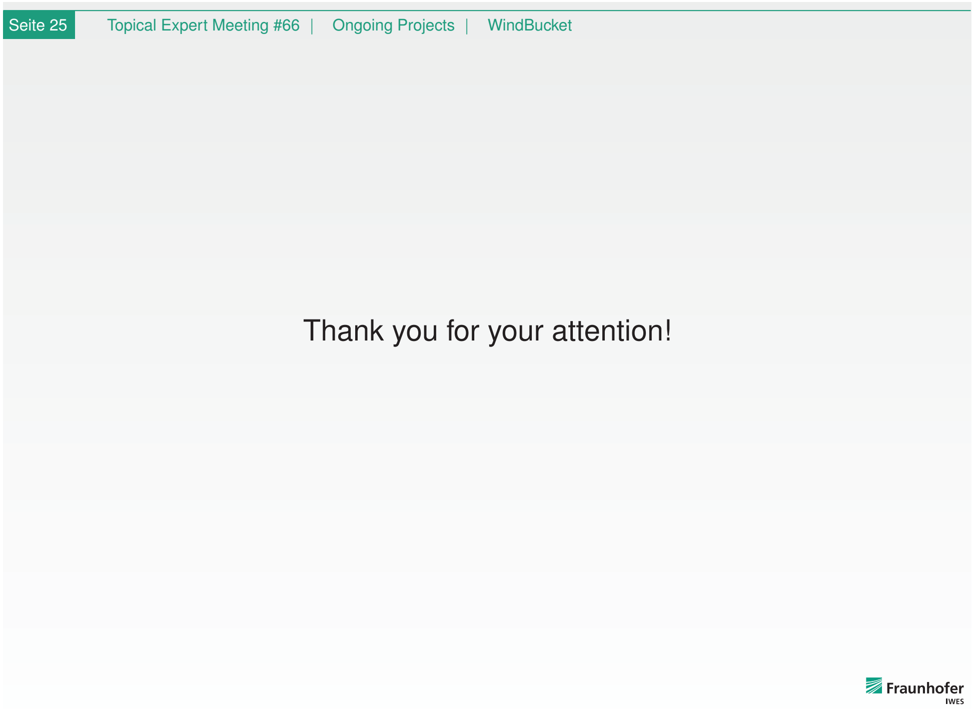
Fraunhofer IWES

Scope

- Assessing the feasibility and possibilities and limits of application
- Creation of licensable installation and design concepts
- Investigations on the potentials
- Alternative designs and materials – concrete monopods



- Numerical Models
  - construction and operation conditions
  - models of details
  - fully coupled simulation
- Small and large scale models
  - IWES Support Structures project group
  - validation and calibration of numerical models


Seite 25
Topical Expert Meeting #66 | Ongoing Projects | WindBucket
Thank you for your attention!
Fraunhofer
IWES

Simulation of support structures for offshore wind turbines and large scale tests

Prof. Peter Schaumann
Jan Dubois

IEA Topical Expert Meeting, Esbjerg
September 20-21, 2011

Agenda

- Introduction
- Simulation and measurements
- Constructional details
- Research needs

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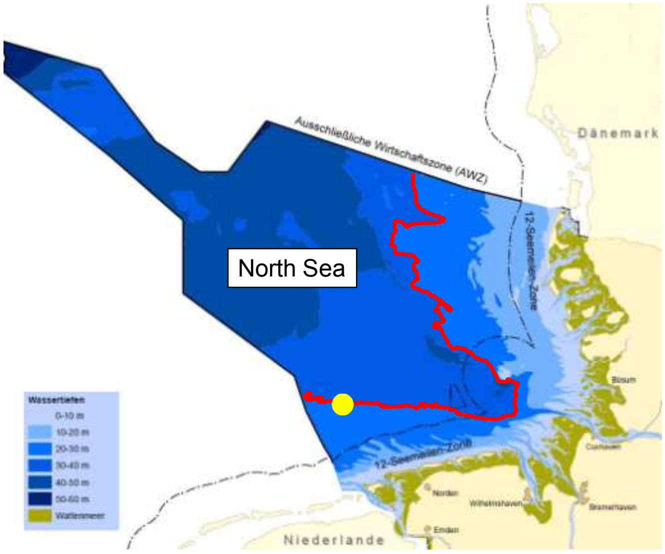
Offshore Foundation Technology and Knowledge, for shallow, middle and deep waters
Institute for Steel Construction
Leibniz University Hannover
Prof. Peter Schaumann

German exclusive economic zone



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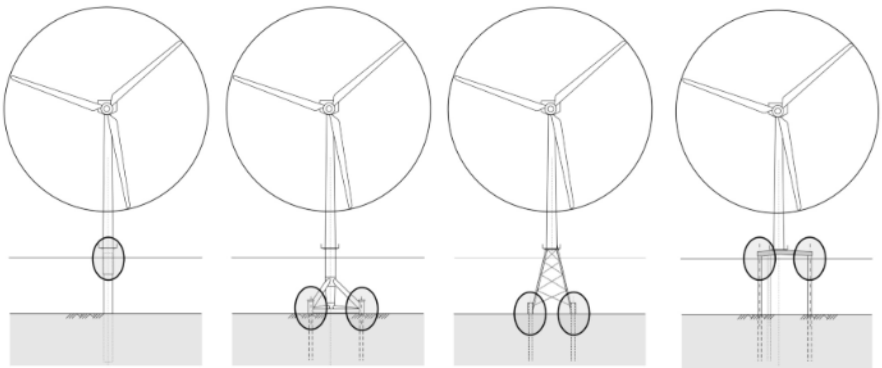
Applied support structures in Germany



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Research Projects

- Holistic Design Concept for Offshore Wind Turbine Support Structures (GIGAWIND alpha ventus)

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

- Verification of Offshore Wind Turbines Turbines (OWEA)

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

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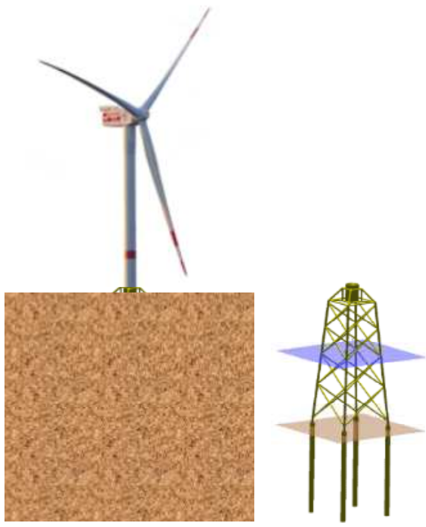
Simulation and measurements



Pictures: www.alpha-ventus.de

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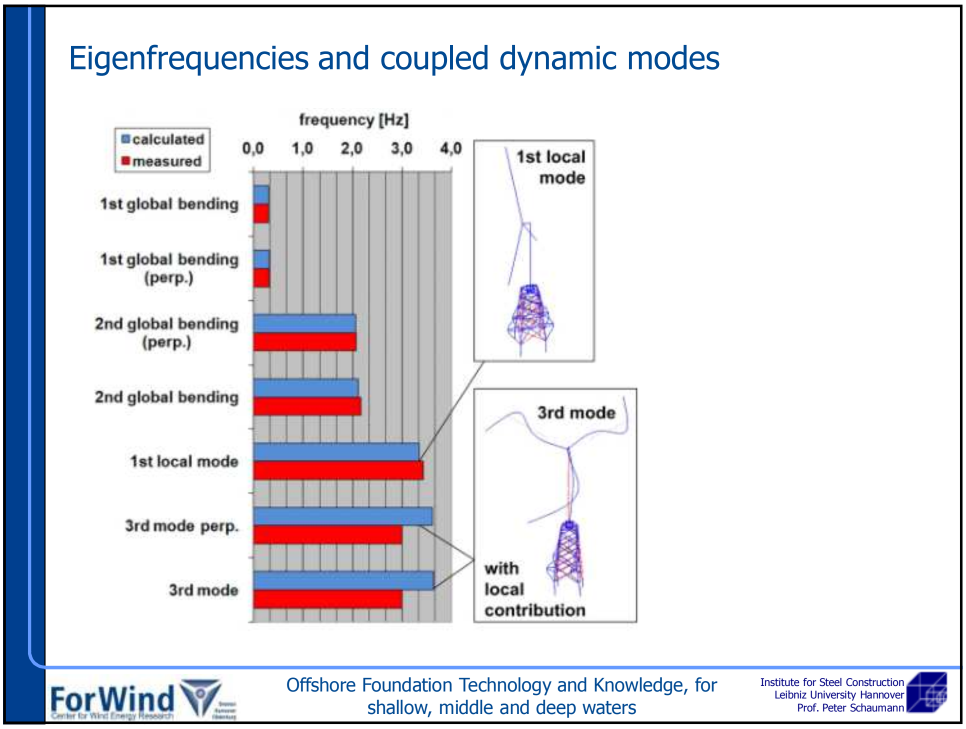
Eigenfrequencies and coupled dynamic modes
calculated
measured
frequency [Hz]
0,0
1,0
2,0
3,0
4,0
1st global bending
1st global bending (perp.)
2nd global bending (perp.)
2nd global bending
1st local mode
3rd mode perp.
3rd mode
1st local mode
3rd mode
with local contribution
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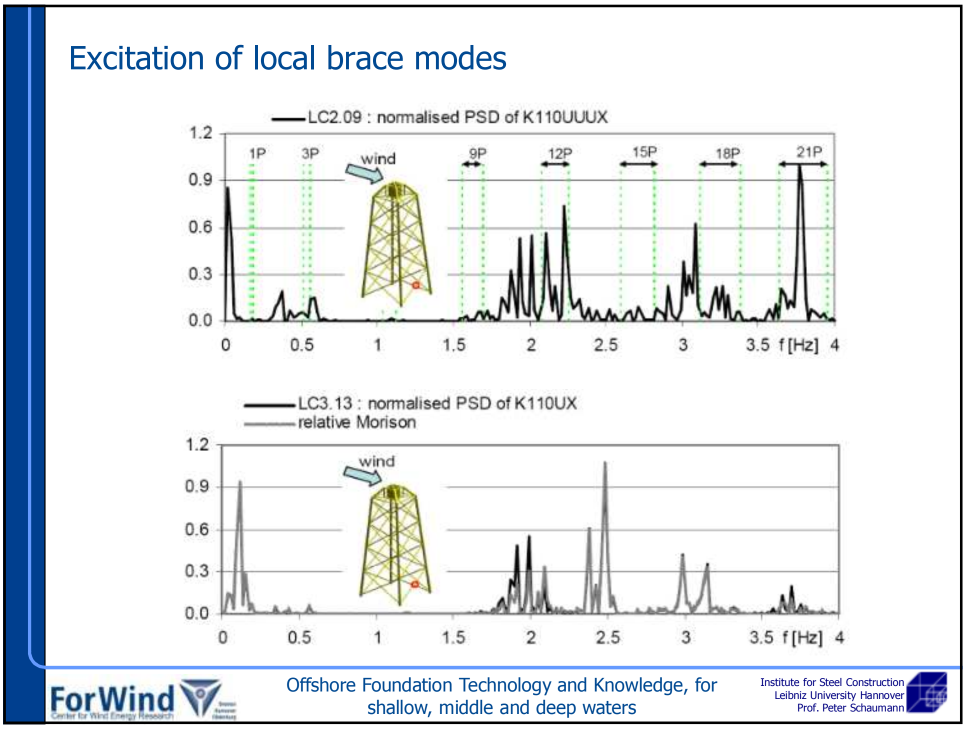
Excitation of local brace modes
LC2.09 : normalised PSD of K110UUUX
1P
3P
wind
9P
12P
15P
18P
21P
1.2
0.9
0.6
0.3
0.0
0
0.5
1
1.5
2
2.5
3
3.5
f [Hz]
4
LC3.13 : normalised PSD of K110UX
relative Morison
wind
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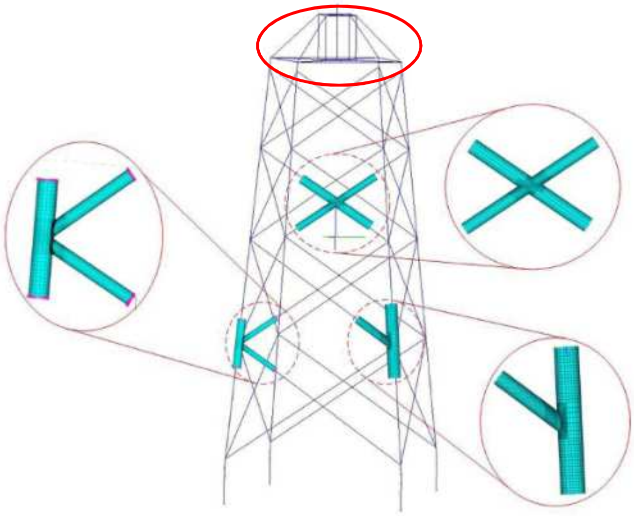
Superelement approach



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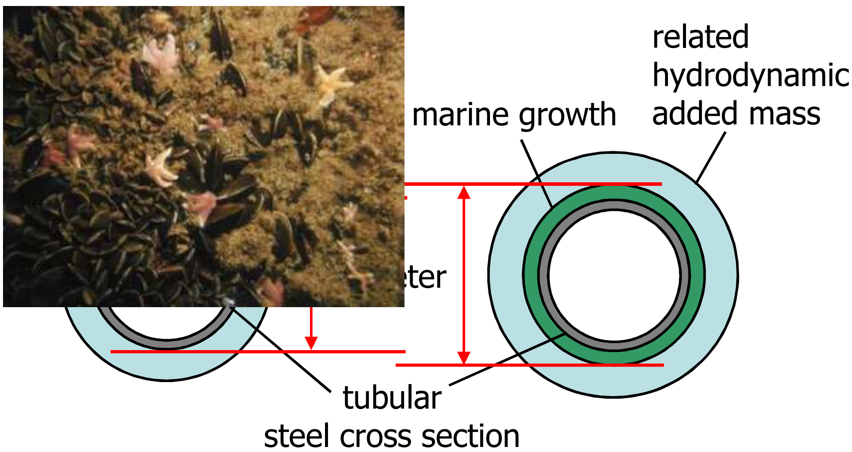
Added masses

- added masses for submerged structural members

Source: www.awi.de



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First results of Jacket data evaluation

- Simulation of global loading acceptable
- Model refinements for local load distribution
- Fatigue load evaluation started

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Fatigue Tests of constructional details of OWT

- Constructional details

welded,
bolted, and
grouted joints

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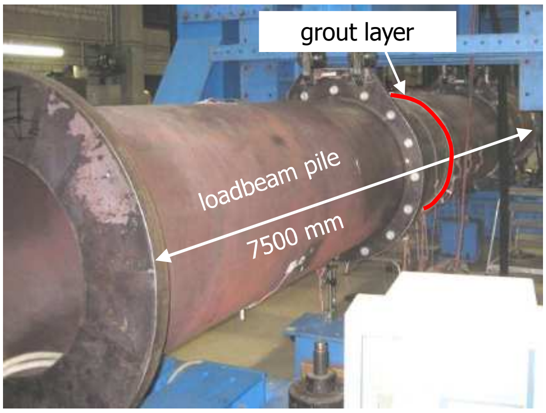
Grouted Joints

- Test setup for bending tests



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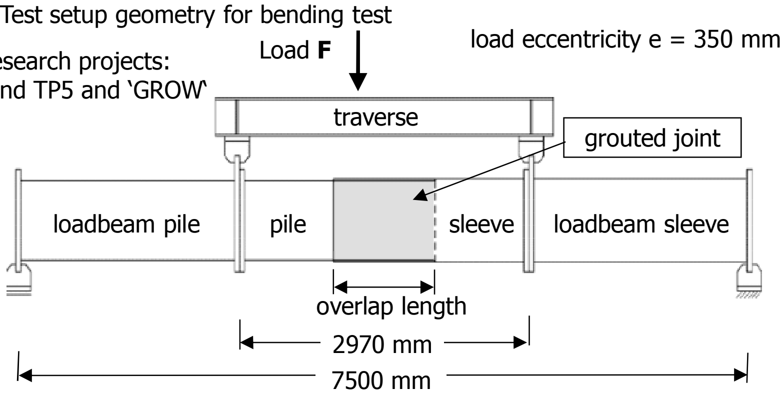
Grouted Joints

- Test setup geometry for bending test

Research projects:
ForWind TP5 and 'GROW'



- Parameters:
  - Grout material strength: 70 MPa, 90 MPa, 130 MPa
  - Overlap factor: $f_{OL} = L_{grout} / D_{pile} = 1.0 \quad 1.3$
  - Shear keys: w/o; 5 or 7

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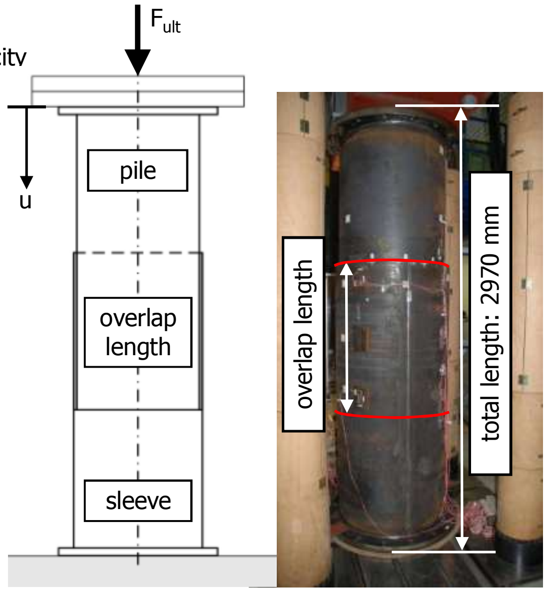
Grouted Joints

- Axial post-fatigue capacity
- Test setup
  - Servo-hydraulic test machinery
  - F_{ult} = 1'000 tons
- Main goals
  - Residual axial force capacity
  - Vertical displacement u
  - Connection ductility



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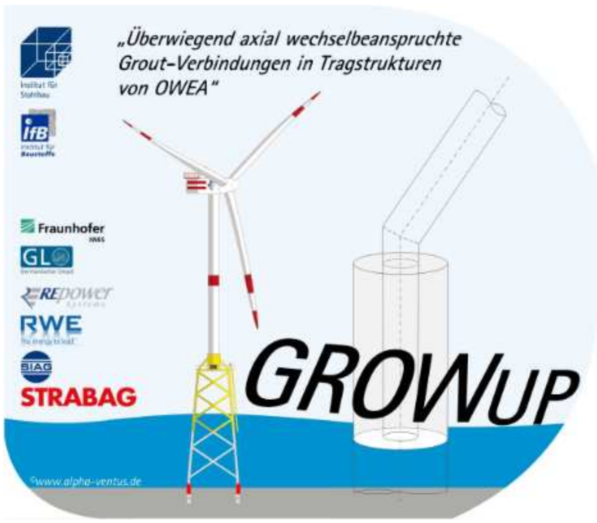
Research Project GROWup



Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

PtJ

- Small scale tests
- Large scale tests
- Numerical Simulation
- Test facility of grouting
- Review of Guidelines

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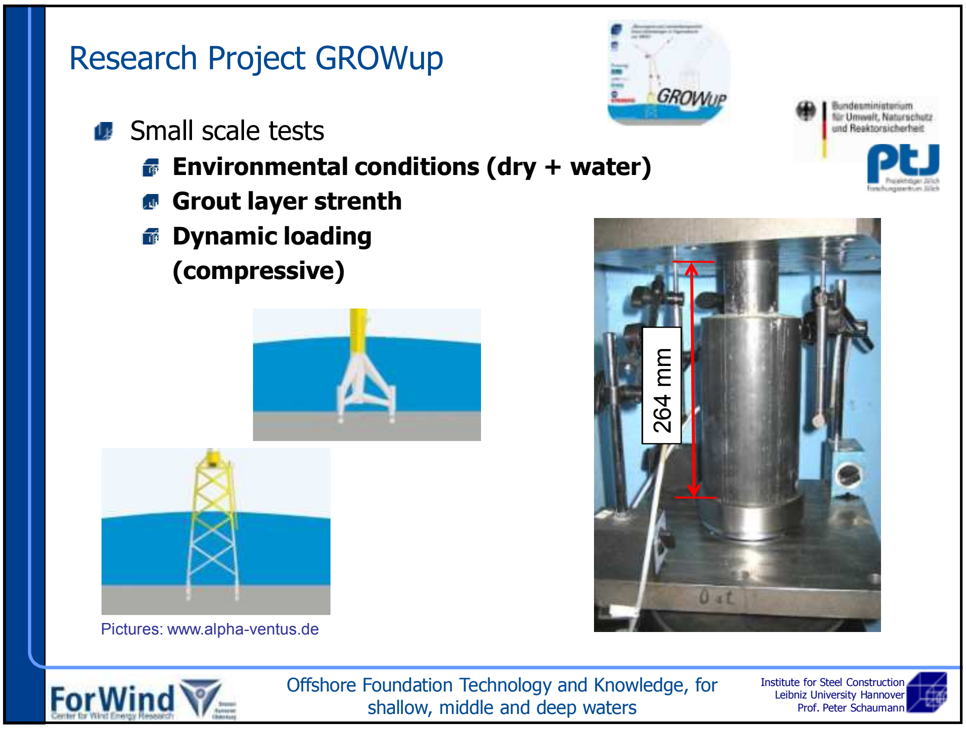
Research Project GROWup
GROWUP
Small scale tests
Environmental conditions (dry + water)
Grout layer strenth
Dynamic loading (compressive)
264 mm
Pictures: www.alpha-ventus.de
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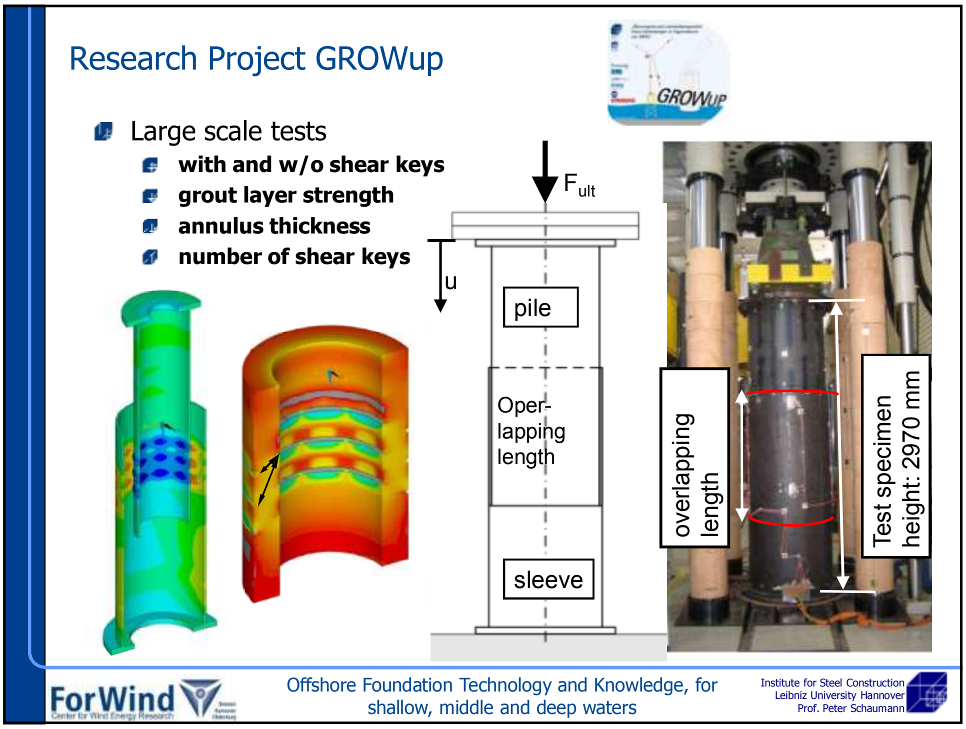
Research Project GROWup
GROWUP
Large scale tests
with and w/o shear keys
grout layer strength
annulus thickness
number of shear keys
F ult
u
pile
Oper-lapping length
sleeve
overlapping length
Test specimen height: 2970 mm
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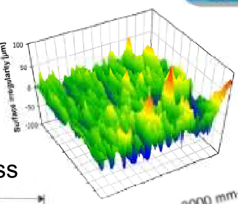
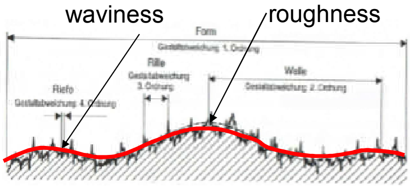
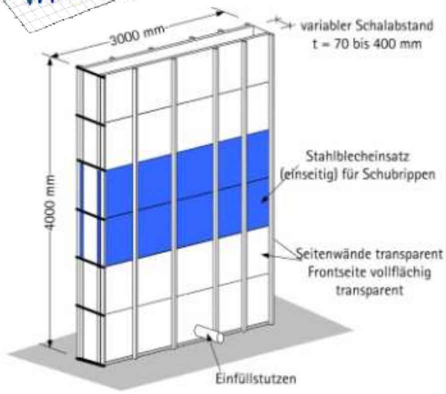
Research Project GROWup

- Additional investigations
  - **surface roughness**
  - **surface waviness**





- Test facility of grouting (Institute of building materials)



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Research needs

- Non-linear superelements for soil
- Fluid structure interaction
- Environmental parameters for simulation
- Reliable fatigue design approaches

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Summary of “Offshore foundation technology and knowledge, for shallow, middle and deep waters”

66th Topical Expert Meeting

Félix Avia, CENER

a) Participants

20 persons attended the meeting from Denmark, Finland, Germany, Ireland, Norway, Spain, Sweden, UK and USA and one participant from the EWEA. The participants represented manufacturers, research organizations, universities and consultants. Nothing was decided for future actions on this topic under the umbrella of the IEAWind. A total of 15 presentations were given:

1. Introduction
Jens Madsen, Acting Competence Unit Manager, Vattenfall R&D AB, Sweden

2. Vattenfall Wind Power
Jens Madsen, Competence Unit Manager, Vattenfall R & D AB, Sweden

3. The European offshore wind industry 2010
AA Arapogianni, European Wind Energy Association, Belgium

4. Status Some Key Offshore Wind Energy Research Activities in the Unites States
Walt Musial, National Renewable Energy Laboratory, USA

5. Offshore Overview at Riso
Thomas Buhl, Riso-DTU, Denmark

6. Market oriented Evaluation and Development of Offshore Foundations for OWECs.

Júrge Reimers, Offshore Structure, Areva Wind GmbH, Germany

7. Experiences with different foundation types

Frank Hermes, RWE Innogy Offshore Wind, Germany

8. Testing and Optimization of Support Structures for Offshore Wind Turbines

Martin Kohlmeier, Fraunhofer Institute for Wind Energy, Germany

9. Physical and numerical modeling of the high cycle fatigue loading of offshore wind turbine foundations - some research results

Peter Kudella, Institute for Soil Mechanics & Rock Mechanics, Germany

10. Improvements to soil-structure interaction and foundation modeling

E. Van Buren, Norwegian University of Science & Technology, Norway

11. Modelling of transition piece in structural and aerolastic codes

Elena Menéndez, Alstom Wind, Spain

12. Efficient foundation design of monopile, jacket and hybrid structures: Limitations of current practice, Recent research and Practical Design Tools

Paul Doherty, University College Dublin, Ireland

13. Ice loads and ice-induced vibrations in offshore wind turbines

Dr J Heinonen, VTT Technical Research Centre of Finland, Finland

14. Simulation and assessment of wind turbines

Urs Wihlfahrt, Fraunhofer Institute for Wind Energy, Germany

15. Simulation of support structures for offshore wind turbines and large scale tests

Jan Dubois, Leibniz University Hannover, Germany

b) Discussion

Following the presentations the floor was opened and a general discussion took place.

During the presentations several issues were identified by the speakers for future research. In particular the NREL presentation clearly defined the following R&D priorities:

- Develop and validate design tools
- Develop integrated control systems for platform stability and load management
- Develop system economic models and evaluate
- Conduct design optimization studies for lowest cost
- Test and validate deployed systems
- Establish floating design requirements and standards

Areva speaker specifically stated the necessity of development of cheaper foundation solutions, solutions for higher water depths and solutions for hard soil conditions.

The following topics were handled during the discussion in order to decide which the priorities for future work are:

- **Experimental data requirements for codes verification**
- **Fatigue resistance of support structures**
- **Scaling process for models**
- **The soil conditions**
- **Decommissioning**
- **Cost and risk**
- **Ice**

b.1) Experimental data requirements for codes verification

Alpha ventus Test Site

Source: Presentation "Simulation of support structures for offshore wind turbines and large scale tests". Jan Dubois, Leibniz University Hannover, Germany

One of the identified priorities is the necessity of available measured data from experimental offshore installations to validate the existing developed models.

It was expressed the necessity of data for different support structures (monopile, jackets, tripods, TLP, etc) and different WT technologies.

For the time being just few data are available to the research community from existing experimental offshore test sites, mainly due to the confidentiality of the data, usually property of the manufacturers involved in the projects.

Standard tests on large scale support structures and foundations are clearly need it for future developments. Detailed multi-axial fatigue tests on large/full scale support structure components like structural nodes, grouted joints and other welded or hybrid connections will be required (IWES presentation).

Also was discussed the requirement of the quality of measured data. Collaboration between people involved in modelling, and people involved in testing of prototype installations will be useful to help in the definition of measurements required.

It was commented that should be very useful to lunch a project were the support structure will be fully designed by the research community, that will facilitate the elaboration of useful data for model validation.

NREL informed that a workshop will be organised next year, under the umbrella of Task 30 of IEA "Offshore Code Comparison Collaboration Continuation (OC4)", on test methods, data availability, and code validation. Tentative plans are to have this meeting at NREL in May of 2012. Experts form organizations not participating in Task 30 will be accepted to attend the workshop.

Alpha ventus Test Site

Source: Presentation "Simulation and assessment of wind turbines". Urs Wihlfahrt, Fraunhofer Institute for Wind Energy, Germany

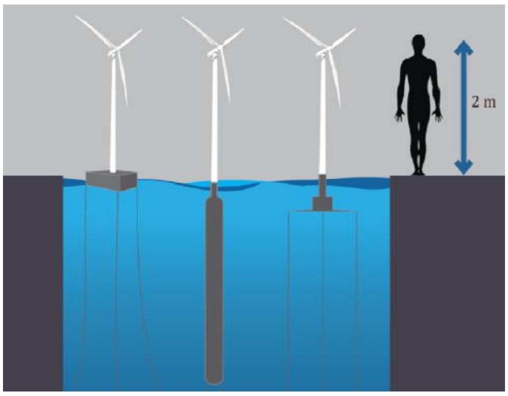
b.2) Fatigue models for resistance of support structures

There was a general consensus about the necessity to improve existing model for fatigue analysis of the resistance of support structures. One of the main problems is that perform a full fatigue analysis require long time, because large number of load cases should be modelled. In the oil and gas industry they use a simple process for the design of the support structures, and they don't perform accurate fatigue analysis, just doing the design using maximum forces and momentum obtained for a few cases and applying a very large factor of safety.

Taking into account that share of the cost of the support structure for offshore wind installations is close to 40 % of the total cost of the installation, optimization of the design of structures for wind turbines it is needed and consequently a more accurate calculations are required.

As general conclusion it was stated that reliable fatigue design approaches are need it.

b.2) Scaling process for models. Sharing of data from model scale test



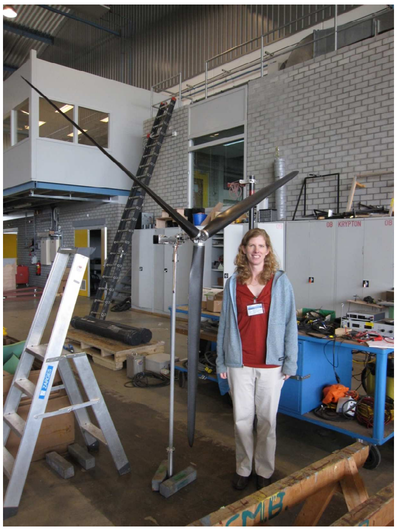
Scale Models for Test

Source: Presentation "Some Key Offshore Wind Energy Research Activities in the Unites States"
Walt Musial, National Renewable Energy Laboratory, USA

In TEM #64 Amy Parsons presented information of the scaling process followed at NREL to obtain the scale factors for modelling. It was expressed the interest to define more precisely the procedures for defining the scaling models.

The attendees expressed also their interest to have access to the available data of scale models tested, that could be very useful for ongoing research projects. It was expressed the necessity to perform different experiments for different technologies. Discussion took place on several scaled issues.

Walter Musial from NREL presented information about the DeepCwind Projet, which main goal is to develop engineering tools to enable the design of optimized full-scale systems for new floating wind technology, it is planned to make $1/50^{th}$ Scale Model Testing and 1/3 scale open ocean testing.

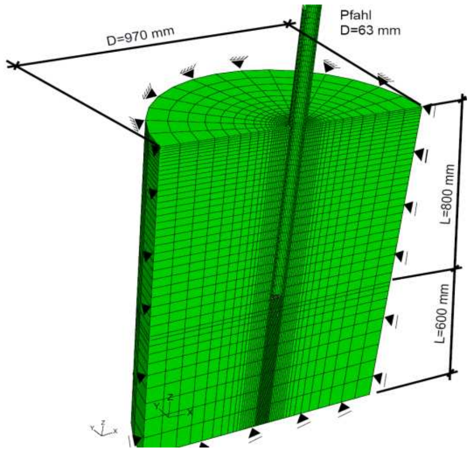


Scale Model for Test

Source: Presentation "Some Key Offshore Wind Energy Research Activities in the Unites States"
Walt Musial, National Renewable Energy Laboratory, USA

Testing of offshore wind scale models it is a very complex task, due to the fact that's very difficult to scale the models as well as the test conditions to simulate the behaviour of a real size installation.

b.4 Characterization of the soil conditions



Numerical Model for monopile. Reference mesh

Source: Presentation "Physical and numerical modelling of the high cycle fatigue loading of offshore wind turbine foundations – some research results". Dr.-Ing. Peter Kudella. Institute for Soil and Rock Mechanics, KIT Karlsruhe

Different subjects were discussed and in particular:

- The influence of the soil properties in different support structures technologies
- The influence of soil conditions in the dynamic behaviour of the WT.
- The influence of uncertainties of the soil conditions in the risk of the projects
- Definition of soil conditions. Available standards
- Procedures for characterization of soil conditions for shallow, medium and deep waters.

According with the data presented in the sessions (mainly presentations 5, 7, and 10), the soil requirements are different depending of the support structure type. For instance the requirements for monopile structures are more strict that for gravity base structures or for jacket foundations. However in all the cases the tower design must be performed with the knowledge of the soil stiffness. It clear that is necessary to have information of the soil conditions to model the dynamic behaviour of the wind turbines.

There are not available standards defining the soil types coming from the gas and oil industry.

In reference to the procedures for characterization of the soil, it was stated that for deep waters the cost could be very high. On the other hand, it is not well defined the numbers of probes that should be required for a good characterization, mainly taking into account that the area of offshore wind farm could be as large as 100 km^2, and in consequence the soil conditions could be different from one zone to another. Therefore to get a large number of samples will be required.

In this case, it was discussed about how to deal with the case when the soil conditions were different in a site, and if is necessary to tail the design for each soil condition. General consensus was that this approach it is not reasonable.

b.5) Decommissioning

Source: Decommissioning Wind Turbines In The UK Offshore Zone. D Pearson. Enron Wind

The problem associated to the decommissioning of the wind offshore installations was commented. For the time being there are a few available studies analysing the decommissioning of offshore wind installations. Decommissioning plans will become important if not critical during the future development of offshore wind farms.

It is assumed that the superstructure decommissioning process (i.e. removal of turbine components including blades, nacelle, tower and containerised transformer) will largely be a reversal of the installation process, and will be the subject to the same constraints.

The decommissioning procedures will be completely different according to the type of support structure used and also depending of the water deep and soil conditions. Suction caissons foundations could have advantages for decommissioning.

Lack of experience in decommissioning offshore renewable installations increases the risk that developers are unable to provide a fair valuation of decommissioning costs.

b.6) Cost and risk

An action to make deep comparison between different technological options and the risk and cost estimated for several site conditions was identified for a future Task, similar to the ongoing work on the EquiMar project. EquiMar involves scientists, developers, engineers and conservationists from 11 European countries working together to find ways to measure and compare tidal and wave energy devices.

The proposed idea is to select different sites with different conditions (wind, waves, water deep, soil conditions, etc) and assess the cost and risk associated for different technologies (monopole, gravity based, jackets, tripods, TLP, etc).

One of the main risks identified is the availability of vessels for installation.

Also, other relevant source of risk during construction is geological or geotechnical risk. This risk refers to the circumstances in which the location proves to be inadequate to support the foundations of an offshore device.

Finally, experience in the offshore oil and gas sector suggests that decommissioning costs can increase substantially beyond initial estimates.

b.7) Ice

Baltic Sea – Windpower Monthly Cover Photo Feb 2003

Source: Presentation "Some Key Offshore Wind Energy Research Activities in the Unites States"
Walt Musial, National Renewable Energy Laboratory, USA

The problems associated to the ice conditions on the offshore wind farms were commented in several of the presentations, not only for sea waters (VTT and IWES presentations), but also for freshwaters (NREL presentation).

The ongoing IEAWind Task 19 "Wind Energy in Cold Climates" does not dealing with this particular issue associated to offshore wind farms.

Some of the participants commented the possibility that in the future this issue could be included in this task.

c) Future actions under the umbrella of IEA Wind

The continuation of interchange of information between the participants was proposed for some of the participants.

The majority of the participants decided that more development is required before a specific task covering the priorities selected could be lunched.

The workshop that will be organised by NREL next year, under the umbrella of Task 30 “Offshore Code Comparison Collaboration Continuation (OC4)”, on test methods, data availability, and code validation, is the main action identified for future interchange of information about this topic.

e

Participants List

"OFFSHORE FOUNDATION TECHNOLOGY & KNOWLEDGE FOR SHALLOW, MIDDLE & DEEP WATER"

September , 20th-21st- 2011 (Esbjerg, Denmark)

	Name	Last Name	Post	Job Center	Country	E-mail
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3	Senu	Sirnivas	Principle Offshore Wind Engineer	National Renewable Energy Laboratory	Usa	senu.sirnivas@gmail.com
4	Walt	Musial	Group Manager	National Renewable Energy Laboratory	Usa	walter.musial@nrel.gov
5	Frank	Hermes	Engineer Civil Works & Foundations	RWE Innogy Offshore Wind	Germany	frank.hermes@rwe.com
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