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SPECIAL REPORT

Support Structures

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Offshore wind energy

In the new energy concept of the German Federal Government an accelerated development of offshore wind energy was pointed out [1]. Together with an economic OWT operation, the technical reliability plays a distinctly major role compared to onshore wind energy converters (WEC). This is true especially for Germany intending to install a very high share of OWT far away from the shore line. Therefore, the further development in offshore wind energy should be planned carefully and step by step.

2011 was another year with a dynamic growth of installed wind energy power [2, 3]. R&D activities are still playing a major role to ensure this positive trend. In the international context further countries like China have enhanced their activities qualitatively and quantitatively. The global economic competition is growing.

Concerning OWT installation under high sea conditions there are still some disadvantages such as high transport, production and maintenance costs. Moreover, during the offshore work job safety and environmental tolerance (acoustic problems) should be further improved. For important environmental reasons, this is especially true for North Sea wind farm projects in the German Bight, which are to be installed far from the mainland in relatively deep sea regions with a water depth of more than 25 m.

The optimization and development of support structures is one of the main issues to improve the technical availability, reliability and economy of OWT. During the design process, the support structures and foundations have to be adapted to the given offshore site conditions, namely to the geotechnical, meteorological and oceanographic data. The planned technical OWT design also has to be regarded.

Support structures and foundations of OWT

In the international context, OWTs were founded using driven piles as monopile or group of piles generally with a great diameter between 2 m and 4.5 m. Moreover, gravity-based foundations have also been used in case of a capable seabed [2].

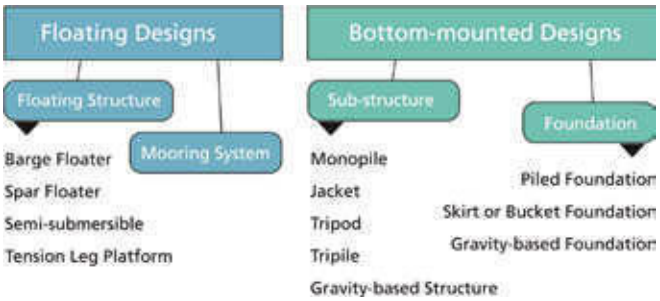


Figure 1: Support structures of Offshore Wind Turbines (OWT)

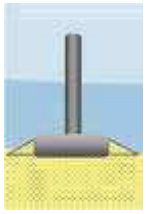
Figure 1 gives an overview of present OWT design and support structures and respective foundations applied. Bottom-mounted structure designs are clearly ruling, using deep (pile mainly) or shallow foundations.

Floating OWT designs are usually applicable for a great water depth. These constructions are moored in the sea ground. These generally promising support structures are under intensified investigation but up to now floating designs have rarely been used.

Bottom-mounted main support structures for OWT are summarized in Table 1, along with some basic structure characteristics, advantages and disadvantages.

Regarding the situation in Germany, a relative small number of OWTs (n <100, until 2011) was installed mainly on driven piles. Monopile, jacket, tripile and tripod structures have been used up to now. Moreover, land-based tests were performed on a gravity-based foundation structure.

Up to now, suction bucket foundations are rare examples worldwide concerning OWT.

Substructures	Basic characteristics	Advantages / Disadvantages
	**Monopile.** cylindric hollow pile, made of steel mainly applicable effectively up to diameter 5-6 m up to max. 20-25 m water depth currently with driven, partly with bored piles load application mainly lateral transition piece to connect the tower	easy transport and installation pile driving with strong sound emission (environmental problem) low cost foundation flexible structure relative low wave intensity is allowed main foundation type today scour protection
	**Gravity Based Structure (GBS).** concrete structure for shallow to medium water depth, pre-fabrication onshore shallow foundation with scour protection needs a stable ground near to surface fabrication in floating docks mainly floating transport or using ships	costs have been reduced now not so depending on steel prices more sensitive to stability and scour, fundament cover often a full base pressure load is needed → weight no pile driving work
	**Jacket.** Skeleton framework made of steel 4 foots are supported/ anchored by pile foundations mainly applicable to greater depth, 25-50 m low structural weigth vertical load application to piles is ruling can be produced onshore	slim structure (steel consumption) easy transport and installation sensitive to clashes has a long application history in Oil & Gas industry a proven construction pile driving with strong sound emission scour protection
	**Tripod.** Skeleton framework made of steel main pipe with 3 steel feet water depth 20-40 m recommended loading variable, compressive and tensile forces supported/anchored by pile foundations can be produced onshore	estimation of acting wave loads is possible empirically and roughly higher material weight smaller piles diameter are possible compared to monopile pile driving with strong sound emission scour protection
	**Tripile**. Skeleton framework made of steel 3 foots are supported/ anchored loading variable, compressive and tensile forces can be produced onshore	estimation of acting wave loads is possible empirically and roughly higher material weight smaller piles diameter are possible compared to monopile pile driving with strong sound emission scour protection
	**Suction bucket (skirt).** open closed steel pipe(s) shallow or deep foundation type under pressure installation of foundation, which is taken sucked up	no pile driving work sometimes tricky installation installation problems are possible, soil (suction) failure observed

Model validation and optimization

Technically safe and economical support structures of offshore wind turbines (OWT) should be obtained using project experiences and an optimized design process with sophisticated, more realistic simulation models and tools. During the structural design process, accompanying experimental tests on scaled support structure models should contribute considerably to the validation of simulation models and tools.

Validation and optimization are among the main goals of research and testing of OWT support and foundation structures. OWT support structures should be constantly better adapted to the specific and demanding offshore site conditions. Among the R&D subjects there is the deformation behavior and capacity of foundation elements such as monopiles, soil-structure-interaction, fatigue, hybrid construction materials, procedures of geotechnical engineering or material protection against corrosion.

Test Center for Support Structures

By 2014 Fraunhofer IWES will start large-scale cyclic and respective dynamic tests on support structures in a new test centre ("Testzentrum Tragstrukturen"). Various designs of OWT structures and single structure components will be tested, applying variable and multi-axial loads to devices under test.

Currently foundation structures of OWEA are in the focus. The investigations are intended to contribute considerably to reliability.

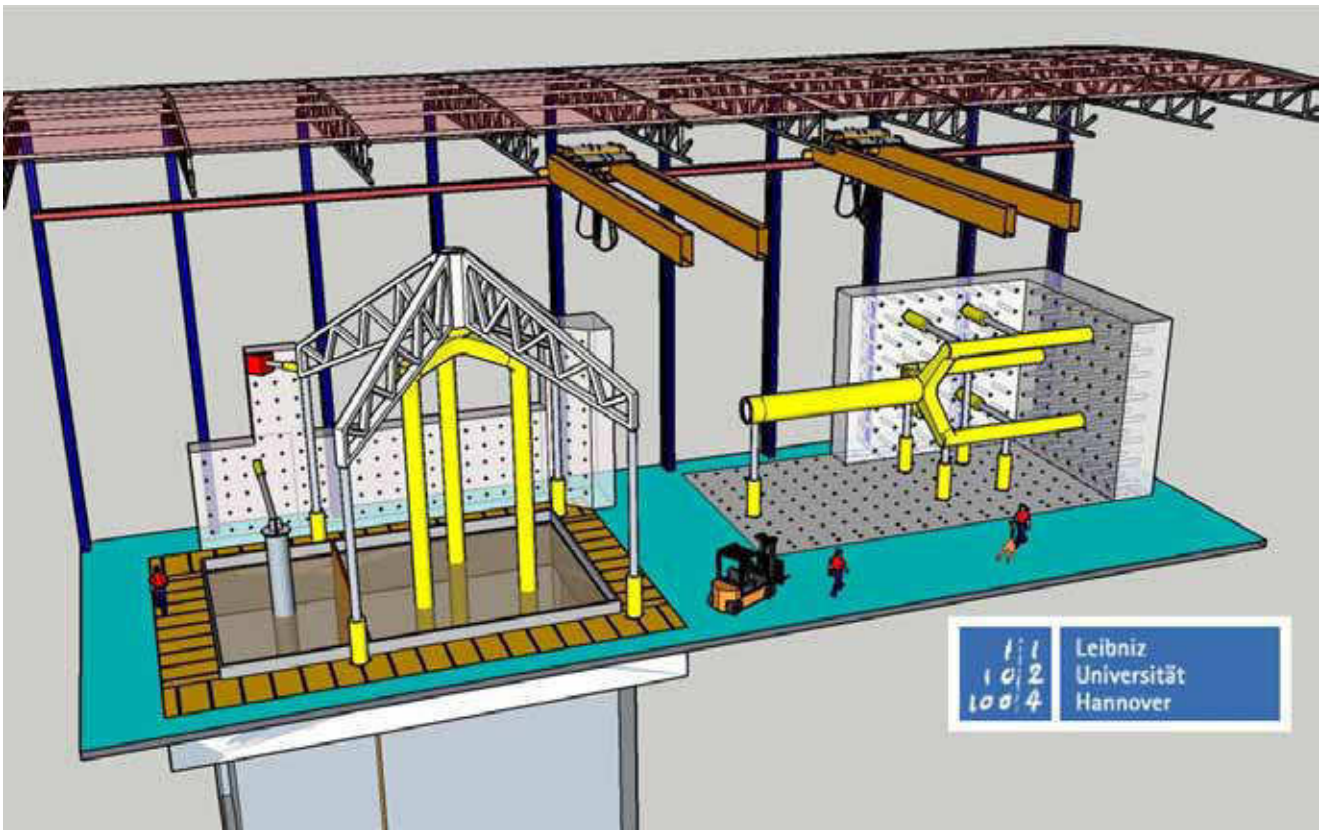


Figure 2: Model of the test hall for support and foundation structures and single structure components with the large-scale test equipment geotechnical test pit and span

Regarding the present level of technical and economical development in the field of wind energy and the main future trends turning energy production from nuclear power to renewables, the construction of a cutting-edge test centre for support structures is a necessary step to use the given offshore wind potential in a safer and more efficient way.

Geotechnical test pit and span

The test center for support structures has been designed as a testing plant for experimental investigations in the field of offshore wind energy turbines on a large scale. Two single large-scale test facilities will be the main pieces of the new test hall – a geotechnical test pit and a span. Using these test facilities, experimental cyclic and respective dynamic tests can be executed, applying multi-axial loads to OWT devices under test. The geotechnical test pit has an outline of rd. 14 m × 9 m and a designed depth of around 10 m. The pit will be filled with sandy material mainly similar to typical sea ground conditions. The sandy filling will be compacted and saturated with water.

Both test facilities have 8 m high reinforced massive concrete abutment walls for introducing horizontal loads.

Test scenario

The objectives of the test centre were developed in collaboration with representatives of the wind energy industry. The main testing objectives can be defined as follows:

- Dynamic tests on large-scale support and foundation structures
- Investigation of structure-soil-interactions on piles and other foundation structures in soils saturated with water, applying lateral and vertical loads to devices under test
- Assessment and optimization of enhanced installation techniques or support structure concepts
- Detailed investigation of structure components (fatigue tests, lifespan prognosis)
- Investigation of hybrid connections and joining techniques.

For example, the load bearing and deformation behavior of a single pile or group of piles of OWT can be tested in the geotechnical test pit, applying variable dynamic loads.

The span can be used for fatigue material tests of structure components, welded joints or hybrid grouted joints; also for construction materials and mechanical joints like large bolts.

Furthermore, tests of the behavior of foundation piles are possible applying a very large number of multi-axial load cycles. Applying lateral and vertical loads, these tests should give detailed information about the long-term behavior of support and respective foundation structure models. The trends of some decisive dynamic soil and material parameters can be investigated and evaluated more precisely.

Using the new, worldwide singular large-scale testing set-up, the experimental investigation possibilities are clearly extended. The test results can be used to answer problems lying beyond the experiences of present OWT operation.

The offshore typical long-term response of structure and substructure can be better investigated under cyclic loads, caused mainly by waves and wind.

Altogether, the designed experimental tests on large-scale structure models or single components are focused on a safer assessment and validation of OWT support structures. This is related to the overall system behaviour, support structure and foundation deformations, material fatigue behavior, operational stability, capacity of pile foundations under long-term cyclic loads, system reliability, lifespan and, last but not least, to more cost effectivness.

Another important aspect of scientific and commercial use of the test centre will be a close cooperation between Fraunhofer IWES and the research network ForWind.

Project group for support structures

Running parallel to the project and design activities of the test center, a new "Project Group for Support Structures" as part of Fraunhofer IWES Bremerhaven is set up in Hannover. The group members are getting permanently more familiar with the subjects of the test centre and the experimental test procedures.

The project group staff are becoming aquainted with aspects of the new test center, hereunder issues of usage and operation, present problems of planning, installation and operation of OWTs, experimental testing and pilot test sets, quality management, measuring methods and data monitoring and numerical calculations with respect to support structure models.

The design of calculation tools for experimental model structures has begun.

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