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Report

Large Floating Coastal Structures

LFCS Review report – Model testing

Model testing of large structures in a wave basin

Author(s)
Bjørn C. Abrahamsen
Carl Trygve Stansberg

SINTEF Ocean AS

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SINTEF

SINTEF Ocean AS

Address:
Postboks 4762 Torgarden
NO-7465 Trondheim
NORWAY

Switchboard: +47 46415000

Enterprise /VAT No:
NO 937 357 370 MVA

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AUTHOR(S)
Bjørn C. Abrahamsen
Carl Trygve Stansberg

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ABSTRACT
This document describes previous model tests on large structures in general and long pontoon bridges in particular. Furthermore, this report highlights the challenges related to model testing of these type of structures. Work to improve the capability of doing this type of model testing is suggested. In addition, possible model test setups for a long segment of a floating pontoon bridge is elaborated.

PREPARED BY	CHECKED BY	APPROVED BY
Bjørn C. Abrahamsen	Halvor Lie	Vegard Aksnes

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Document History

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0.4	2018-06-28	Initial draft for internal discussion
1.0	14.09.2018	Including complete reference list, missing image, new chapter: Snøhvit-barge in dock. Single pontoon tests in ocean basin 2017 added. Comments to further work implemented.
2.0	16.11.2018	Final version
2.1	18.03.2019	Minor fixes and misprints.

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APPENDICES

None

1 Introduction

1.1 General

The KPN project "Design and verification of Large Floating Coastal Structures" (LFCS) started with a kick-of Nov.30, 2017, with a planned duration to summer of 2021. The project was established by SINTEF Ocean and NTNU with the support of the Norwegian Research Council, the Norwegian Public Road Administration, Hydro ASA, Multiconsult AS, SWECO AS, and LMG Marin AS

Compared with well-established methods in ocean engineering, the following critical issues are initially identified for the analysis of large floating coastal structures,

- varying bathymetry and inhomogeneous environmental conditions over the extension of the structure
- inhomogeneous environmental loads over the structure,
- hydroelasticity of large floating coastal structures under inhomogeneous conditions,
- mooring and station-keeping of large flexible floating structures,
- modelling of hydroelastic effects in combinations with articulated/elastic interconnections between structural parts.

One objective of the present project is to improve the understanding of each of these separate topics, and then to provide input to a consistent procedure for design and verification of large floating coastal structures. The project is then organized in work packages according to the identified topics above:

- WP1 - Environmental description
- WP2 - Environmental loads
- WP3 - Structural response
- WP4 - Mooring and positioning
- WP5 - Model testing

In addition, the LFCS administrative tasks have been organized in a work package WP0.

Review phase:
The first phase of the project is devoted to a review of work already performed for relevant existing structures, for conceptual studies performed for potential crossings as well as additional work on measurements, modelling, simulations related to coastal areas which in all comprises the state of the art. This also included a 2-day workshop on March 7-8 with emphasis on environmental description, modelling and loads, and structural response based on presentations from the LFCS industry partners and specially invited external presenters.

This emphasis for this report is the review work performed for Work Package 5 (WP5) – Model testing.

1.2 Work package 5 description

The purpose is to study the behaviour of varies type of coastal structures by highlighting the importance of issues related to the wind wave and current environment (WP1), the implied forces from the environment and the structural response (WP2, WP3 and WP4), through model tests.

The model test will consist of a large model test in SINTEF's ocean basin. A floating bridge model inspired by an existing concept design with main prototype flexibility and positioning properties will be tested in waves with current and possibly also wind loads, where the model will probably be truncated /shortened in order to compromise between the dimensions of the model, the wave height, and the water depth in the basin. In the hydroelasticity model testing, flexible beams/pipes with designed cross section properties will be used to simulate the flexibility of the structures, and both the strains and motions of different cross sections of the tested model will be measured. The corresponding numerical simulations should also be performed by means of the numerical model in WP3.

1.3 This report

Historically, model testing of structures spanning several kilometres has proven to be challenging. Experience from the very large floating structures like floating air ports indicates the problem of scale. This means the problem of fitting these models into laboratory basins, and still being able to model the environment, like waves, wind and current in a satisfactory way.

SINTEF's Ocean Basin has been used to study smaller structures, and in some cases larger structures has been tested. Some critical issues related to these previous experiences are looked upon. This primarily concerns environmental modelling for testing of floating bridges, also addressing the wave and current modelling over large areas. This report refers to previous work performed by MARINTEK. Through a merging process MARINTEK is since 2017 part of SINTEF Ocean.

The purpose of this document is to describe previous model tests on large structures in general and long pontoon bridges in particular. Furthermore, this report highlights the challenges related to model testing of these type of structures. Work to improve the capability of doing this type of model testing is suggested. In addition, possible model test setups for a long segment of a floating pontoon bridge is elaborated.

2 Purpose of experiments

When designing and planning the experiment it is important to have in mind what do we really wish to get out of it. The *general* purpose is:

A) Validate / calibrate numerical models

B) Demonstrate function of a complex system for which there is limited experience from before.

C) Check physical behaviour during different design states: ULS, ALS, FLS.

Particular issues for experimental testing in wave tanks:

- Hydrodynamic wave and current loads and responses on a very large flexible structure, e.g. with many pontoons. The relevant effects arising will depend strongly on actual natural periods in the system. Some possible issues for investigation:
    - Multibody effects and other spatial coupling effects
    - Wave drift and slowly varying forces
    - Behavior in short-crested waves
    - Sum-frequency springing?
    - Viscous forces from current
    - Other nonlinear phenomena.
    - Hydro-elastic effects?
- Effects from wave+current interaction on hydrodynamic loads, and effects from combined wave+current+wind on the responses.

- Demonstrate response effects from inhomogeneous environment
- Other

3 Literature study on model testing of large structures

In this chapter published literature on model tests of large structures floating in the ocean, and on the corresponding modelling of wave and current fields over relevant areas, is reviewed. By large we mean structures which can cover up to several kilometres in full scale. Emphasis is on floating bridges but model tests of this type of structures are limited, more literature is available for floating air ports or the more general class of structures denoted very large floating structures (VLFS).

3.1 Previous SINTEF Ocean/MARINTEK studies

Model tests with stationary models in SINTEF's Ocean Basin (operating since 1981) have mostly been done with model scale sizes ≈ 1 - 5m, in the centre of the basin, in scales typically in the range 1:30 – 1:80 (with some exceptions). Within such ranges, waves are reasonably homogenous. However, some tests have been done with larger models covering wave field and/or models over a larger area, of which a selection is briefly reviewed below. Tests have been done in both long-crested and short-waves. Also testing with free-running models covering a large basin area are being done; they are not addressed here.

The Ocean Basin is described below since it is also planned to be used in the forthcoming LFCS model tests.

3.1.1 SINTEF's Ocean Basin

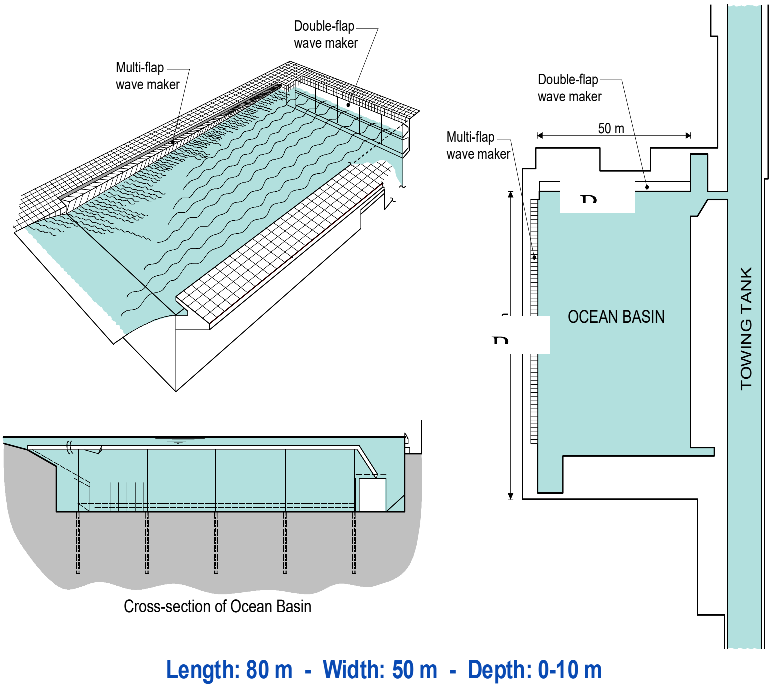


Figure 1: Main dimensions of SINTEF's ocean basin laboratory.

Figure 2: Photo from SINTEF's 80m x 50m Ocean Basin

Figure 1 shows SINTEF's Ocean Basin Laboratory with a total area of 80x50 m^2 and usable area 50x50m^2, and a total depth of 10m. Figure 2 shows a photo of the basin with a typical offshore structure. An adjustable steel floor can be moved vertically to model different water depths from 0 to 8.7m. The floor covers an area of 42x48m of the basin. The basin is fitted with two sets of wave makers. Along one of the short ends of the basin, a double flap, hydraulically operated unit capable of generating long crested irregular as well as regular waves (BM2), is situated. The maximum wave height that can be generated using this wave maker is 0.9 m for regular waves. For irregular waves, the maximum significant wave height is 0.5 m. Along the 80 m side of the basin, a multi-flap unit consisting of altogether 144 individually controlled flaps (BM3) is arranged for the generating of short crested as well as oblique long crested seas.

The Ocean Basin Laboratory has wave absorption beaches (parabolic profiles, rigid and impermeable) along both the short and the long basin sides, which reduce the problems of wave reflections to a minimum. For the Ocean Basin laboratory, the wave reflection is less than 5 % (amplitude) of incoming waves. Due to the large basin area and the large total beach length, reflections from the models are normally negligible.

The current generating system is based on pumping water around the adjustable floor, with the space underneath the floor serving as a return channel for the current. The current direction is in-line with the waves generated by the double flap wave maker. The maximum current speed in the basin is approximately 0.20 m/s with the adjustable floor at depth 5 m and fluctuations with standard deviation of about 8-12 % of the mean current velocity. With the floor at a water depth of approximately 2 m, maximum current velocity is about 0.25 m/s. The standard deviation is about 5-10 % of the mean current velocity at this depth.

The vertical current profile in the basin has a triangular shape, a speed at the basin floor of about 20-30% of the surface speed. This profile is determined by the shape of the basin and the location of the jet nozzles. A specified current profile different from this can therefore generally not be modelled.

The wind generating system consists of a movable fan battery, blowing at the test set-up from any heading angle. Both constant and varying wind (gust spectrum), can be provided.

3.1.2 Wave reduction in the Ekofisk field (1985)

In a study for Norsk Hydro, a model test to investigate finite water depth wave refraction due to large submerged objects resting on the bottom was carried out [1]. The overall purpose was to find whether such a principle could be used to reduce waves in a local range, such as the Ekofisk field for which a subsidence was observed at that time. Eventually, such an installation of objects on the bottom was not chosen, and other mitigation actions were chosen instead, but nevertheless the study confirmed significant refraction effects and was very informative as an experimental observation of such effects. The wave field over a relatively large basin area was mapped by use of a linear array with many wave probes, which was successively located at various distances from the wave maker. The large wavemaker BM2 was used.

Resulting wave amplitudes for a given case in regular waves are shown in Figure 3, both without (calibrated) and with the model. Ideally, the calibrated waves should represent a homogeneous wave field in this case; in practice we observed that the amplitude variability was approximately around 5 – 10% over approximately 10m (width) x 20m (length) in the basin (model scale), with some deviations. Over a smaller area the variability is lower. This variability is believed to be representative also today. From a realistic point of view, such a level of variability over such an area is actually something that one should expect in a confined physical laboratory; it is in fact difficult to obtain much better. With such conditions, experience has shown that useful model testing is definitely possible. For the case with breakwater, a strongly modulated wave pattern is observed right above the bodies, while a reduced and mildly refracted wave field was observed behind them.

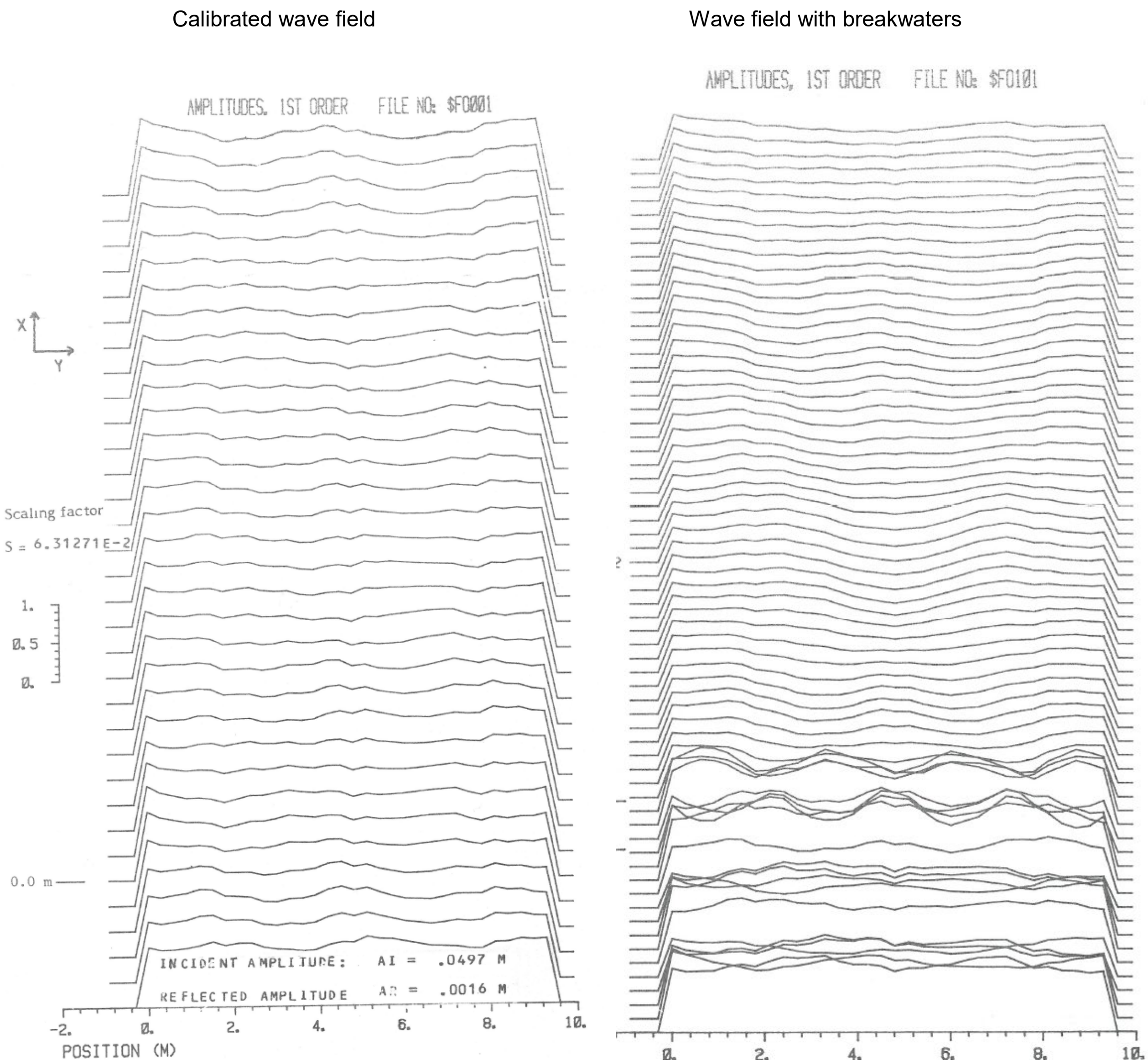


Figure 3: Model tests on wave reduction at Ekofisk using submerged breakwaters [1].

3.1.3 Floating breakwaters (1986)

MARINTEK performed a series of model tests with various box-type floating breakwaters, for CERC (USArmy) [2] and Det Norske Kystverket [3]; see also PIANC (1990) [4], VLFS (1996) [5]. Altogether four breakwater versions were tested: Two stiff body versions (long and short versions), and two with fendered, shorter boxes hinged to each other (long and short versions). The mooring lines were crossing underneath the breakwaters (see Figure 4 and Figure 5), with fairleads on opposite sides. All wave conditions were run with the multiflap wavemaker BM3 located on one of the long sides of the basin; mostly with short crested irregular waves but also some waves with long crested irregular and regular waves. The moored model was installed parallel to BM3, at a distance of 15m (model scale). The model scale was 1:10.

Measurements included wave elevation at a number of positions in front of and behind the breakwater, breakwater motions for one / two bodies, mooring line tensions, and pressures on the hull. Structural loads in the hull structure were not measured. The calibrated wave field was found to be reasonably homogeneous over the actual area (about 6m x 4.5m), with similar or slightly higher variability than for the BM2 waves above. The results were very helpful in the demonstration and understanding of major mechanisms for the actual concept, such as the significance of roll motions, and of slowly varying wave drift forces which led to the events with the largest mooring line forces, where snap forces could also occur. They also form a valuable data base for numerical studies.

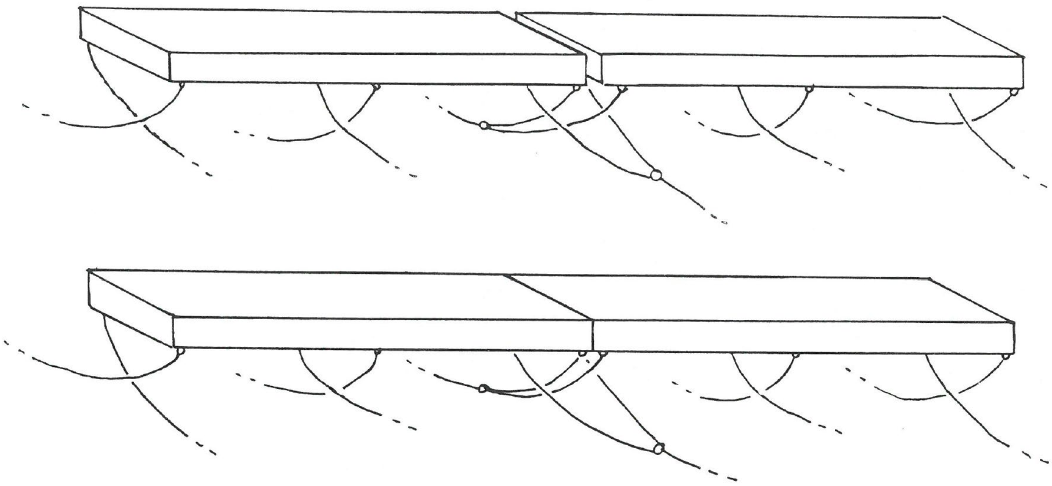


Figure 4: Sketch of moored breakwaters (from [2]): Fendered (upper) and stiff (lower)

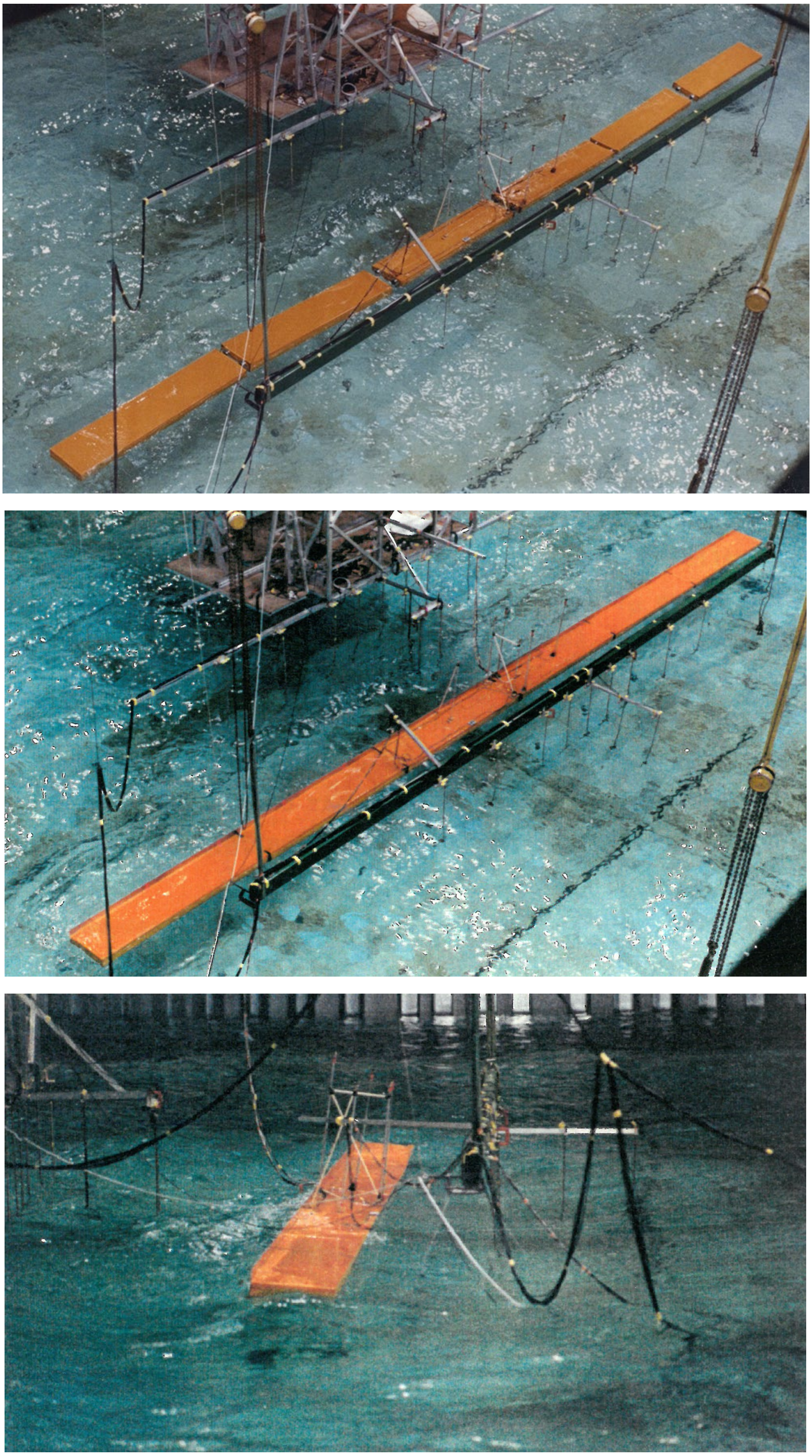
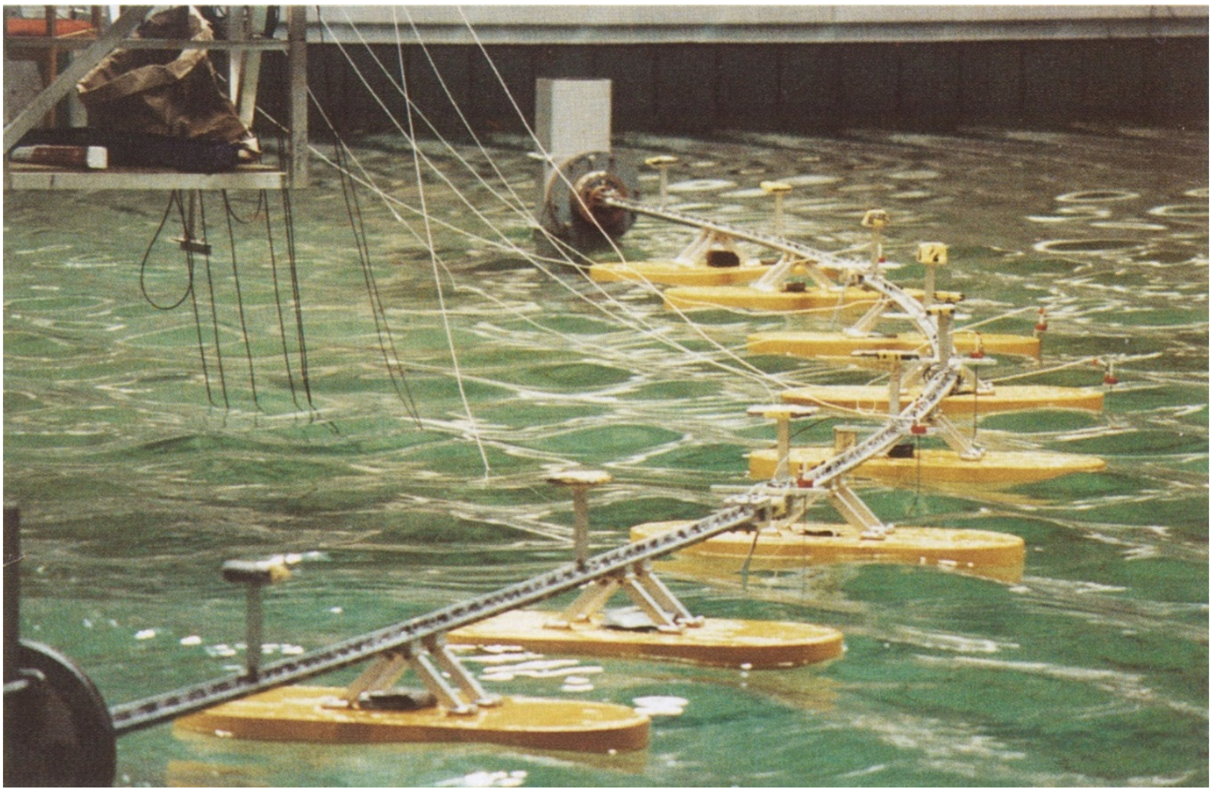


Figure 5: Model tests with long floating breakwaters – fendered (upper) and stiff versions.

3.1.4 Floating bridge and submerged tube tunnel experiments (1989-90)



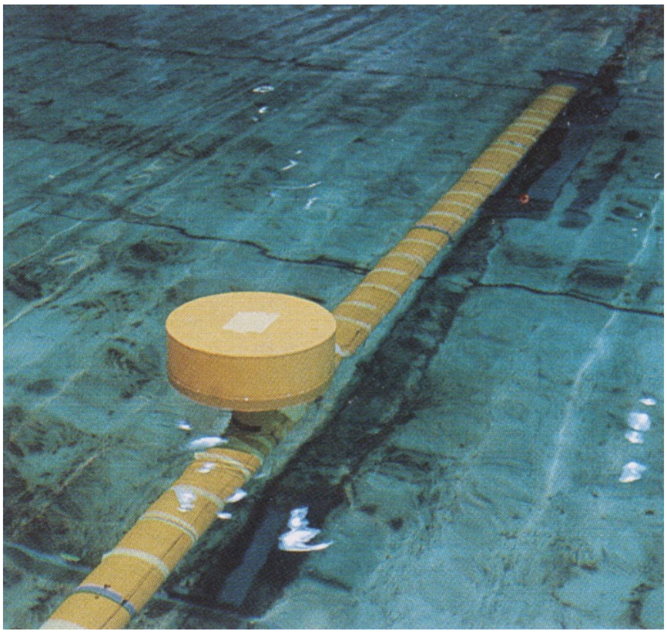


Figure 6: Photos from tests with pontoon type floating bridge (upper) and submerged tube tunnel (lower)

An extensive programme including testing of two floating bridge concepts and one tube tunnel concept was carried out in the Ocean Basin for Vegdirektoratet (see Figure 6). In the following a pontoon bridge experiment [6] is reviewed in some detail, in order illustrate how the Ocean basin can be used for the purpose of testing floating pontoon bridges.

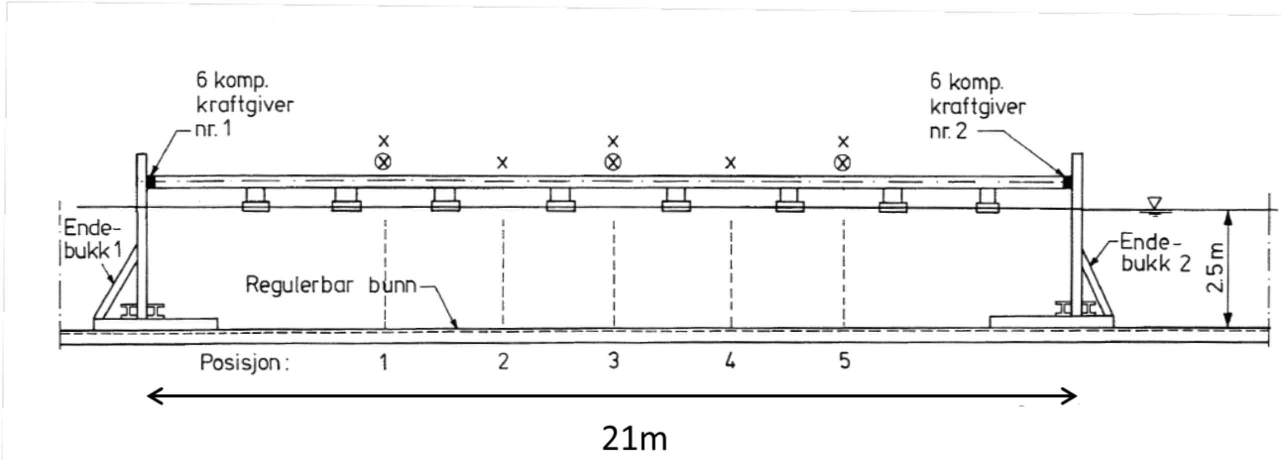


Figure 7: Side view of the pontoon bridge tested in [6].

The model tests with structural properties close to what was installed at Bergsøysundet were carried out in 1989. The bridge model was not truncated and represented a complete curved pontoon bridge. Figure 7 shows a sketch of the model. The length of the bridge model was 21.12m long and the scale of the model test was 40. The bending stiffness of the arc was modelled correctly using a cross section shaped like a pluss (+). This cross section also provided approximately correct torsional stiffness. Aluminium was used for modelling of the arc. The bridge was built as 4 separate sections which were connected with force transducers in order to measure the cross-section forces. The four sections were assembled in the basin. The ends of the bridge were connected to "rigid" frames which was welded onto the bottom. The connection between the frames and the bridge was pin-pin. A special type of connection was used which fixated the model from axial motion and axial (arc-direction) rotation at the end points. All 6 components of the forces /moments at the ends were measured using force gauges.

Table 1: Table of irregular waves tested in 1989 pontoon bridge model tests.

Full scale		Model scale 1:40	
Hs	Tp	Hs	Tp
[m]	[s]	[m]	[s]
0.9	4.9	0.023	0.780
1.4	4.9	0.035	0.780
1.4	7.0	0.035	1.100

Table 1 show examples of the significant wave height and spectral peak period of the waves studied in the 1989 model tests. The irregular waves are typical storm conditions for quite sheltered fjord locations with significant wave height and spectral peak periods between 0.9 to 1.4 m and spectral peak periods between 4.9 and 7 s. It is interesting to compare these waves to the capacity limits of the wave makers in the Ocean basin.

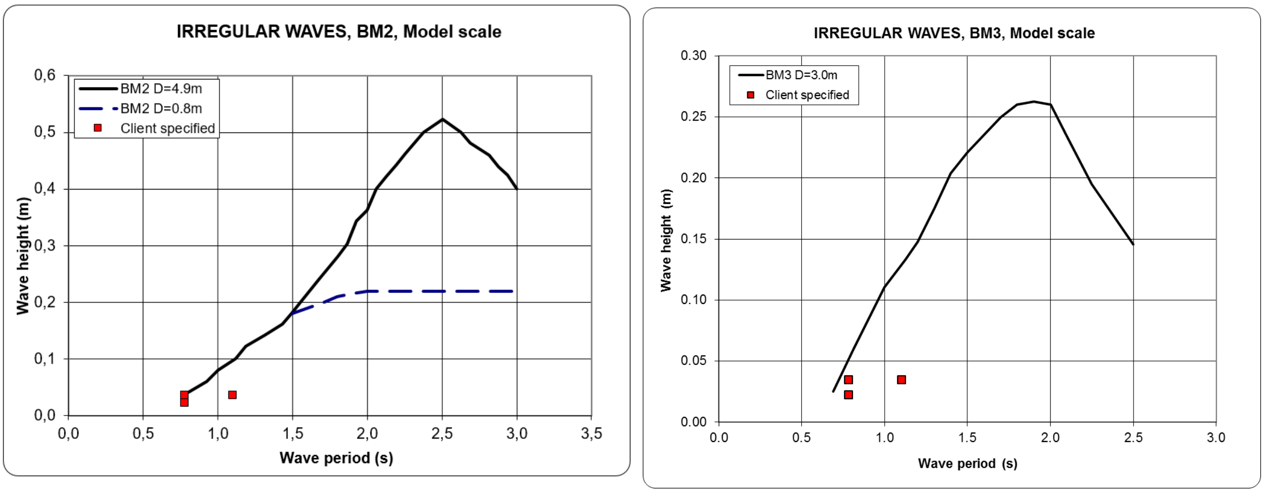


Figure 8 Significant wave height and peak period of fjord type waves compared to wave maker capacity curves at a scale of 1:40, based on tests in [1]. Left: BM2 wavemaker. Right: BM3 wavemaker.

The red dots in Figure 8 show the significant wave height and spectral peak period for some of the waves tested in 1989 [6] for the pontoon bridge model test. The black curve defines the capacity of the BM2 wave maker. The black line starts at 0.75 seconds which reflects the frequency limitation of the wave maker. From the plot it is concluded that the waves tested are close to the limit of the wave maker capacity for the chosen scale of 1:40. It should be noted that the significant wave height was about 25mm and that the accuracy of the wave gauges are usually +/- 1mm.

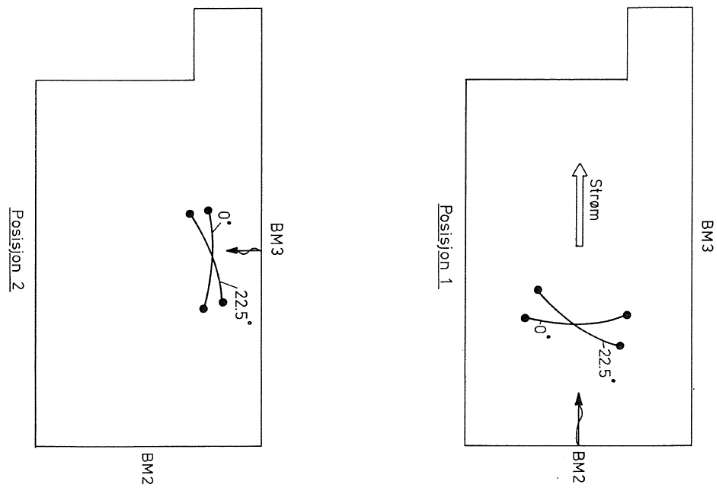


Figure 9: Location of the model during the model tests [1]: Left: The centre of the model was located 12.5 m from the BM3 wave maker during the short-crested wave tests. Right: The model was located 30.8m from the BM2 wave maker during the long-crested wave tests.

The left illustration in Figure 9 shows the location of the model during model tests from BM3. The model was located only 12.5m from the BM3 wave maker during the tests. This to ensure homogeneous short crested wave conditions. The right illustration shows the location of the model during the BM2 tests. This figure is a bit misleading, since the model was located in the middle of the basin, 30.8m from the BM2 wave maker. In order to minimize wave reflections between the model and the wave maker, the model was rotated to face the beach part of the basin.

3.1.5 NFR programme "Ekstreme forhold på sjøen", short-crested waves (1995).

Within a large research program "Ekstreme forhold på sjøen", financed by the Norwegian Research Council (NFR) [7], a minor task to study the coherence and decorrelation characteristics in short-crested linear numerical wave fields was carried out. The results are quite helpful in the interpretation of correlation lengths etc. in the wave field, for various degrees of short-crestedness. The final part of project also included a study on the encounter wave observation by a point moving in the wave field, simulating a (small) vessel with speed, while this part is probably not very relevant for the present project.

3.1.6 EU-LSF and Hydralab: Nonlinear wave studies over large areas (1999-2011)

Several experimental wave test campaigns partly financed by the EU have been carried out in the Ocean Basin in the period 1999 – 2011. One example is [8]. The projects were carried out by researchers from various European universities, in cooperation with technical staff and researchers from MARINTEK. Some funding also came from NFR and MARINTEK. The main focus has been on the spatial development of wave nonlinearities, and resulting changes in characteristics, in waves propagating over large areas. Both long-crested and short-crested waves were included. Valuable experiences have been accumulated, both for scientific understanding of physical processes and thereby leading to a number of journal publications, but also for practical knowledge when using the basin.

3.1.7 Model testing and wave modelling in shallow water (2000 – 2018)

Especially since 2000, several test campaigns of both commercial and research purpose have been performed with fixed and moored vessels in shallow water. Some of them include vessels and structures of considerable sizes, single or in multiple body set-ups, that can be relevant for the present scope. A typical example is shown in Figure 10. Furthermore, there are particular challenges connected with shallow-water laboratory wave generation, which need an even stronger focus on the spatial homogeneity as well as other aspects, and a part goal in many of these tests has been to study the spatial wave field over a large area. A related issue the presence and minimization of unwanted so-called "parasitic" long waves [9,10]. A significant amount of experiences and improvements has been accumulated in this field at SINTEF Ocean/MARINTEK as well as in several other offshore and coastal engineering laboratory facilities.

Since most of the wave conditions in Norwegian fjords represent deep or near-deep water depth conditions, many of the experiences from the tests mentioned above are probably not very relevant in the present LFCS project, for which the water depth is not very shallow. Still it is useful to be aware of them, and some are relevant in the project. One quite special shallow-water study is described below.

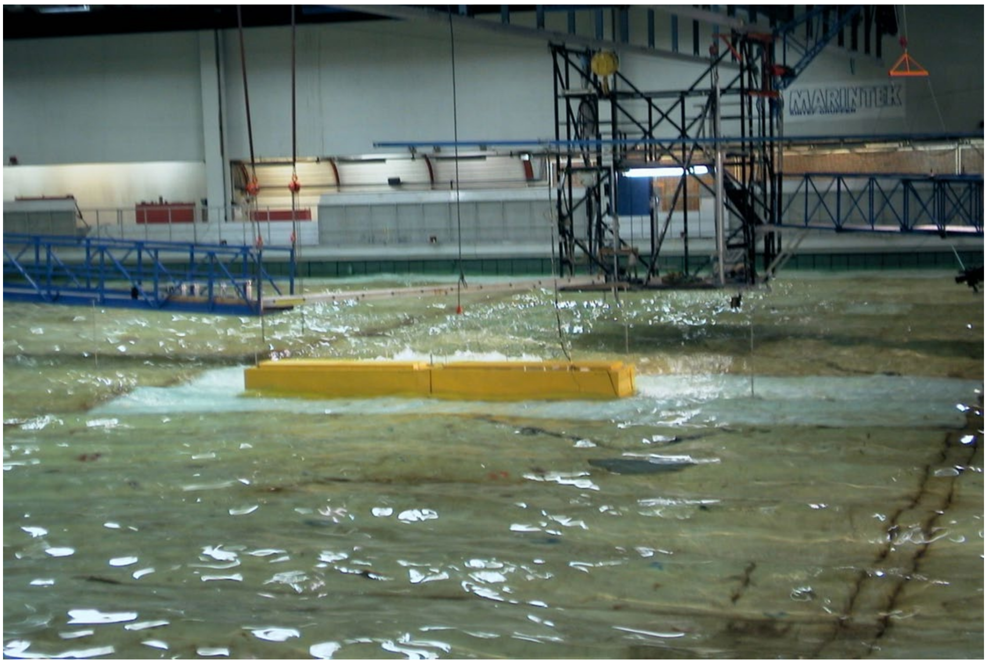


Figure 10: Testing of LNG terminal in shallow water (MARINTEK).

3.1.8 Snøhvit barge in-docking at Melkøya (2004)

The in-docking of a 154m x 54m large barge into its permanent position on Melkøya was modelled in the Ocean Basin [10]. The scale was chosen as large as 1:20; this was in order to obtain a sufficiently high accuracy on the modelling of the smallest wave conditions (≈ 1cm model scale), as well as on barge and dock geometry (clearances) and motion measurements. Hence the total model, including the dock model and a sloping topography around it in addition to the barge itself, covered a total area of around 15m x 15m in the basin. In addition to the challenges with accuracy around generation of small waves and motions, possible basin wave re-reflections due to the large model were also addressed. It was found that the resulting wave conditions were acceptable for this purpose; while these aspects need also to be further addressed in future testing with large models.

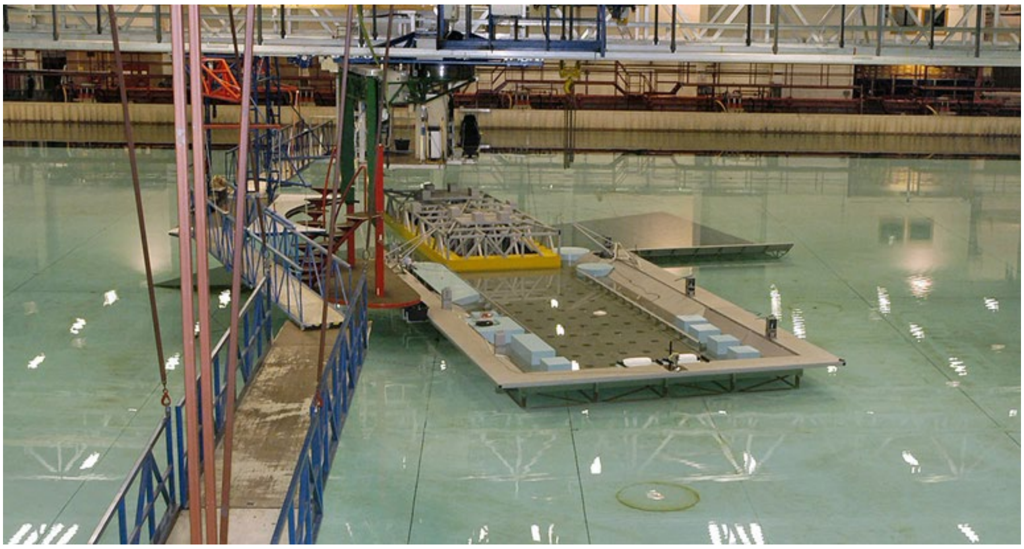


Figure 11: Snøhvit barge in-docking at Melkøya (2004)

3.1.9 Model Tests of floating bridge pontoons

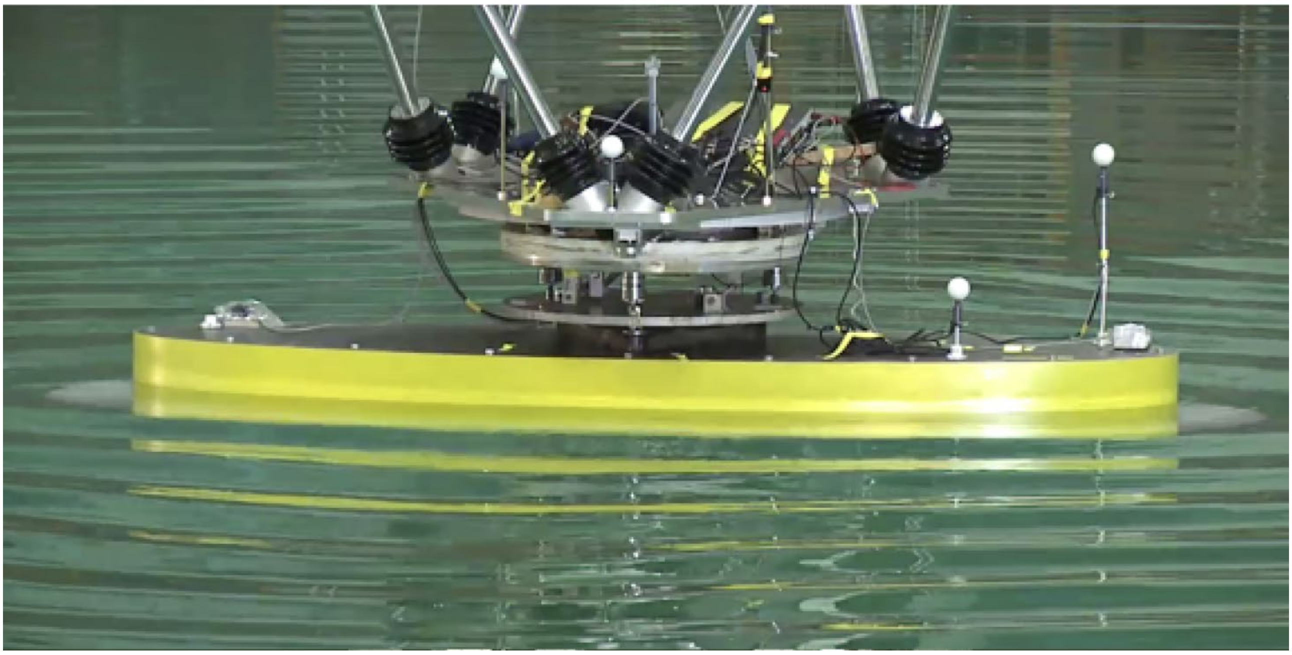


Figure 12: Model tests of pontoons at SINTEF ocean in 2017 [30]

Figure 12 shows forced oscillation tests of a pontoon relevant for large pontoon bridges. The model tests were carried out in SINTEF's large ocean basin in 2017. A total of 3 different types of pontoons were tested and compared with the computer code Wamit. Forced motion tests resulted in added mass and damping coefficients for 5 degrees of freedom. In addition, tests in waves with the pontoon fixed was carried out in order to measure the wave excitation forces. Added mass coefficients compared well with Wamit, but the damping coefficients were larger than the Wamit estimates.

3.2 Previous studies on VLFS

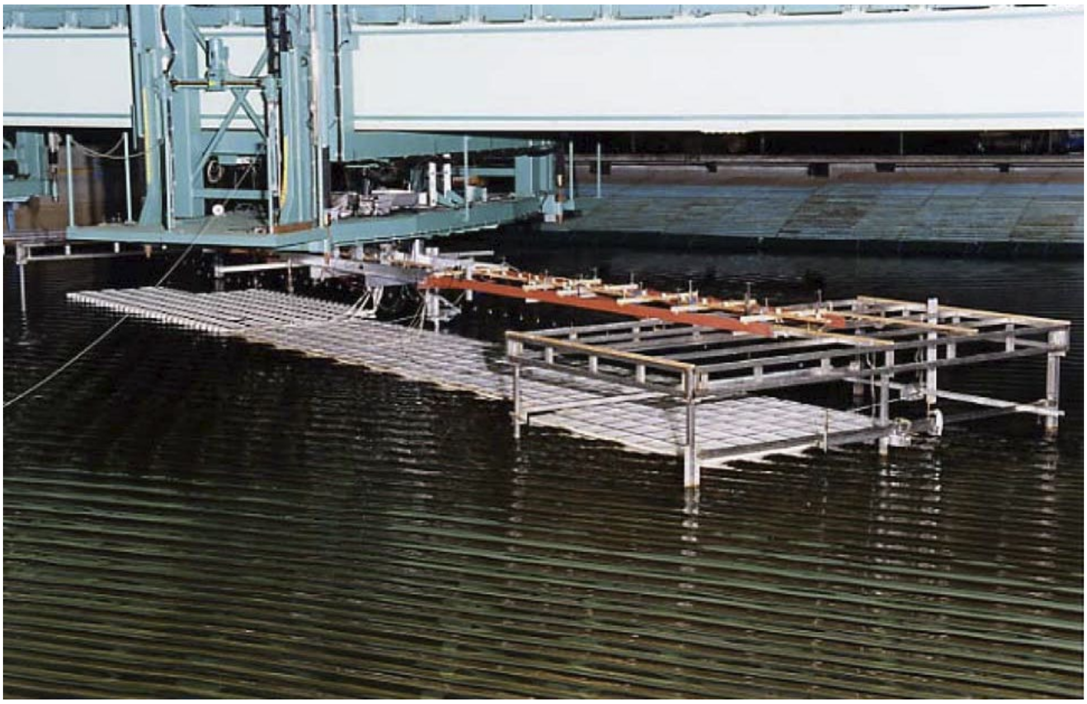


Figure 13: Model test of a floating air port tested at a scale of 1:200. Image taken fro Ohmatsu[11]

Ohmatsu [11] provides a good overview of the numerical and experimental work carried out on very large floating structures, specifically during the years 1995 to 2000 in Japan during the Mega-float project. The article is a review of numerical models, but also refers to model tests carried out for a floating airport concept. The airport studied was 3km long and was tested at a scale of 1:200 (See Figure 13). Details of this model test is only available in japanese.

Kagemoto et. al. [12] studied theoretically and experimentally a very large floating structure which could serve as an international airport. An international airport should be at least 5 km long and 1 km wide. A relevant height is 10m and relevant draft is 1m. The huge difference between the vertical and the horizontal dimensions represent challenges for model testing. Kagemoto's model was 2m long which, if geometrical scaling was adapted, implies a geometrical scaling factor of 2500. This means that the draft of the model would only be 0.4mm. Furthermore, relevant model scale waves would be very low at this scale. Kagemoto et. al. [11] solve this problem by deliberately breaking the scaling laws and performs model tests of a modified geometry in order to validate numerical calculations.

Song et. al. [13] performed model tests of a VLFS which was 1km long, approximately 60m wide, depth of 3m and a draft of 1m. The model tests were carried out in a scale of 1:100. The model tests were conducted at the Offshore Wave Basin, Shanghai JiaoTong University, China. This wave basin is 50m long, 30m wide with a depth of 6m. The objective of the model test was to study the effect of inhomogeneity caused by an uneven bottom. Different shoal geometries were set on the bottom of the wave basin. The tests were carried out in regular long crested waves, without wind and current. The water depth, incident wave angle and shoal shape was varied. The results are compared with a coupled and linear hydroelastic numerical model. The results show that the effect of the uneven bottom topography increase in shallow water.

Yoon et. al. [14] validated their numerical model of a multiply hinge connected VLFS with experiments carried out in a 15m x10m basin. The structure was 3m long, 0.6m wide with a thickness of 4cm and a draft of 11mm. The tested structure is a generic type which allows for validation of numerical modelling. The tests were carried out in regular long crested waves for different heading angles. No wind or current force effects were modelled. The mathematical model of the problem consisted of a finite element description of the structure and boundary element formulation for the water domain. Comparisons with the experimental results shows the effect of inserting hinges into the structure on the deflections of the VLFS. It is found that the maxium bending moment of the VLFS reduces when increasing the number of hinges on the structure.

3.3 Wave, current and wind field generation over large areas in a wave basin

3.3.1 Wave field generation

The generation of a homogeneous wave field over a large area in a confined basin can be challenging, since there are several disturbing factors. Most disturbing sources in a laboratory can to a large extent be considered linear (although some nonlinear effects are definitely present), such as reflections (from walls/beaches, also including re-reflections due to models), diffraction and refraction. Refraction is relevant if a finite water bottom is not perfectly flat and horizontal, and, if current is included, the current field is not perfectly homogeneous. Such effects can be laboratory defined (unwanted), or they can be modelling a real field (see below). In addition, there are other, nonlinear physical processes including various wavemaker induced effects such as parasitic waves (which are to a large extent laboratory defined) and nonlinear wave propagation defined effects, including dissipation (which are real physical processes also happening in the field).

It is also relevant to consider the generation of an inhomogeneous wave field by purpose, reproducing real field effects, if the environmental input specifies so. This is also a challenge and has not been much in focus earlier except for coastal engineering studies that include cases with the modelling of a coastal topography and variable bathymetry and resulting diffraction and refraction effects. Thus, a controlled generation of an inhomogeneous wave field by use of wavemakers, if relevant, needs thorough investigation. In any case, numerical wave basin modelling is very helpful in advance of experimental generation, as described below.

3.3.2 Numerical modelling of waves in a basin

Waves in model test basins can be modelled using different mathematical and numerical models. For the optimal modelling in a wave basin, it is of great help to establish a numerical reproduction and carry out studies to identify, analyze and improve challenging issues.

<u>Examples from numerical wave basin modelling studies</u>:

A numerical study on the spatial homogeneity of multidirectional waves in a wave basin was carried out by Miles et al. (1997) [15], from which selected results are shown in Figure 14. Four cases are shown: Two different directional spreadings (P1=wide spread, s=6, and Q1=narrow spread, s=40) with no beach reflection left) and an amplitude reflection coefficient C=0.20 (right). We observe that the effective homogeneous field is decreasing with the shortcrestedness. and that reflection adds to the inhomogeneity.

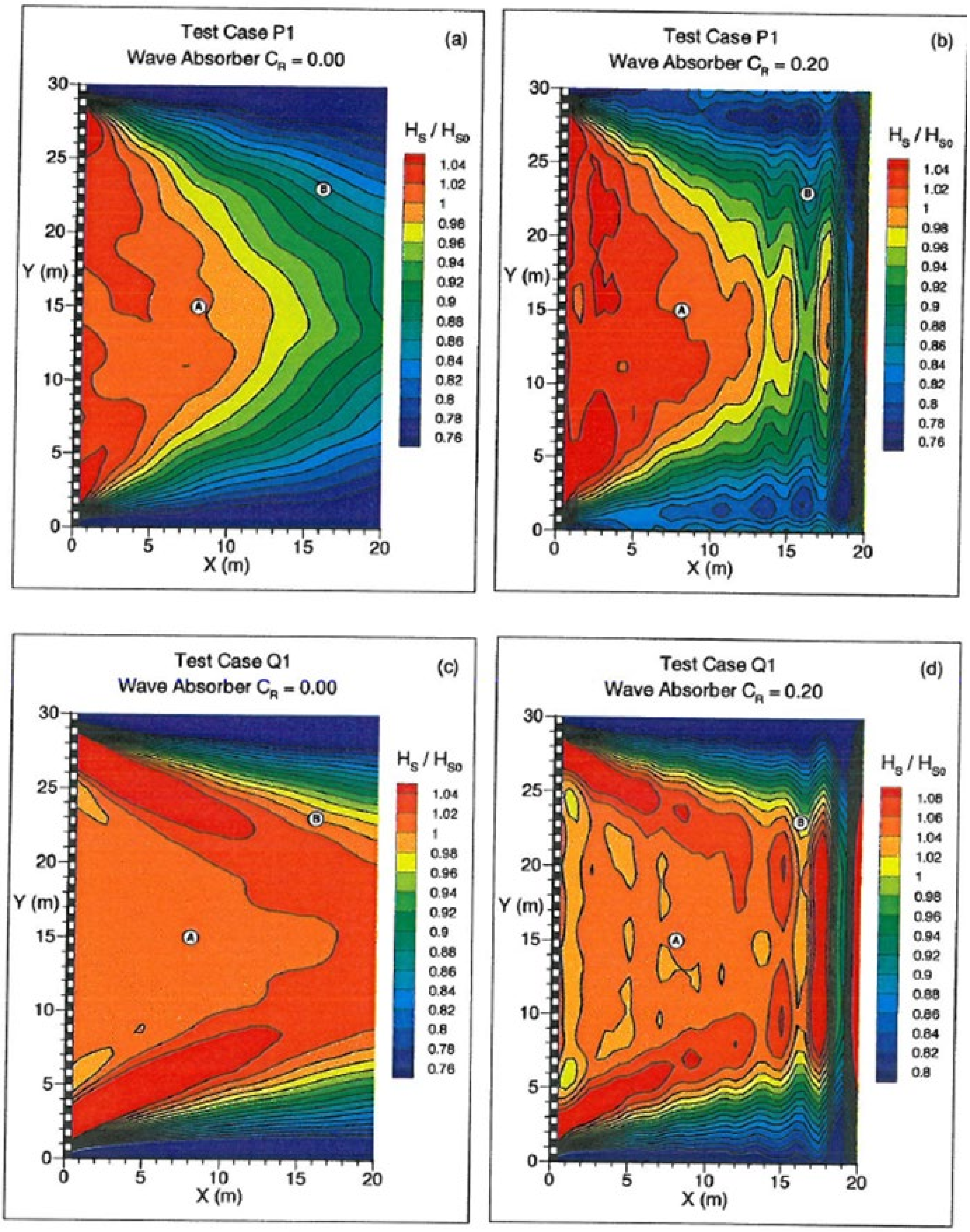


Figure 14: The plot shows how the significant wave height varies from the target wave height for two short crested sea states with different reflection properties for the numerical beaches.

Recently, numerical studies on a similar problem were carried out by O'Boyle et al. (2013, 2017) [16] [17]. See Figure 15 and Figure 16. Quite detailed observations can be made of the spatial structure pattern.

L. O'Boyle et al. Ocean Engineering 135 (2017) 158–169

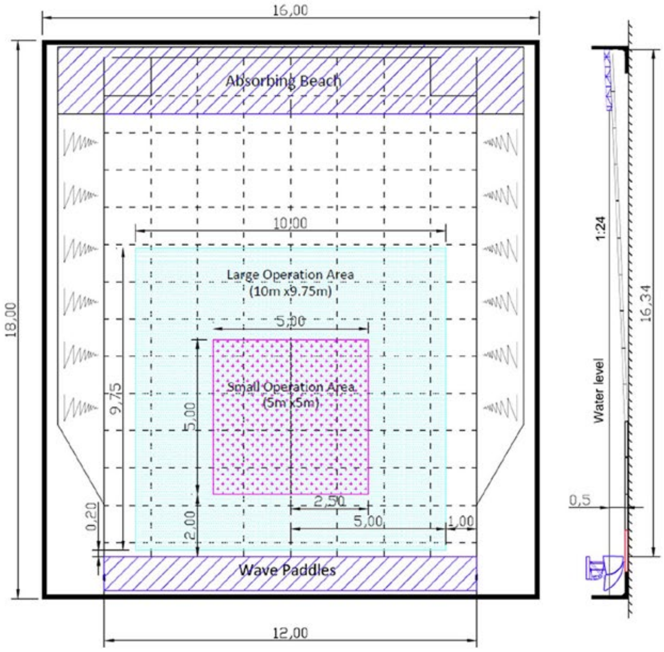


Fig. 1.1. : Layout and bathymetric profile of the original wave basin (2010) including the position of the large and small operation areas used for assessment of performance.

Figure 15: Basin geometry studied by by O'Boyle et al. (2013, 2017) [16] [17].

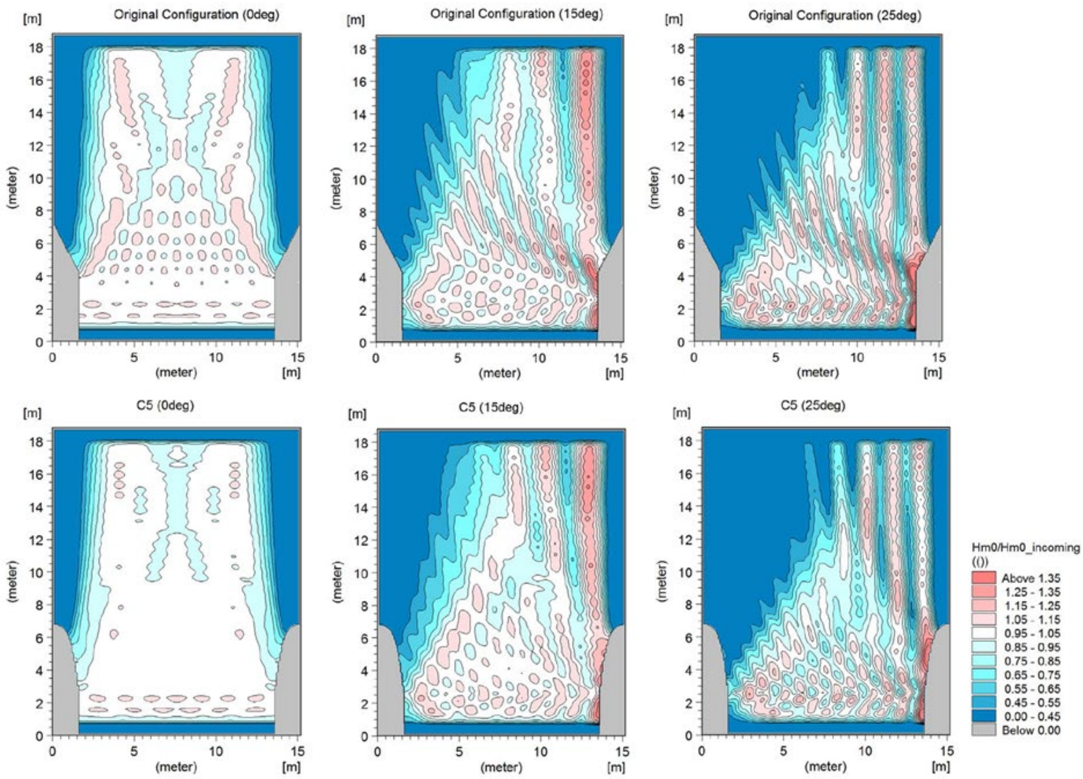


Fig. 2.3. : Comparison of wave disturbance in terms of significant wave height (H_{m0}) calculated for the original configuration and the new curved transition panels using the MIKE 21 BW model within the entire numerical model domain for incident waves of 1 s wave period, 12 mm amplitude and 0°, 15° and 25° angles of incidence.

Figure 16: Disturbance of the significant wave height from the study by O'Boyle et al. (2013, 2017) [16] [17].

In the recent decades, several tools and studies on nonlinear wave simulation methods have become available. An overview of such tools that can be relevant for wave basin modelling is given in the following Section.

3.3.3 Numerical modelling tools for wave, current and wind for model test purposes

In order to efficiently carry out ocean basin experiments it is relevant to model the wave, current and wind environment in the model test facility. A primary question related to the current project is how large part of the ocean basin which can covered by the model. Or stated differently, how are we able to control the wave, current and wind environment in the ocean basin?

Two broad categories of models are in use:

1) Potential flow models which assumes the water flow to be inviscid, incompressible and irrotational.

2) Computational fluid mechanics (CFD) methods where the full Navier-Stokes equations are solved with or without viscosity.

In this report it is considered not relevant to describe all possible methods. The following presentation is biased towards methods that are relevant for the current project. A subset of these methods, which are relevant for modelling wave conditions in model test basins will be described in this review.

<u>BEM</u>

A flexible and reliable mathematical representation of a model test basin can be achieved with the boundary element method (BEM), see for instance [18]. This method relies on the Green's functions which exist for Laplace equation. This means that only the surfaces of the domain need to be discretized. Furthermore, if the free surface is linearized, extensions to the Greens function exist which means that free surface does not need to be discretized. This leads to large savings in number of unknows. The method leads to dense matrix systems which are more demanding than the sparse matrix systems which results from standard CFD methods. The waves in SINTEF's Ocean basin can be modelled with the boundary element method. It is also fairly easy to add a geometry in the computational domain. This could be a pontoon bridge model or sea bottom topography.

<u>HOS</u>

The higher order spectral method is a potential flow method which solves Laplace's equation in the water domain by expressing the solution as sum of products of time (t) and space (x,y) dependent functions. Examples of implementations of the methods can be found in [19] and [20]. The spatial modal functions contain the analytical solutions for linear gravity waves above a horizontal bottom. The method can be used in 2D and 3D, and it is possible to solve the second and third order problem for the free surface condition. The method is not computationally demanding and can be used to simulate three hour irregular seas. However, the method is based on an expansion of the free surface conditions assuming that the wave steepness is small. In steeper sea states the method become unstable. This problem can be partially avoided by regularization strategies. It is also not easy to insert a body into the water domain. It is also hard account for the variation of the sea bottom topography.

<u>CFD</u>

Computational fluid dynamics (CFD) methods is a class of methods which solves the Navier-Stokes equations with or without viscosity. We do not try to describe all different types of CFD methods in this report. A relevant code for CFD calculations of complex marine structures is the commercially available

StarCCM+ which numerical background is described in [21]. In general, these type of methods are more computer demanding than the potential flow models. They also need to discretize the whole fluid volume which means that more unknowns are needed to describe the solution, which leads to larger equation systems than what is the case for the potential flow methods. The physics of breaking waves can in principle be handled using these methods. However, this type of physics is hard to capture accurately and there might be challenges related to convergence and stability for this type of physics. This means that three hour simulations of a numerical wave tank with steep sea states is challenging.

3.3.4 Short crested vs. long crested wave fields

Linear simulation of wave fields for large floating structures were addressed in several numerical studies around 30 – 40 years ago; a few examples are given in [22, 23, 24]. Similar wave models are also applied in recent studies, such as [25]. The significant influence from short crested wave characteristics and the resulting spatial coherence to the structural response is emphasized in most of these studies. It will be essential to include short crested wave generation in the model tests, i.e. the use of a multi-flap wavemaker. This requirement may in practice introduce restrictions with respect to the relative directions between current and waves. In the SINTEF Ocean Basin, for example, the multi-flap wavemaker BM3 generates waves in the direction perpendicular to the current direction (plus/minus 40 degrees), while the large long crested wavemaker generates only waves collinear with the current. The generation of short-crested waves also impose additional restrictions with respect to the spatial homogeneity (see above).

4 Model test data interpretation (system identification / data processing)

In order to identify different properties of the model, specialized test procedures are carried out and followed by specialized analysis methods. One of the simpler of these procedures are decay tests where the model is excited in different degrees of freedom. The measurements are then analyzed in order to obtain the natural periods and damping of the system. A second example is the identification of response amplitude operators or transfer functions through cross-spectral analysis. In this case, it is common practice to impose wave from a broad band spectrum of constant amplitude on the model and obtain RAO's which can be compared with numerical calculations.

The motions of moored floating structures may experience considerable excitation due to second order wave forces. This may take the form of slowly varying motions with large amplitude at a frequency equal to the natural frequency of the system. The forces causing this type of motions can be estimated through different types of identification procedures.

5 Challenges, limitations and mitigation with respect to model testing of LFCS

Model tests will be used to reduce uncertainties of numerical modelling of floating pontoon bridges. One model test with a pontoon bridge will take place in SINTEF Ocean's large ocean basin. Although the details of the purpose of these model tests are not clear, it is already envisaged that a large bridge model will be tested. These ultra large structures cause new challenges related to model testing which is covered by this review. Due to the length of long floating bridge, only a section of the bridge can be tested in the ocean basin. In order to design the bridge model, it is needed to study how the bridge should be truncated. This concerns which section of the bridge to model, and how to impose end conditions on the bridge in order to imitate the most important part of the full scale bridge behaviour.

Even with a truncated model, the model will cover a larger part of the ocean basin than what is usually used. This pose challenges related to wave, wind and current generation. When the model covers a larger part of the ocean basin, it is a question how well the waves can be calibrated inside a larger area of the ocean basin, Large models, may also induce larger reflections which cause unwanted waves going back and forth between the wave maker and the model. A relevant topic for review is the modelling of local bottom topography, which may be relevant depending on the final scope of the model tests. Wind loads are often modelled using fans in the ocean basin. Hybrid testing of wind is an alternative which should be covered in this review.

5.1 Actual environmental conditions

- For homogeneous wave conditions a relevant option is to use standard parametric wave spectra.
- For inhomogeneous wave conditions the input for the wave modelling will likely be results from SWAN analysis, generating numerical directional frequency spectra in a spatial grid. The actual wave basin modelling will be using either equivalent parametric or numerically generated spectra
- Wave periods typically between 5s and 10s and wave heights around 1m – 2m
- Wave short-crestedness: In any case some tests should be done in long-crested waves, while short-crested waves should also be included. The latter leads to reduced spatial correlations in the wave field, which can be important for a large structure.
- Current and wind should also be included. Include also some tests in waves only, current only, waves+current only, and wind only. Wind modelling by use of hybrid methods must be considered. The actual relative direction between current and waves can be important, while this will meet limitations in a wave basin and needs to be addressed.
- Controlled spatially inhomogeneous conditions: It is known that the waves, currents and winds can vary significantly over a large coastal area, both in magnitudes and directions.
- The scenario addressed in this project does include “moderate” finite water depth from a wave hydrodynamics point of view. However, it does not include very shallow conditions, so particular nonlinear shallow water effects do not need to be addressed except if/when local bathymetri requires it.
- Challenge: Wave influence on wind and vice versa? Without and with structure. Literature? New wind experiments?
-

5.2 Size and scale of physical model

A floating bridge can be typically of length 2km - 4km. This represents significant challenges with respect to laboratory modelling. In a 50m x 80m wave basin, one would try to avoid models larger than 15m – 25m model scale, to avoid large re-reflections between the model and the wavemaker (see below), and for optimal control of the spatial homogeneity. For full modelling of the longest bridges a scale of 1:100 – 1:150 would then be needed. However, the actual mild wave conditions (see above) lead to optimal scales larger than around 1:50 due to the wavemaker characteristics. A lowest scale of around 1:80 might be a compromise choice. It will also be relevant to consider testing with a truncated model, e.g. corresponding to a length of up to 1km, still long enough to represent the essential characteristics of a “large structure”. The choice of model size and scale is going to be a compromise between wave quality, the importance of modelling wind in the model test and the importance of testing a long flexible bridge.

5.3 Generation of spatially homogeneous and inhomogeneous environment in a wave basin

A. Minimizing unwanted spatial inhomogeneity: It is an aim to be able to generate spatially homogeneous conditions over a relevant area in the basin. Usually, for testing of stationary (moored and fixed) models the focus has been on the central basin area, typically within 4m x 4m within which the variations should be < 3 - 5%. For larger areas such as in the present cases, there will inevitably be some spatial variations, especially due to wave diffraction from the basin boundary geometry and spatial variations in the current and wind fields. For the wind one may improve this by use of hybrid testing. Spatial variations in the current will affect the waves by refraction. Similarly, unwanted bottom refraction effects due to small bottom imperfections can also occur in rather shallow water, while this may not be a problem in the present case. Furthermore, there are special area challenges for the generation of short-crested waves, limiting the useful homogeneous area as a natural result of the finite length of the wavemaker. For the model tests it may be necessary to accept some basin induced wave inhomogeneity in order to increase the size of the model as much as possible.

B. Controlled modelling of spatial inhomogeneity: Up to now such modelling has usually not been included in model testing with ships and offshore structures. Possible methods to, and limitations in, generating such conditions in a wave basin need to be addressed. For waves, this can to some extent be obtained by use of tailor-made input signals to the individual units in the multi flap wavemaker. The spatial input at the target locations will likely come from a SWAN analysis or similar analysis.

The actual need to include such modelling or not will depend on the actual fjord case and the size of the model (or part of model). A numerical sensitivity check would be helpful in this before the planning of the tests.

5.4 Local coastline and bathymetry

The need to model parts (major features) of the local topography will have to be considered. For this type of tests, such modelling, if needed, will probably be a simplified version that reproduces essential items for the resulting loads on the structure. Including such items will also generally by itself lead to spatial inhomogeneous conditions.

5.5 Wave basin reflections

With the large basin area of 50m x 80m, and the relatively good wave absorbers, unwanted wave reflections have usually not been a large problem when testing ships and offshore structures in SINTEF's Ocean Basin. With larger models, however, re-reflections between the model and the wavemaker may become a challenge (note that the model reflections themselves are of course an integrated part of the real problem to be investigated). Such effects must in any case be investigated and documented in the project, and can then be taken into account in the final evaluation of results. Ideally, the best options would be to minimize re-reflections if possible. There do exist advanced wavemaker methods to reduce this effect, but it has not yet been found necessary to implement it in the Ocean Basin. It is not a straightforward issue and needs some efforts to be installed; however, whether or not it is possible to be included in this project should be addressed.

5.6 Wind force modelling in the ocean basin

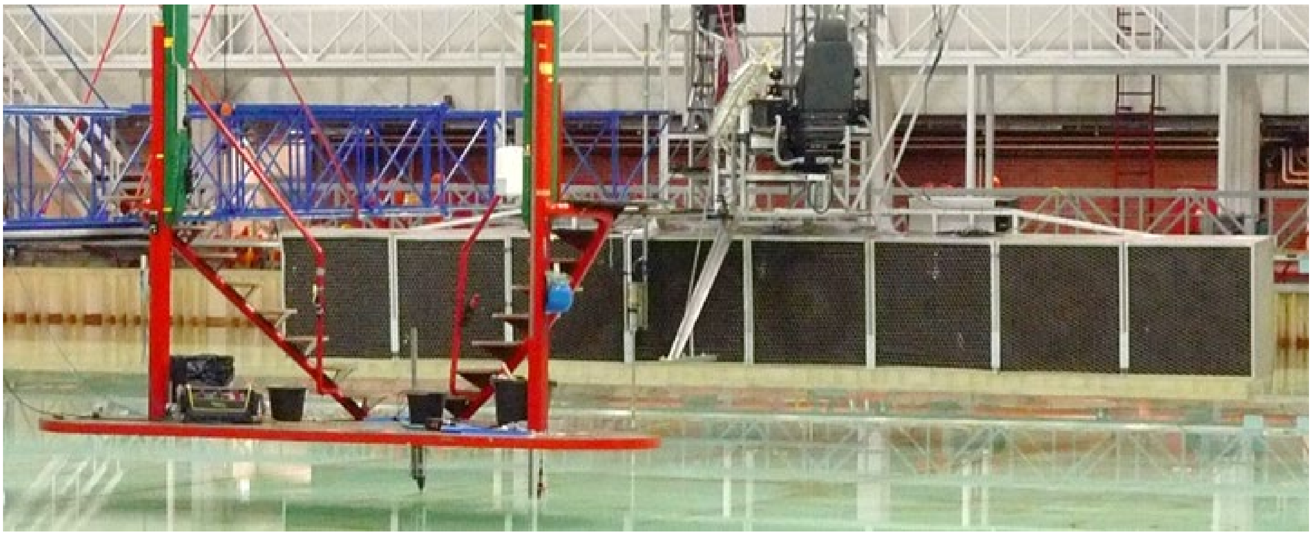


Figure 17: The standard wind battery of the ocean basin.

The effect of wind on the models in the ocean basin can be applied in different ways. For standard models which are not too big (<6m) it is customary to insert a wind battery in front of the model. The wind fans are computer operated and is usually calibrated in order to obtain the correct wind conditions at a point near the model. This could be (nearly) constant wind conditions or wind gusts as specified by a wind spectrum. The wind is usually calibrated at a point close to the expected centre of the wind force. The wind velocity is usually calibrated without water above the movable bottom with a wind speed gauge located at the calibration point.

The wind field obtained by these fans are not as accurate as the wind field in wind tunnels. It is hence, generally advised to carry out separate wind tunnel tests in order to obtain wind force coefficients. If these type of wind data is available prior to execution of basin tests, it is standard practice to modify the wind field or model wind geometry in order to obtain more accurate wind forces. This extra wind force calibration is performed with the model floating in the basin. Even with accurate wind data from wind tunnel tests, these force coefficients do not take into account the modification of the wind field due to waves. The modification of the wind field due to waves depends on the height of the waves compared to the height of the model.

A challenge of using wind batteries for long pontoon bridge models is that many wind fans needs to be installed in order cover the whole model.

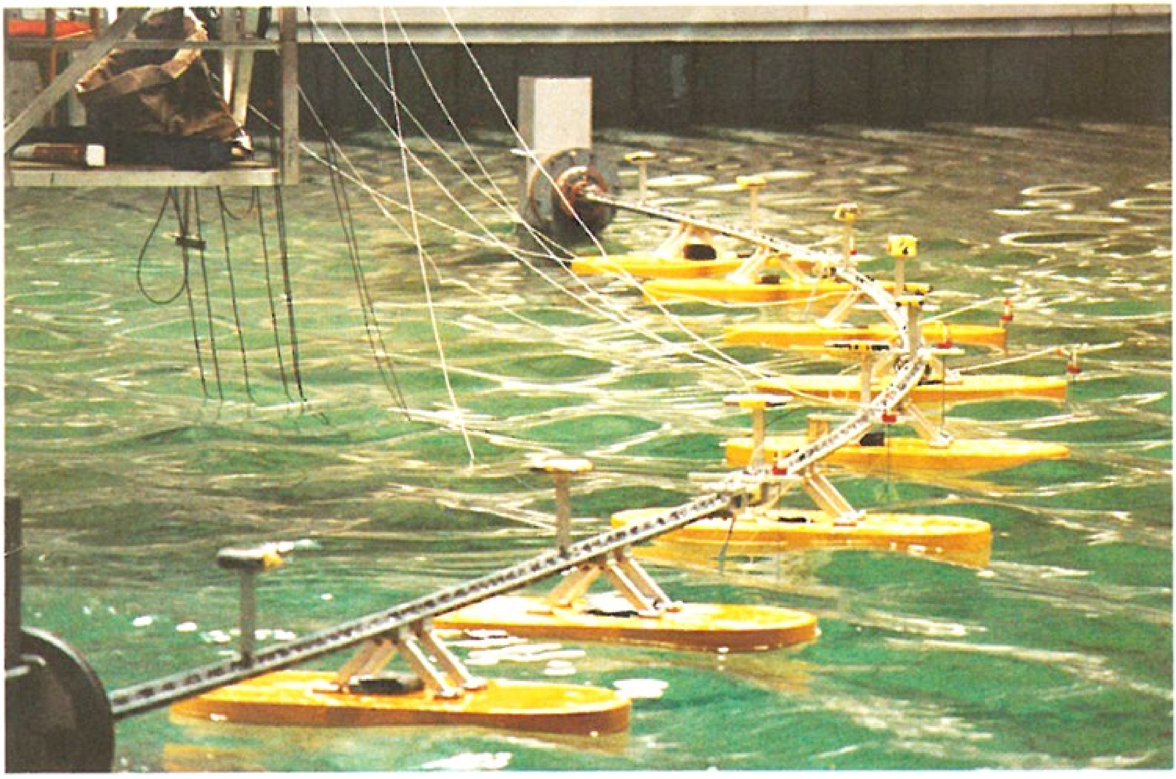


Figure 18: Wind force simulated using wind fans attached to the bridge model.

A second option is to set small wind fans on the model and run the fans at the speed necessary to obtain the target wind force on the model. Figure 18 shows a pontoon bridge model including wind fans on the model in the ocean basin. One challenge with using wind fans on the model is that the wind force will be applied at the point corresponding to the centre of the fan. This might in general be different from the location of the wind force in real wind condition.

A third wind option is to attach lines to the model and apply a force on the line. In the simplest case this force can be applied with a mass hanging over a wheel and varying the force by varying the hanging mass. A more sophisticated method is to operate the force using winches which is set to apply a prespecified force time series. The most sophisticated option is to operate the winches according to the aerodynamical loads from a numerical model which depend on the actual model motions in real time. This principle is denoted "Real-time hybrid model testing" and is developed for the model testing of floating wind turbines [27]. The great advantage of this technique is that it solves the general scaling problem when applying physical wind in a Froude scaled model experiment. A consistent scaling of the wind force according to Froude scaling will lead to very low Reynold's number which depending on the body tested, may lead to wrong aerodynamic forces.

5.7 Current modelling in the ocean basin

The current in the basin is usually calibrated at one point in the centre of the basin where the model is most often located. The mean current speed is usually calibrated to fit a certain specification. The time series of the current speed shows oscillations due to turbulence. These fluctuations depend on the submergence of the adjustable floor. In general, there are variations of the current depending on location in the basin. It is not possible to control and calibrate the current at several locations in the basin.

6 Alternatives for floating pontoon bridge model tests in the ocean basin

Long pontoon bridges may be built in both straight and curved versions, hence model testing of both versions is relevant. For the curved bridge, global buckling may be an important failure mode. It will be hard to model this failure mode with a truncated model. The model test scope is not settled in due time before the writing of this document, but it is still useful to describe different scenarios for the model testing. The suggestions given in this chapter describes a standard model test, which is aimed to be improved through the suggested work in the following section.

6.1 Possible objectives of the model tests

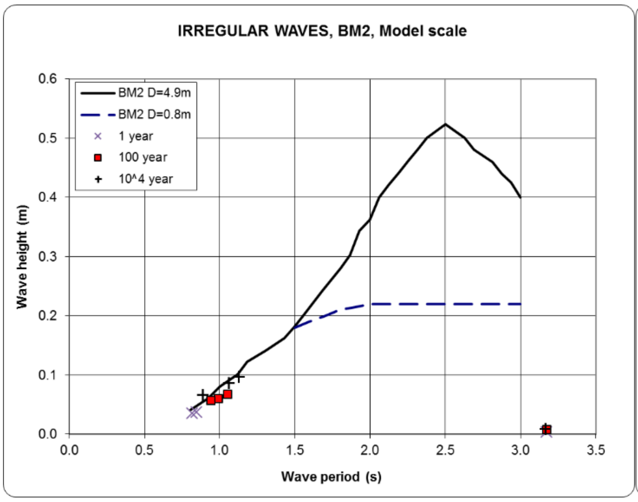
SINTEF's Ocean basin is suited for testing the hydrodynamic performance of long pontoon bridges. The bridge generally deforms due to the action of waves, current and wind. A primary objective of the model test is to obtain the model test data which reduce the uncertainty of the numerical models. The numerical models can be improved by adjusting them to fit to experimental measurements. A thorough definition of the focus areas of the model tests needs to be decided together with the other work packages. The review from WP2 shows that wave-current and the effect of multi-body interaction are relevant. WP1 shows that the spatial inhomogeneity is relevant. It is also relevant to study if waves will flood the pontoons during design weather conditions. The distance from the mean free surface to the top of the pontoon is 3.5m (Phase 3).

6.2 Relevant wave, current and wind conditions for fjord type locations

Clues of what may be relevant wave conditions for very long pontoon bridges can be found from [28] for Bjørnafjorden. This report describes relevant 1 year, 100 year and 10^4 year conditions. The weather conditions are listed in Table 10-1 page 58 in [28]. The waves and current directions for the weather combinations suggested in [28] are almost collinear. In the ocean basin the current can be generated in the direction of the waves generated by BM2, only. The BM3 wavemaker can generate long crested waves at an angle of 50 to 55 degrees relative to the current direction. The significant wave height and spectral peak period combinations in [28] are listed in Table 2. The table assumes a scaling factor of 40.

Table 2: Relevant design storm conditions for the Bjørnafjorden location according to [28]. Wave wind and current directions are aligned in order to fit for model testing

Scale: 40	Full scale				Model scale			
	Wave		current	wind	Wave		current	wind
Wave conditions	**Hs** [m]	**Tp** [s]	**Uc** [m/s]	**U** [m/s]	**Hs** [m]	**Tp** [s]	**Uc** [m/s]	**U** [m/s]
1 year case 1	1.6	5.3	1	18.3	0.040	0.84	0.16	2.89
1 year case 2	1.5	5.1	1	21.5	0.038	0.81	0.16	3.40
1 year swell case 2	0.26	20			0.007	3.16		
100 year case 1,2	2.8	6.6	1.4	25.1	0.070	1.04	0.22	3.97
100 year case 3	2.5	6.2	1.4	29.5	0.063	0.98	0.22	4.66
100 year case 4	2.4	5.9	1.4	29.5	0.060	0.93	0.22	4.66
100 year case 3,4 Swell	0.4	20			0.010	3.16		
10^4 year case 1 and 2	3.9	7.1	1.4	25.1	0.10	1.12	0.22	3.97
10^4 year case 3	3.5	6.7	1.4	29.5	0.09	1.06	0.22	4.66
10^4 year case 4	2.7	5.6	1.4	29.5	0.07	0.89	0.22	4.66
10^4 year case 3,4 swell	0.4	20			0.01	3.16		



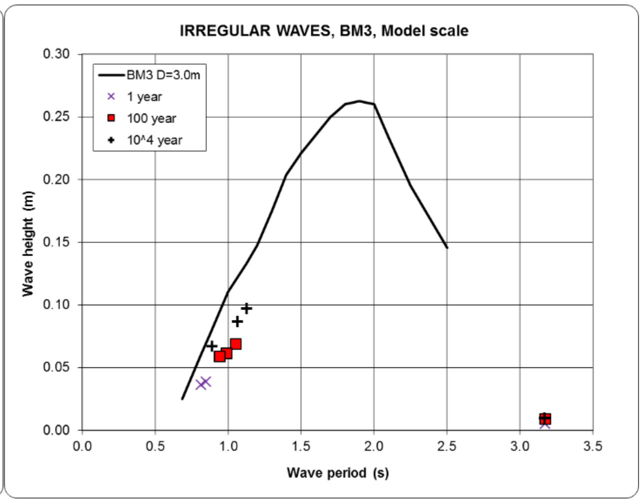


Figure 19: The critical storm waves reported in [28] compared with the capacity curve for the ocean basin for a scaling factor of 40.

It is relevant to study if these waves can be generated by the wave makers in the ocean basin. Figure 19 shows a comparison of the storm wave conditions with the capacity curves for the double flap wave maker BM2 and the multi-flap wavemaker BM3. The significant wave height and spectral peak period combinations falling below the capacity curve (black line) can be realized by the wave makers. The left plot shows that the steep wind generated sea states are at the limit of the generation capacity of BM2. The limit is due to wave breaking and the frequency limit of the wave maker. The waves defined in [27] consists of both swell and wind sea. The swell components fall on the other side of the plot due to the long period of these waves. If a larger scaling factor than 40 is chosen, these waves could be generated, however the wind generated sea would be harder to generate. The right plot shows the storm sea states defined in [27] when inserted in the capacity curve for BM3. The high frequency component of the waves falls nicely inside the capacity curve, while it is not possible to generate the swell waves. Both plots assume a scaling factor of 40.

Table 2 shows that wind and current speeds for 100- year return periods are of similar magnitude as offshore the Norwegian coast. However, the wave height is much smaller. From this it is expected that wind forces are important. In addition, the hydrodynamical forces is expected to have stronger influence from the current than what is usual offshore. The mean drift forces can be expected to be less important than offshore but the influence of current on the mean drift forces is bigger than offshore. From [29] page 146 the second order mean wave force is roughly 30 % higher in the case of current of 1.4m/s than without current. The calculation assumes a period of the waves of 6s.

6.3 Suggestions for the test program

It is relevant to test a section of the bridge in different environmental conditions. In order to validate numerical models it is customary to carry out a sequence of tests from simple to complex, order to study and validate different aspects of the numerical model before comparing it with complex response in realistic weather conditions.

It is suggested to do:

1) Decay tests in order to document natural periods and damping of the system.
2) Pullout tests in different directions in order to document the restoring force from the mooring system.
3) Pink noise tests or tests in regular waves in long crested waves, in order to obtain transfer functions for different interesting response parameters like displacements and bending moments.
4) Irregular wave tests in longcrested waves with and without current.
5) Irregular short crested waves without current.
6) Regular waves.

Tests carried out in current only may be considered in order to study the viscous forces only.

6.4 Suggestions for the tested structure

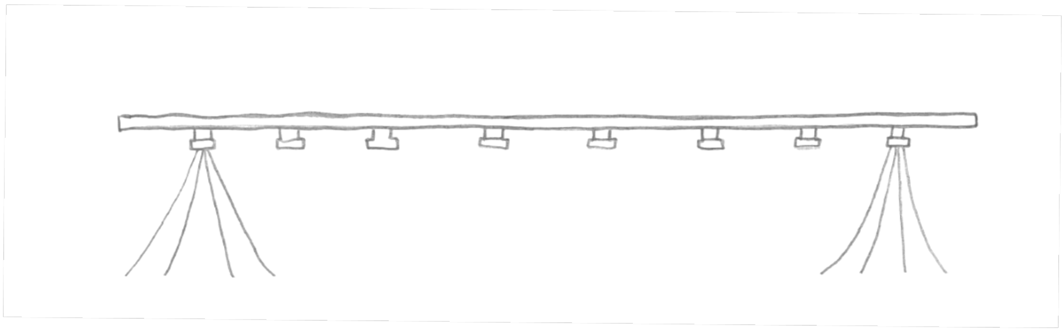


Figure 20: Illustration of a potential set up of a model test. The model is shortened compared to the full scale pontoon bridge.

It is clear that the model of the pontoon bridge needs to be shorter than the full pontoon bridge. The straight pontoon bridge is simpler to truncate than the curved bridge. Figure 20 shows a 1km long truncated pontoon bridge from the side. The distance between the pontoons are roughly 150m and it is moored at both ends. This is a segment of the full bridge which may be 4 or 5 km long. A crucial point is how to model the interaction with the rest of the bridge. Here it is required to do numerical analysis (see suggested work in the next section). The end condition can be modelled by a passive spring system, or in principle with an active system.

7 Suggested work

In order to improve our ability to perform model tests of large floating bridges, targeted work efforts are necessary.

7.1 Improve calibration procedures of wave conditions in the ocean basin.

Testing large structures, means that the model will cover larger parts of the ocean basin. This means that the wave field needs to be controlled/calibrated for a larger part of the basin than what it has historically. The increased size of the model will cause reflections, and the size suggests also that parts of the model will be located in areas of the basin which are more prone to reflections from the wave makers, and beaches.

Reliable and useful model tests require that the wave conditions must be calibrated as close to the target conditions as possible. It should also be studied to what extent inhomogeneous waves can be calibrated.

It is proposed to:

1) carry out numerical simulations of the wave field in the ocean basin
2) compare numerical simulations with model tests. (Is it required to carry out wave calibration?)
3) look into calibration procedures for inhomogeneous wave conditions.

Fjord type of waves should be emphasized.

7.2 Design of bridge truncation method

It will be impossible to model the full bridge in the ocean basin. This means that the bridge needs to be truncated. How should this be done?

It is suggested to study different truncation methods through a numerical model. The performance of the truncated bridge should be compared with the performance of the full bridge. The truncation may differ depending on the objective of the model test. It should be elaborated if the truncation can be modelled by a passive spring system or an active system.

7.3 Importance of coupled wind and wave-current response

The response of a pontoon bridge depends on wave, wind and current loads. Wave and current load effects interact, meaning that model tests should be carried out in combined waves and current. For the model tests it is important also to assess if there are important coupling effects between wind and wave-current response. If this coupling is large, it means that the effect of wind and waves needs to be tested simultaneously. WP1 discuss this topic in chapter 4.7. Here two interaction effects which may be of some importance are mentioned: 1) The slowly varying excitation of the bridge due to wind increases significantly the standard deviation of the slowly varying horizontal motions. This in turn may alter the second order slowly varying excitation and damping due to for instance viscous effects. This effect has been experienced from model tests in offshore wave conditions for floating structures like semi submersibles and FPSOs. For this type of structures slowly varying motions are very important. However, since waves are much lower in fjords, the effect of slowly varying motions due to waves is expected to be less important in fjords. It is also noted that there is no clear method for identifying wind-wave coupling effects using practical numerical or theoretical methods. 2) For a bridge with non-linear mooring stiffness, the static offset caused by the mean wind force may give different mooring stiffness compared to the non-deformed configuration, which could give different response to wave loads than if wave load were considered separately. It is believed that this effect can be studied using numerical methods.

Aerodynamic instabilities caused by interaction with wave induced motions are considered to be out of scope for the model tests, as it needs to be studied in a controlled aerodynamic environment in a wind tunnel. The importance of the expected interaction effects should be studied using numerical simulations. Other effects, that are not foreseen, may also be discovered in such an analysis.

Wind modelling on large models covering 10 to 20 meters of the basin is demanding. In order for the project to invest in this effort an attempt should be made in order to quantify how the wind and wave response interact. If wind loads are to be included in the hydrodynamic test, it will be through simplified representation. The implications of simplified representation should be studied through numerical analysis. This work may overlap with other work packages.

If the total response of the bridge due to wave wind and current is to be reported directly from the model test, then wind needs to be accounted for in the model test. However, if the model test is designed to only focus on the uncertainty related to the wave and current load models, then the wind loads may be neglected in the basin model test. In this case the total motion of the bridge due to wave, current and wind will only be available in the numerical calculation of the full bridge. The final choice for the wind modelling will be left for the work connected with the model test planning.

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