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COMMITTEE V.6
OCEAN SPACE UTILIZATION

COMMITTEE MANDATE

Concern for investigation and applications of ships, offshore structures and engineering equipment for ocean space utilization in the context of marine resource exploitation, human habitation and other marine infrastructure. Focus should be given to fluid-structure interaction associated with large marine structures and structural flexibility. Due consideration should be given to the comparison of modelling approaches, existing and emerging guidance & best practices.

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KEYWORDS

Ocean Space Utilization; VLFS; Hydroelasticity; Coupled Mooring Analysis; Multi-body Hydrodynamics; Floating Cities; Floating Airport; Offshore Aquaculture; Offshore Floating Photovoltaics; Floating Offshore Wind Turbines; Risk Assessment; Rules and Regulations

CONTENTS

1. INTRODUCTION

In the light of rising sea level, scarcity of land-based resources and increasingly populated coastal areas, interest of project developers and countries turns towards the ocean, exploring the possibilities of utilizing this space for various purposes. With the oceans covering roughly 70% of the Earth's surface and more than half of the world's population clustered in coastal areas, the oceans are a natural direction to turn to.

Ocean Space Utilization (OSU), i.e., the use of ocean waters and/or the seabed for human activities, is by no means new. Shipping and fishing in ocean waters date back millennia. During the last century, aquaculture of seafood production developed into a global industry. Also, the seabed has provided minerals (mostly sand) as building material. Recently, the marine mining industry experienced a development from traditional sand dredging to deep sea mining for precious or rare mineral resources. The offshore oil and gas industry developed from first wooden platforms in the shallow coastal waters of the Gulf of Mexico to Floating Production Storage and Offloading systems and subsea equipment in more than 2000 m water depth offshore Brazil. More recently, the wind energy industry followed the steps of the oil and gas industry and moved from land-based installations first to shallow coastal waters with bottom-founded wind turbines and now starts developing offshore floating wind turbines for larger water depth and greater distances to shore. Marine Renewable Energies (MRE) including Wave Energy Converters (WEC), flow turbines for electricity production from ocean or tidal currents, and Ocean Thermal Energy Conversion (OTEC) are emerging. Another recent form of renewable energy production on the ocean are Offshore Floating Photovoltaic (OFPV) Installations (Karpouzoglou et al., 2020; Trapani & Millar, 2016; Trapani & Redón Santafé, 2015). Furthermore, marine infrastructure projects of floating airports (Suzuki, 2005), floating bridges and submerged tunnels (Moan & Eidem, 2020; Watanabe et al., 2015), floating oil storage terminals (Ueda, 2015; Zhang et al., 2020), floating logistics hubs/ports (Waals et al., 2018), a floating event stage (Koh and Lim, 2015), as well as even entire floating cities (Callebaut, 2015) are discussed in the literature. Eventually, recreational use and ocean research also belong to the broad field of Ocean Space Utilization.

As an inventory of Ocean Space Utilization projects, this committee gathered as many OSU projects as possible in various stages (from concept study to commercial project) and from various fields in a project atlas based on Google maps. Offshore oil and gas projects are excluded from the atlas to prevent overloading it. Figure 1.1 shows a screenshot of the project atlas with a global overview of all projects. The projects can be grouped and color-coded by OSU field or by project status as shown in the two columns on the right of the figure. At the time of writing, this project atlas contained 235 projects. Even without offshore oil and gas projects, the energy field, comprising mainly offshore wind farms, dominates the list with 90 projects. Two other large fields of OSU are food production, i.e., mainly (offshore) aquaculture with 46 projects, and infrastructure projects (35) like floating bridges and airports. From the project list by field, it is apparent that there are many projects associated with more than one field. This signifies the new trend of multi-use ocean space utilization. An example for this multi-use is mussel farming within an offshore wind farm (see Edulis project in food & energy field). Regarding the project stage, the project entries range from mere concepts and research projects to fully operational structures. The database behind this project atlas contains more information on the individual projects with details on the field (use), project name and location, coordinates, the associated institution as well as a link for further information. The project atlas is available under the following link:

https://www.google.com/maps/d/u/0/edit?mid=19csABz093PieNrk-wVvbdXYWkjHjpjOSR&ll=4.4954840168199155%2C0&z=2.

Please note the project database is not complete and is not automatically updated. However, it provides a good overview of OSU activities and can serve a starting point for future dataset development.

Figure 1.1: Screenshot of the OSU project atlas with project classification based on project stage (left column) or project field (right column and map coloring).

From the project atlas, there is a clear geographical concentration of the OSU projects in South-East Asia and Europe with considerably less projects in American and African waters. In Europe, there is a clear distinction between mainly Offshore Wind Farms in the North Sea and Baltic Sea on the one hand and dominating offshore aquaculture projects along the Norwegian coast. In Asia, there are predominantly aquaculture and floating infrastructure projects.

The type of floating structure that is used or proposed for projects in the different OSU fields of the project atlas is summarized in Table 1.1. It is apparent that many OSU fields consider Very Large Floating Structures (VLFS). According to (Suzuki et al., 2006), VLFS “may be thought of as potential megaprojects given their anticipated length scales, displacements and estimated costs (i.e., 10^3– 10^4 m, 10^6 – 10^7 tons, and 5bn-15bn $US, respectively)”.

In the original source, Suzuki et al. (2006) considered a monolithic floating structure that drew its flexibility from the elastic bending of the structure itself. More recent projects consider modular structures of interconnected floaters that form a combined floating structure. In terms of dimensions, displacement, and costs, these Modular Floating Structures (MFS) also match Suzuki’s definition of a VLFS. In MFS, the individual floater may be considered a rigid body and the flexibility comes from the interconnections. An example of an MFS is described by Waals et al., (2018) for a floating mega island made up of triangular floaters.

The third group of large floating structures with potentially equally large horizontal dimensions and investments as Suzuki’s VLFS are the floating membranes considered for OFPV installations (e.g. Trapani & Millar, 2016). However, these structures, by definition of a membrane, have negligible structural bending stiffness due to very small height. Also, their draft is considerably smaller than that of monolithic or modular VLFS.

Apart from VLFS and floating membranes, deep sea mining is likely to use more conventional, ship-like structures, which are dealt with by other ISSC committees. Offshore wind turbines (bottom founded and floating) are primarily considered by the ISSC2022-V.4 committee on Offshore Renewable Energy.

In this committee, the focus was placed on floating structures for human habitation and infrastructure as well as food production (aquaculture) as the two large groups of the project atlas after excluding offshore wind farms. The typical structures considered for floating logistics islands, floating airports, floating cities, or similar projects have horizontal areas of more than 1 square kilometer. On the other hand, the draft and depth of the structures is limited to only several meters (only counting the floating support structure, excluding any superstructures). Furthermore, these projects are mostly considered in coastal waters with limited water depth.

As floating infrastructure projects, the service life of the structures is commonly envisaged to be 50 to 100 years and thus longer than for conventional ships and even most offshore oil and gas platforms.

Table 1.1: Overview of OSU structures

OSU field	**Structure type**			
	Monolithic VLFS	**Modular VLFS**	**Floating membrane**	**other**
Floating infrastructure (ports/airports/bridges)	x	x		
Floating cities	x	x		
Food production (fish farms/aquaculture)		x		net cages
Deep sea mining				Ships, subsea equipment
Offshore renewable energy production				
OFPV		x	x	
OWT				Bottom-founded/floating wind turbine
WEC		x		
OTEC				Ship-like structure

The large structural dimensions, together with the location in shallow coastal waters, and long service life, lead to several challenges for OSU structures from different perspectives. From an environmental loading point of view, due to the size of the structure, the environmental conditions can be significantly different across the structure. This is partly due to blocking and shielding effects of the structure itself and partly due to the spatial variability of the environmental conditions. One prominent example for different environmental conditions is a locally varying bathymetry, which combined with shallow water can significantly affect the motion response of the floating structure.

From a hydrodynamic and structural perspective, the hydroelastic effects of monolithic and modular VLFS need to be reviewed. Considering that monolithic VLFS are likely to be built up on site from smaller units and MFS consist of individual interconnected floaters, connectors are used to keep the individual units and modules together. These connectors are focal points for the loads in the structures. Therefore, their design requires careful attention and due consideration of the hydroelastic coupling effects among the individual floaters in the motions and loading analysis of the structures.

Closely connected to the motions and loading analysis are the mooring systems. For VLFS, these mooring systems are not easily transferable from other large floating structures due to considerable interaction of the mooring system with the floating structures, especially for MFS and floating membranes.

Also, from a broader technical and societal perspective, OSU involving VLFS poses some challenges. There is very little experience with these structures and, therefore, hardly any industry guidelines and standards exist. Furthermore, standards from e.g., the offshore oil and gas industry are not easily transferable. From a societal acceptance point of view, risk assessment of OSU projects as well as a regulatory framework are required. For the risk assessment, the procedures of the offshore industry might be applicable. However, the hazards and the consequences can differ considerably, e.g., due to the number of people in a floating city compared to an offshore oil platform. The current regulatory framework for structures at sea knows ships and (industrial) offshore structures that have an owner and a single responsible person on board. This is likely to change for floating ports and cities. Therefore, new ownership models, regulations, and legislation are required for financing and eventually operating large-scale OSU projects.

This report addresses the aspects of environmental conditions particular to these large structures in Section 2. The main focus of the report is on the loads and global response of the structures in waves presented in Section 3, followed by an overview of station keeping methods and their challenges in Section 4. The hydrodynamics and the hydroelastic problem of both monolithic and modular floating structures has received much scientific attention over the past 15 years since the dedicated VLFS ISSC committee in 2006. Therefore, this committee placed the emphasis for the hydrodynamic loads and structural response part of this report on the recent developments in the hydroelastic research of very large floating structures. Section 5 zooms out from the structures and provides an overview of risk assessment approaches for OSU projects based on the examples of Offshore Aquaculture, Offshore Floating Photovoltaics, and Offshore Floating Wind Farms. As OSU is a new field with very few commercial projects, there are few established industry standards and common practices. Section 6 provides an overview of the existing rules and guidelines that can serve as a starting point for OSU projects. Conclusions of this survey are presented in Section 7.

2. ENVIRONMENTAL CONDITIONS

A very important aspect for Ocean Space Utilization is the characterization of the environmental conditions for design, operation, and extreme loading. In particular, reliable long-term statistics, taking into account relevant short-term effects, are required for wind, waves and currents in coastal and sheltered areas. Since the focus here is on very large structures, typically on the order of a kilometer or more in size, inhomogeneity in the environmental conditions is to be expected. The effects of a variable bathymetry, diffraction of waves from nearby coasts and islands, wave-current interaction, and wind blowing over variable topography will generally be important over the length of the structure. Thus, this section summarizes the state of the art for establishing the environmental design basis for very large floating structures in nearshore regions and highlights the differences to established methods used for ships and conventional offshore installations like oil and gas platforms. Also, areas are identified where knowledge and information are missing.

2.1 Design conditions

Regarding the design perspective, environmental data is required for fatigue limit state and for ultimate limit state analyses (FLS and ULS). The data includes wind, waves and current, (ice effects are not discussed) and it should be provided with the correct statistical correlations. Regarding FLS, the design procedures use scatter tables with the annual probability of occurrence of the environmental conditions. The ULS analysis provides the expected extreme loads over a defined return period, which may be for example 100 years, or 50 years. In this case, the analysis requires the environmental extreme conditions leading to the extreme loads.

For the design of offshore structures, good quality wind and wave data is often available from hindcast models. This is the case for ocean areas developed by the oil and gas sector. For example, the Nora10 hindcast model operated by the Norwegian Meteorologic Institute covers the North and Norwegian Seas with more than 50 years of data and 10 km grid resolution (Reistad et al., 2011). However, many of the marine structures for more general OSU will be installed in coastal areas where the offshore hindcast data is not applicable. Furthermore, the environmental description for coastal areas is very much site specific, more complex and in fact significantly more difficult to characterize with good accuracy.

The common practice to establish an environmental design basis for waves and wind in coastal areas consists of two steps. First, long-term offshore wind and wave conditions near the focus area is analyzed from a reliable source of data (e.g. Hersbach et al., 2020; Reistad et al., 2011). Second, a detailed bathymetry of the coastal area is implemented and combined with the off-shore conditions to transfer the environmental data from offshore to nearshore region using a nearshore wave model such as SWAN (Booij et al., 1999). The quality of input (both offshore conditions and coastline/bathymetry) is very important and determines to a large extent the quality of the output. Another important factor is the definition of the appropriate computational domain, as well as the nesting scheme (if needed) to be applied as one approaches the target points.

Recently, in order to obtain the characteristics of wave evolution principles and the hydroelastic responses of the VLFS near islands and reefs, three categories of wave models including mega-scale, middle-scale and local-scale models were used, and some numerical simulation tools have been employed as well, including the viscous solvers ANSYS, Fluent, etc., and potential flow theory solvers including WAMIT, AQWA, etc. They are described below and summarized in Table 2.1 by (Yang et al., 2019b).

Table 2.1: Categories of ocean wave models near shore or around the floating structures (Yang et al., 2019b).

Category	**Zone**	**Issues**	**Theory**	**Solvers**
Mega scale	Hundreds to thousands of kilometers	Wind generated wave growth and propagation	Wave action density balance equation	WAM, SWAN, WW3
Middle scale	Several kilometers	Refraction, diffraction, and dispersion of waves in coastal regions	Wave action density balance equation, Green-Naghdi theory, Boussinesq equation, mild-slope equation	SWAN, WW3, FUNWAVE, MIKE21, etc.
Local scale	Hundreds of meters	Disturbance of waves with floating structures	Viscous models (N-S equations); potential solves (BEM)	ANSYS Fluent, WAMIT, AQWA.

(1) Mega-scale models are based on the wave spectral action density balance equation, software packages such as SWAN and WW3 (Wave Watch III) can deal with wave growth and propagation in several hundreds of kilometers zone (Jiang et al., 2010) and the Gulf of Mexico (Fan et al., 2009).

(2) Middle-scale models are based on one of the following equations, i.e. mild-slope equation (Berkhoff, 1972), Boussinesq equation (Madsen et al., 1991) and Green-Naghdi equation

(Zhao, 2010), and can be employed to simulate the wave refraction, diffraction, and dispersion characteristics near shores or islands.

(3) Local-scale models including viscous models and potential flow solvers, which can describe the details of wave disturbances around the floating structures. In the local-scale models, the effects of seabed profile on the responses of the floating structures must be taken into consideration.

Wave-current coupling is important for the correct modelling of both waves and current as well as for determining wave-structure interaction and related loads. Relevant work has been developed in recent years concerning the coupling of wave and current models to improve predictions in both (see e.g. Chen et al. (2018) and references cited therein).

The present challenges to characterize the environmental conditions for coastal areas include:

- Correct modelling of the propagation of waves from deep water to coastal areas with complex bathymetry and irregular coastal shape. Existing wave propagation methods are based on a mild slope approach, while the coastal sea bottom may be quite uneven and shore diffraction effects may also be relevant. For example, the bathymetry on the Norwegian coast often includes shoals near the coast, before the water depth increases again in the fjords. The wave propagation models and simulations need to include the correct physics to represent the dissipation, refraction and diffraction effects associated with complex bathymetries and coastal shorelines.
- Existing hindcast wave data is based on phase-averaged wave propagation models, which solve the space and time evolution of the wave spectrum. For this reason, wave inhomogeneity, which may be important for some VLFSs, is restricted to the wave spectrum while wave phase information is lost. The inhomogeneity may be related to the referred dissipation, refraction, and diffraction effects. It is therefore important to implement time-domain propagation studies to characterize the inhomogeneity.
- Current is driven by wind, tide and river discharges and it may exhibit complex three-dimensional patterns. Recent numerical models based on a fine discretization of the shoreline and the bathymetry make it possible to provide estimates of the current velocity for coastal design applications. The challenge on this topic consists of relating the simulation conditions and results with the required probability levels for fatigue analysis and extreme load analysis.
- Existing offshore wind information also needs to be transformed to the near-shore site-specific location, since the surrounding topography strongly affects the mean wind velocity, direction and turbulence. The models will need to apply a finer grid resolution than those used for offshore hindcasting.

2.2 Extreme waves

Long-term wave statistics are investigated by processing wave data, in the given area of interest, from different sources: e.g. buoys, satellites, or hindcast data (see, e.g., Goda, 2000). Different approaches can be considered for the extreme value analysis, including annual maxima, and Peaks Over Threshold (Castillo, 1988; Coles, 2001; Ferreira & Guedes Soares, 1998, 2000; Neelamani, 2009), or more recently, approaches based on Storm Models.

Storm Models provide useful tools for estimating the design wave for both offshore and coastal structures, based on a design storm (non-stationary event). The design wave is related to the design storm, which is characterized by two the parameters intensity (maximum significant wave height) and duration. The temporal evolution over the duration of the storm depends on the storm shape.

This class of models is employed to extrapolate actual significant wave height time series via a sequence of simplified storms with a given shape, e.g., triangular, both in time- and space-time domains (see next subsection for space-time domain references). The basic concept is to substitute the actual storm sequence at a given site by a sequence of simplified storms, keeping the wave risk unchanged. This equivalence between actual storm and simplified one is achieved by keeping the same maximum expected wave height and the same probability that the maximum wave height exceeds a given threshold. The main difference between the storm models is related to the storm shape, which can be triangular (Arena and Pavone, 2009, 2006; Boccotti, 2015, 2000), a power law (Arena et al., 2014; Fedele & Arena, 2009), exponential (Laface and Arena, 2016), or trapezoidal (V. Laface et al., 2019). Using these models, it is possible to derive analytical solutions for the calculation of return periods of a storm with assigned characteristics, e.g., the return period of a storm whose maximum significant wave height exceeds a given threshold. The last-mentioned trapezoidal-shape storm model has been developed on the basis of the DNV storm temporal evolution given in DNVGL RP C-205 (DNVGL, 2017). This model provides a very simple approach for calculating return values of significant wave height based only on the probability distribution of the significant wave height at the site.

A contribution with a different approach related to Equivalent Storm Models was given by Mackay & Johanning (2018), who based their method on generalized extreme value (GEV) distributions.

Recently, Samayam et al. (2017) gave a general review of extreme wave height prediction models, with a comparison among four different models: (1) the GEV distribution model based on samples of the annual maxima, (2) the generalized Pareto distribution (GPD) model based on peaks over threshold (POT) samples, (3) the equivalent triangular storm (ETS) model, (4) the P-app method based on extrapolation of the tail of the provision function.

In general, one of the advantages of the storm models, for example with respect to the POT method, is that the return values have a low variability to changing the threshold. In addition, Storm Models provide a time evolution of the design storm instead of a single design sea state, giving an idea of the sequence of sea states characterizing the design event. This last aspect could be a key element for fatigue analysis (see DNVGL RP C-205).

2.2.1 Extreme waves in the space-time domain

The wave statistics in the space-time domain, for Gaussian seas, may be investigated with Adler's theory (Adler, 1981; Adler, 2000; Adler & Taylor, 2007; Piterbarg, 1995) on the Euler Characteristics of Excursion Sets and their related probability for a multidimensional domain. Adler's approach was investigated for ocean engineering applications by Krogstad et al., (2004), Forristal (2006), and Baxevani & Rychlik (2006). The probability of exceedance of the maximum crest height in a given area and during a particular sea state, was introduced by Fedele et al. (2011) and Fedele (2012).

A different approach was given by Romolo & Arena (2015), for the prediction of extreme ocean waves in the space-time domain. Effects of nonlinearities were taken into account by considering Forristall's model for nonlinear crests. Then, the long-term statistics in the space-time domain were investigated through considering the DNVGL trapezoidal storm models by Laface et al. (2020). The results show how the highest crests in the space-time domain can be significantly higher with respect to the values achieved with the analysis in the time domain. This suggests that models for the prediction of extreme ocean events on very large structures should take temporal and spatial variability into account.

2.3 Wind-wave-current-shoreline interaction in coastal regions

As noted above, spectral wave modelling of the environmental conditions in nearshore/coastal regions is challenging due to the difficulties of including significant effects from coastal and island diffraction, refraction from rapidly changing bathymetry, and highly variable local wind and current, along with surf zone dynamics. There is work in progress to better understand and model these processes. For example, Addona et al. (2020) performed experimental measurements of long waves with varying partial reflection from the tank boundary and an opposing (offshore) wind. They found a complicated interaction between the wind-generated short waves, the mechanically generated long waves, and the subsequent internally generated currents. The results were fairly well captured by existing theories, but only when phase information was included. They highlight the need for further experimental work to improve and validate theoretical modelling.

A new model for capturing the shoreline dynamics of the swash zone in phase-averaged models was developed by Memmola et al. (2020), who showed promising results. In terms of the detailed behavior in the surf zone, Martins et al. (2020) demonstrated the importance of non-hydrostatic and nonlinear effects on the correct prediction of wave heights, and also showed that rotational (viscous) effects are negligible. Bertin et al. (2020) studied the generation of infra-gravity waves by wind-wave interaction with the beach during storm conditions. The generated long waves were found to reach a significant wave height of 1.85 m in a wind-wave spectrum of significant wave height up to 9.5 m. Numerical calculations indicate that the generation mechanism is mainly the release of bound harmonics.

J. Zhang et al. (2019) as well as J. Zhang & Benoit (2021) studied the generation of extreme waves in the coastal zone using high-fidelity, phase-resolving numerical models, and found that both second- and third-order effects are important. In the second study, they considered the experimental measurements of Trulsen et al. (2020) to shed light on how the statistical properties of irregular waves are modified by propagating over a shoal. Tayfun & Alkhalidi (2020) illustrated the limitations of second-order theory for describing irregular wave statistics in restricted water depths and proposed a simple modification with much better performance.

Dalsøren et al. (2020) proposed a new intuitive method for validating numerical fjord models by comparison with field measurements.

2.4 Further environmental aspects of OSU structures

For ships and conventional offshore structures, their effect on the surrounding wave field is commonly neglected. Large floating structures however can have a significant effect on the environmental conditions in their vicinity. Floating breakwaters are specifically designed to reduce the wave height on their leeward side (J. Dai et al., 2018; Peña, et al., 2011). Artificial islands or floating cities of several square kilometers in size will also cause significant wave scattering that alters the wave conditions in their vicinity as shown e.g. by Ertekin & Kim (1999) for a floating airport.

An additional aspect of environmental conditions specific to Offshore Floating Photovoltaics (OFPV) and some forms of aquaculture is the solar irradiation. Where dedicated irradiation measurement data exists for land areas, this information is scarce for nearshore and offshore locations. Local wind systems based on temperature differences between seawater and coastal land can lead to cloud forming either on land or at sea increasing or reducing solar irradiation at sea compared to nearby land. Examples for this effect are the Dutch coast as well as the coastal waters along the Namib and Atacama deserts.

As solar irradiation is the basis for biological primary production, the ecological effect of very large floating structures blocking sunlight entering the water needs to be investigated for large OSU projects. Karpouzoglou et al., (2020) investigated this effect for OFPV structures at the Dutch coast. On the other hand, OSU structures add large surface areas of hard substrate at their location, offering a habitat for marine organism.

3. GLOBAL LOADING, MOTIONS, AND STRUCTURAL RESPONSES

For the development of ocean space utilization, Very Large Floating Structures (VLFS) will play the dominating role. The global loading, motions, and structural responses of VLFS are critical issues investigated by both academic and industry. This section focuses on the summary of the important and latest research outcomes of these issues.

3.1 Characteristics of VLFS structures

Compared to an ordinary ship, VLFSs are unprecedentedly large and flexible floating structures with structural natural frequencies dropping down to the wave frequency region. In the assessment of wave responses and structural safety of a VLFS, the hydroelastic effects, see Figure 3.1, naturally are of great concern.

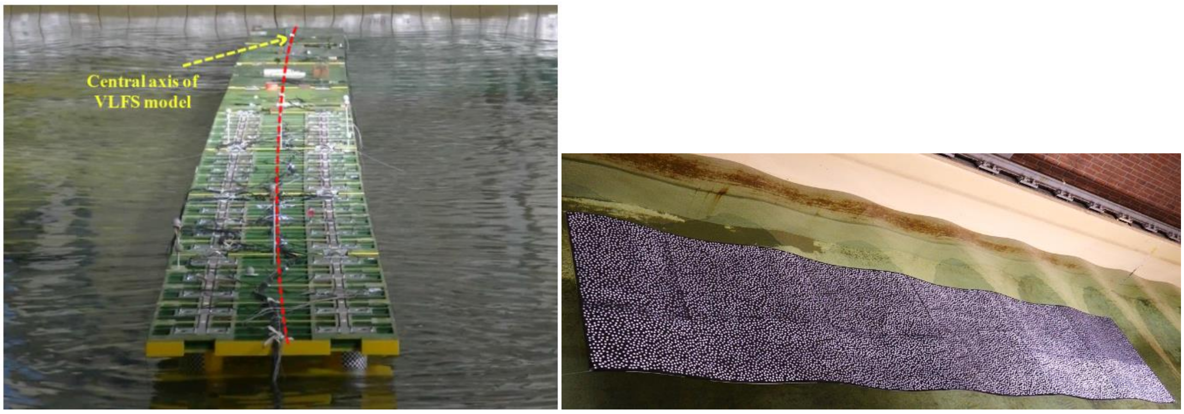


Figure 3.1: Lateral bending deformation of a VLFS model (left); vertical deformation of a very flexible floating sheet in waves (right)

VLFSs have their advantages in offshore engineering applications. For example, such compliant structures can be applied to a floating hydrocarbon storage facility, as shown in Figure 3.2. VLFS are floating multi-body systems, which have more degrees of freedom than conventional floating structures that are often treated as rigid bodies with 6 degrees of freedom (DOF) motions. As for VLFSs, simplified numerical models may neglect important effects. Therefore, a multi-body hydrodynamic analysis is essential for VLFSs.

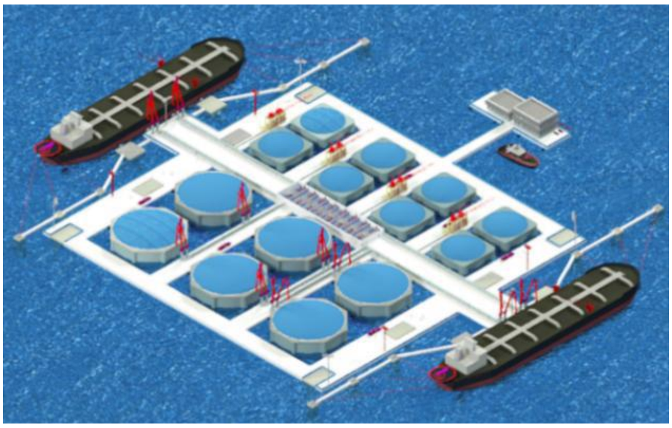


Figure 3.2: Floating hydrocarbon storage facility

However, different from most marine and offshore structures, the development and application of VLFS deployed near the shore or an island will face some critical challenges. Wu et al. (2021) as well as J. Ding et al. (2021b) made a summary on the verification of key technologies for floating structures near islands and reefs and identified the following three challenges.

- Assessment of hydroelastic effects of VLFS with complex shape and multi-module connections.
- Description of complex environmental conditions and coupling with hydroelastic analysis of floating bodies.
- The object of experimental simulation involves not only the coupled response between modular floating bodies, connecting device and complex mooring system, but also the

multi-scale propagation of waves and current in complex seabed topology and geographic environment.

3.2 Hydroelastic modelling approaches

In this section, traditional hydroelastic modelling approaches are summarized. Then, three new challenges due to complex sea environments, i.e., inhomogeneous incident waves, shallow water effect, and seabed topography, and the latest modelling approaches are introduced. Finally, the numerical tools for hydroelastic analysis are described.

3.2.1 Classical hydroelasticity modelling

In the early 1980s, three-dimensional hydroelasticity theory was established and developed by Wu (1984) through unifying the three dimensional potential flow theory and Finite Element Method (Bishop et al., 1986b; Price & Wu, 1985). Several important research projects have been conducted in USA, Japan, and China, aiming to achieve in-depth understanding of hydroelastic modelling theories. The motions, wave loads, and structural responses of VLFS were investigated based on these theories in the VLFS project supported by National Science Foundation of America (Du & Ertekin, 1991; Ertekin, et al., 1993; D. Wang, et al., 1991; Wu et al, 1993). The Mega-float project in Japan included two phases and landing and take-off experiments with small aircrafts were carried out on a VLFS model with 1000 m in length (Suzuki, 2005). A project was carried out at Shanghai Jiao Tong University sponsored by National Science Foundation of China (Cui et al., 2007; Wang et al., 2001). In this project, based on the second-order hydroelasticity theory developed by Wu et al. (1997), the nonlinear hydroelastic response method of large floating structures was investigated by X.-J. Chen et al. (2004). Besides, the project 'Response and Structure Safety of VLFS in Complex Environment' was conducted by CSSRC from 2013 to 2017, mainly in view of major scientific problems such as hydroelasticity, complex geographic environment, flexible connectors, complex mooring system, structural reliability and safety (J. Ding et al., 2021b).

The interest in VLFS prompted the International Ship and Offshore Structures Congress (ISSC) to establish a specialist committee on VLFS (Suzuki et al., 2006), whose task was to consider the state-of-the-art in VLFS analysis and design procedures including the application of hydroelasticity. Comparative studies of the hydroelastic analysis results from different computing codes for a pontoon (mat-like) VLFS were carried out, covering a mix of both fluid models (potential and linear Green–Naghdi) and structural models (3-D grillage, 2-D plate, 3-D shell), see (Riggs et al., 2008). The similarities in the results increased the confidence level of the state-of-the-art in predicting the hydroelastic responses of such structures. Another similar comparative study of pontoon type VLFS with shallow draft was also conducted by Jiao et al. (2006).

For a large array of floaters, the wave-structure interactions can be calculated with analytical or semi-analytical solutions (Kagemoto and Yue, 1986; Newman, 2001). When the large array of floaters is the substructure of VLFS, numerical methods with proper approximations can further accelerate the computations (Murai et al., 1999). These methods were applied to floating structures with simple geometries. Mirafzali et al. (2015) employed the fundamental solution method, which is a meshless numerical method to solve hydroelastic analysis of fully nonlinear water waves with a floating elastic plate. Cheng et al. (2016b) investigated the hydroelastic responses of a mat-like, rectangular VLFS edged with dual horizontal/inclined perforated plates using Eigen function expansion-matching method, FEM-BEM hybrid method and experimental test. Y. Sun et al. (2018) divided a continuous (single-module) flexible structure into several rigid sub-modules with a virtual beam added between the center of each sub-module and simplified the coupled fluid-structure interaction problem as equivalent multi-body hydrodynamic problem with elastic constraints.

Furthermore, the hydroelastic analysis of VLFS is very relevant to problems concerning the interaction of water waves with ice sheets, and many research results can be found in the polar science and engineering field. Recent examples are (Ilyas et al., 2018; Kalyanaraman et al., 2020; Papathanasiou & Belibassakis, 2019; Papathanasiou et al., 2019; Sergienko, 2017).

3.2.2 Inhomogeneous incident waves

Over the past few decades, there are many investigations of hydroelastic response of VFLS in deep and open sea encountering one-directional incoming waves of a specified wave spectrum. However, since VLFS are huge structures in the order of several kilometers, the sea environment is no longer homogeneous over the structure. One of the challenges due to complex environment is the inhomogeneous incident waves at different locations of the VLFS, and how to describe these inhomogeneous waves. More recently, this problem was specifically addressed in the following studies.

Ding et al. (2016, 2019) and Wu et al. (2016) analyzed the effect of inhomogeneous wave distribution on the VLFS by dividing the sea area into several blocks and considering different wave conditions on each sub-module of the VLFS. It was found that the motions and connector loads of the VLFS increased by 40%-80% compared to results calculated by traditional method with homogeneous incident wave. An indirect method has been proposed to study the unsteady external loads and hydroelasticity of VLFSs under inhomogeneous sea conditions (Wei et al., 2018).

The inhomogeneous incident wave analysis method also applies in some other fields involving long floating structures, such as floating bridge. Wei et al. (2017) and Fu et al. (2017) applied different wave excitation forces onto different modules to analyze the effect of inhomogeneous wave distribution on the hydroelastic response of floating plates and a floating bridge respectively. Z. Cheng et al. (2018, 2019, 2021) and Dai et al. (2020) also used this method in the analysis of dynamic responses for very long floating bridges in a Norwegian fjord under inhomogeneous incident wave conditions. Z. Cheng et al. (2020) also made an in-depth investigation on the extreme responses of the long floating bridge.

3.2.3 Shallow water effects

When the draft of a floating body is not small compared to the water depth in coastal regions or near islands, effects of the sea bottom on wave-body interactions may become more important than those in deep water conditions (Oortmerssen, 1976). A general step to consider the bottom effect is to make the constant-depth assumption. Hydrodynamic theories concerning wave-body interactions over flat bottom have been developed from two-dimensional (2D) approaches to three-dimensional (3D). From the numerical point of view, these approaches of the boundary value problem can be generally divided into analytical methods and numerical methods.

The analytical methods, for instance eigen-function matching method, generally require the floating bodies to be assumed to be of rectangular or circular/spherical shape in 2D problems, see e.g. Zheng et al. (2004a, 2004b), Yang et al. (2017), and this requirement is also included in 3D problems by Wu et al. (2004) and Hulme (1982), respectively. In contrast, numerical methods generally deal with floating bodies of arbitrary geometry. Among them, Boundary Element Method (BEM) is used widely because all its unknowns are distributed on the specified boundaries, realizing a reduced computational burden. A typical BEM involves a complicated finite-depth Green’s function, which automatically satisfies the free surface condition, the bottom condition and the far-field radiation condition. It shall be noted that the most time-consuming part of this method is the evaluation of the troublesome finite-depth Green’s function and its partial derivatives. Computational strategies related to this function have been well established by many scholars using various numerical techniques, such as polynomials to approximate slow-varying components (Newman, 1985), and different asymptotic or power series expansions in different regions (Linton, 1999; Liu et al., 2015). Detailed classification of these strategies has been given by Liu et al. (2020).

Rankine source approach is another representative BEM method, which requires to calculate the integral of simple Green’s function and its partial derivatives over all fluid boundaries. The far field radiation condition must be treated carefully in this approach since the infinite fluid domain does need a truncation in numerical practices. In order to avoid unexpected wave reflection from the truncated boundaries, scholars have brought up several numerical techniques, among which methods involving the numerical beach (Moshe et al., 1981) and absorbing layer (Filippas and Belibassakis, 2014) are widely applied. These methods commonly create a circular area to encompass the truncated free surface and artificial damping is added into the free surface conditions to eliminate negative effects of the truncation. Zhang & Beck (2007, 2008) used the division of the free surface into inner domain and outer domain. Based on this, Feng (2014) developed a new source point distribution strategy with increasing spaces between points to replace the even spacing method for free surface treatment.

3.2.4 Seabed topography effect

The seabed topography and local bathymetry does not only affect wave propagation. The hydroelastic response of the structure also depends on the local water depth. This is another challenge for the application of VLFS near islands where seabed topography effect must be taken into consideration. When a VLFS is deployed in coastal region, near islands, or in otherwise complicated geographical environment, the environment conditions, wave loads and the hydroelastic responses of the structure will be quite different from those in open and deep sea. The seabed topography in nearshore areas is usually in a rugged state and water depth may change from several hundred meters to several meters in a short distance, which has brought up great challenges to the analysis of wave-body interaction. The effects of coastlines (Xia et al., 1999), seawalls (Ertekin & Kim, 1999) and varying sea bottom topographies (Utsunomiya et al., 2001b) on the hydroelastic responses of nearshore structures have been recognized as important issues in recent decades. Sturova (2008) investigated the effect of bottom topography on the unsteady behavior of an elastic plate floating on shallow water. The results showed that the form of the bottom irregularities can have a considerable effect on the oscillations of an elastic plate floating on shallow water.

Semi-analytical and simple methods

To study 3D wave-body-seabed interaction problems, several numerical methods were proposed. Murai et al. (2003) separated the pontoon-type VLFS into many small floating bodies and the local water depth for each body is assumed to be constant, thus forming a succession of fluid domains of constant water depth. Then Eigenfunction Matching Method (EMM) was applied in each domain and the velocity potential was represented by a series of eigenfunctions associated with the local depth. It is assumed that in the method of Murai et al. (2003) the water depth of external region is required to be constant. Sun et al. (2003) investigated the hydroelastic behavior of an elastic plate floating on the sea surface with 2D and 3D uneven seabed topography. The influence of uneven sea bottom on vertical displacements of a VLFS model was studied by Song et al. (2005) using finite water depth Green’s function. Utsunomiya et al. (2001a) used a Fast Multipole Method to study VLFS response in variable water depth and topography.

Cheng et al. (2017) employed a 2D fully nonlinear numerical wave tank to investigate the interaction between a monochromatic wave and a floating elastic plate over a variable seabed in time domain. The frequency-domain hydroelastic responses of a 2D floating structure in variable bathymetry was investigated by Liu et al. (2019) based on Eigenfunction Matching Method in conjunction with Discrete Modules Method (DMM). Yang et al. (2019b) concluded that the wave statistics experienced obvious changes when propagating and approaching towards an island; meanwhile, the complicated seabed profile has an apparent influence on the hydroelastic responses of the VLFS including the vertical deflection responses and connector loading.

Fixed boundary condition on seabed

It is found that VLFS show obvious coupling responses with the depth-varying seabed (Yang et al., 2019b), when VLFS are located at the mouth of a river (Utsunomiya et al., 2008), and when VLFS with one module and 8-module are located near islands (Ding et al., 2017, 2019). This shows that hydroelastic responses are greatly influenced by the depth-varying seabed. Besides, Liu & Sakai (1997) developed a time-domain method for the hydroelastic response of VLFS in arbitrary bathymetry. After that, Liu extended their method to nonlinear wave cases to account for solitary Tsunami waves (Liu et al., 2002). In their works, the velocity potential satisfies the impermeability condition along the bottom boundary.

In the models employed by Buchner (2006) as well as Ferreira & Newman (2009), a second fixed body was introduced to represent the sloping bottom. It was suggested that refraction and interference effects were too strong and affected wave exciting forces on the floating bodies in an incorrect way by the truncated edge of the second body by Buchner (2006). To eliminate these unphysical effects, De Hauteclocque et al. (2009) proposed a modified formulation of the boundary element method by introducing partially transparent panels representing the uneven seabed to improve this situation and investigated the hydrodynamic properties of a LNG carrier over sloping bottoms. Distribution of the transparency coefficient over the bottom panels and size of the partially transparent region are determined empirically. Note that the second fixed body approach requires the far field wave pattern to be characterized by finite-depth Green's function, rendering itself an incomplete formulation for the diffraction and radiation problems.

To study the effect of various seabed topographies on the hydroelastic responses of VLFS, Kyoung et al. (2005) presented a finite-element method based on the variational formulation used in the fluid domain and the seabed was treated as fixed boundary condition. In order to deal with the tremendous number of panels in treating the uneven seabed as a fixed boundary condition, a fast paralleling algorithm was proposed by Tian et al. (2014) in the load determination, structural design and safety assessment of floating platforms near islands and reefs. Using this method, a single-module barge (Lu et al., 2018), single-module semisubmersible platform (Yang et al., 2015), three-module semisubmersible platform (Yang et al., 2015; Yang et al., 2019b) have been calculated and compared with model test data.

Based on linear Rankine source method, Kim & Kim (2013) developed another complete formulation to treat this problem. The incident wave was generated numerically by deploying a wave-making wall on the inlet boundary. This scheme was added directly to the Rankine source method, and the incident and disturbed potential can be solved both simultaneously and separately. Numerical damping was added in the free surface boundary conditions in the damping zones, giving rise to artificially induced errors. Two parameters, the damping intensity and size of the damping zone were determined case by case. Consequently, the accuracy of numerical results considering the sloping bottom will be affected. Yang et al. (2019a) proposed a three-step time-domain hydroelasticity method for VLFSs over the sloping bottom under inhomogeneous waves based on the Boussinesq equation and Cummins' theory. For the diffraction and radiation problems, finite-depth Green's function was employed, and no penetrating conditions were applied to the complicated bottom.

Eigenfunction Expansion Method (EEM)

Seto et al. (2005) developed a versatile modal approach for fluid–structure interactions, which incorporated the use of NASTRAN and a newly formulated, hybrid, finite/infinite element method of the domain decomposition type. The velocity potentials for the inner and outer subdomains were expressed by the corresponding vertical orthogonal eigenfunction expansions. Such an approach can be used for water waves in a protected sea with irregular boundaries. Belibassakis & Athanassoulis (2005) developed a coupled-mode method and applied this to hydroelastic analysis of large floating platforms of shallow draft over variable bathymetry regions, characterized by parallel bottom contours. Pham et al. (2008) extended the eigenfunction expansion matching method to develop a horizontal submerged annular plate attached around the perimeter of a pontoon-type circular VLFS. Based on Eigenfunction Expansion Method, Sturova (2008) investigated the behavior of a floating plate for different actions and shapes of bottom irregularities. It was shown that the bottom topography can have a considerable effect on the deformation of the plate.

Bottom-dependent Green's function

A representative complete formulation for 3D problems concerning the sloping bottom is a boundary element method proposed by Belibassakis (2008) based on 3D bottom-dependent Green's function by Belibassakis & Athanassoulis (2004) and a consistent coupled-mode theory of water propagation by Athanassoulis & Belibassakis (1999) to treat the diffraction/radiation and incident wave problem, respectively. It should be noted that numerical evaluation of the 3D bottom-dependent Green's function is a quite cumbersome task, especially when considering floating bodies of complex geometries, as large numbers of sources are required. Gerostathis et al. (2016) extended the coupled-mode model developed by Belibassakis & Athanassoulis (2005) and Belibassakis (2008) to include hydroelasticity of structures with shallow drafts floating over regions with variable bathymetry. Considering constant and variable seabed bathymetry, Karperaki et al. (2016) analyzed the transient hydroelastic response of floating elastic plates connected with multiple elastic connectors.

Inner-and outer region matching method

To obtain a rational description of the influence of uneven seabed and sheltering effect of islands on the hydroelastic responses of a VLFS deployed near an island and reefs in shallow water, Ding et al. (2017) and (Wu et al., 2017a) established a rational direct coupled analysis method (DCAM) to analyze the hydroelastic response of floating bodies near islands and reefs. In this method, the fluid domain is divided into the outer region and the inner region where Boussinesq equations and Rankine source method, respectively, are utilized to solve the seabed-wave-body problems.

3.2.5 Numerical methods and tools for hydroelasticity analysis

There are several numerical methods and tools used in hydroelasticity analysis and simulations of VLFS. As for the execution of traditional hydroelasticity theory, examples of the most important tools are program THAFTS-IHIW (Ding et al., 2019) and THAFTS-BR (Ding et al., 2017). Both tools have been playing an important role in the VLFS engineering application, and they are able to estimate the hydroelastic responses of VLFS in inhomogeneous waves. Liu & Sakai (2002) investigated the interaction of regular waves, random waves and solitary waves with a pontoon-type VLFS by satisfying the second order continuity of the pressure and displacement on the fluid-structure interface, respectively. Kyoung et al. (2006) employed FEM to simulate the hydroelastic deformation of VLFS with fully nonlinear free-surface conditions. Nguyen et al. (2018, 2019) performed a hydroelastic analysis of VLFS with vertical mooring lines modelled as vertical elastic springs in frequency domain using the hybrid finite element–boundary element (FE-BE) method. They examined the effectiveness of vertical elastic mooring lines in reducing hydroelastic responses for various wavelengths, incident wave angles, and aspect ratios.

Besides, Computational Fluid Dynamics technology has also been employed in hydroelastic simulations. Mollazadeh et al. (2011) and Mirafzali et al. (2015) adopted a meshless numerical method to calculate hydroelastic responses of fully nonlinear water waves with both semi-infinite and finite horizontal floating plates. Li et al. (2017) studied the interaction of water waves with a hinged multi-module floating structure, using a numerical model based on smoothed particle hydrodynamics (SPH) method. The simulation was performed in a 2D nonlinear numerical wave tank and the motion of the multi-module floating structure, hydrodynamic forces, mooring force, and collision forces on neighboring modules were calculated.

3.3 Multi-body hydrodynamics

VLFSs are typical multi-body structures, so multi-body dynamics is also of crucial importance for the dynamic analysis of VLFS. For a floating multi-body system with a limited number of bodies, many studies focused on the hydrodynamic interactions and mechanical couplings. For example, Kim (1972) and Ohkusu (1976) revealed the importance of hydrodynamic interactions between two ships. Following their studies, Kodan (1984) and Fang & Kim (1986) explored the motions of adjacent floating structures in oblique waves. Koo & Kim (2005) compared cases with and without consideration of the hydrodynamic interactions of two side-by-side floating platforms. It was found that neglecting hydrodynamic interactions may lead to a significant discrepancy in the motions of both platforms. Meanwhile, to consider the mechanical couplings, Langley (1984) presented a general dynamic analysis method for floating multibody systems. Sun et al. (2011) introduced the Lagrange multiplier to solve the dynamic responses of float-over installations. Based on a fully nonlinear potential flow theory, Feng & Bai (2017) developed a numerical model of two floating barges with and without connections. The contribution of nonlinearities was found significant under a steeper wave condition.

The multi-body interaction effect has already raised many related investigations in the offshore oil & gas engineering field. As for the well-known side-by-side floating liquefied natural gas (FLNG) and LNG carrier (LNGC) system connected through hawsers and fenders, Pessoa et al. (2015) developed a linearized coupled model in frequency domain, which showed fairly good accuracy compared to experimental results. Recent research done by D. Zhao et al. (2018) presented a time-domain analysis to investigate the hydrodynamic interactions between FLNG and LNGC. In their comprehensive work, the coupling between sloshing and vessel motions and the effect of the connection system consisting of fenders and hawsers were presented. The above research works were mostly based on linear potential flow theory; however, nonlinear effects may contribute to the dynamic responses of the floating multi-body system. Pessoa et al. (2016) revealed that the second-order wave excitations are important for the side-by-side floating system. Compared to the research focusing on side-by-side floating systems, the hydrodynamic interaction and mechanical coupling in a floating system with more than two bodies were less investigated. Lu et al. (2010) investigated a three-body system with two gaps in a two-dimensional numerical wave tank. Ning et al. (2018) reported the difference between a mono box and an equivalent tandem floating box system with narrow gaps in two-dimensional cases.

Recent research work was presented by Otto et al. (2020) and Waals et al. (2018) on a floating mega island consisting of interconnected triangular pontoons. They simulated mechanically and hydrodynamically coupled rigid body motions of all pontoons in waves and compared their results to model tests. Other floating multi-body systems are frequently seen as floating wave energy converters (WECs). As for the large number of arrayed WECs, an optimal arrangement for maximizing the power generation of the whole array considering hydrodynamic interaction among the multi-WECs was examined by Murai et al. (2020).

3.3.1 Resonant motions in the gaps

In addition to the research on hydrodynamic and mechanical interactions of floating bodies, attention has also been paid to fluid resonance in narrow gaps. Fluid resonant motions may occur when the incident wave frequency is close to natural frequencies of fluid resonant modes in narrow gaps. This phenomenon was identified clearly in experimental studies (Fredriksen et al., 2015; Molin et al., 2009; Perić and Swan, 2015; Zhao et al., 2018). An analytical solution on the mode shape and corresponding natural frequencies in both narrow gaps and moonpools under infinite and finite water depth were derived by Molin (2001) and Molin et al. (2018), respectively. The existence of gap resonances may influence hydrodynamic forces on the two floating bodies as illustrated in Lu et al. (2011) and Jiang et al. (2019). Kristiansen & Faltinsen (2010) investigated the strong hydrodynamic coupling between the resonant piston mode in a narrow gap and the motions of a ship in shallow water. The potential flow method tends to unphysically overestimate fluid resonances since the viscous effects are neglected. Computational Fluid Dynamic (CFD) method may be directly utilized to predict gap resonant motions (Y. Yang et al., 2018) or combined with potential flow models (Chua et al., 2018; Chua et al., 2017; Kristiansen & Faltinsen, 2012).

However, very few studies have been conducted on applying CFD to a large floating multi-body system due to the high computational cost. Instead, potential flow theory is still favored for hydrodynamic analysis of multi-body systems. To overcome the problem in the framework of potential flow theory, a rigid gap lid was introduced to reduce the free surface oscillation (Buchner et al., 2001). A flexible gap lid with generalized mode was developed by Newman (2003). Meanwhile, Chen (2005) introduced a free surface dissipation term on the free surface boundary condition. Recently, a new method was implemented by Lee & Zhu (2018) to model viscous effects in resonant free surface motions through a dipole lid.

3.4 Connector loads and responses

VLFSs are always assembled or constructed by joining base units either with flexible or rigid connectors, which are the most critical devices in the entire structures. However, the connectors are also the weakest link members of the whole system. Under severe sea states, the connectors will inevitably bear large loads and if the load exceeds the designed ultimate load, first the connection and possibly the overall structure will fail. To ensure safety and structural integrity, many investigations have been conducted on the design and safety assessment of connectors.

3.4.1 Equivalent mechanical connector models for VLFS

In dynamic response analysis and connector load calculation, the equivalent calculation model of floating module and connector mainly includes three forms: rigid module flexible connector (RMFC), flexible module rigid connector (FMRC) and flexible module flexible connector (FMFC).

RMFC model is a common model, in which the floating module is considered rigid, while the connector is flexible. Based on 3D hydroelasticity theory, Wang et al. (1991) established a simplified analysis program to calculate the motion response and connector load of a five-module floating body system using RMFC model. Riggs et al. (1999) studied a 1500 m × 152 m Mobile Offshore Base (MOB), which was solved by RMFC and FEA models, respectively. The results show that when the natural frequency of the RMFC model is similar to that of FEA model, RMFC model can reflect the response of floating body well.

FMRC model assumes that the flexibility of the floating module itself is much greater than that of the connector, and all the deformation occurs in the floating module. When studying the MOB proposed by McDermott, Kim (1999) discovered that the stiffness of the floating module in the system was smaller than that of the connector. By comparing the FMRC model and RMFC model, Kim found that the connector load in RMFC model was smaller than in the FMRC model.

In the FMFC model, both the floating module and the connector are assumed to be flexible. Wu et al. (1993) used FMFC model to study a five-module system. The deformation of each module and connector was taken into consideration in the calculation. The calculation results showed that the longitudinal connector force was greater than the transverse and vertical forces. Ertekin et al. (1993) used RMFC and FMFC models to calculate a floating system with 16 modules. The results showed that the calculation efficiency of both methods was very high even for large floating systems.

Wu et al. (2021) deployed a scaled two-module semi-submersible VLFS with a connector monitoring system near an island and reefs, as shown in Figure 3.3. The numerical calculation results of the significant stresses in longitudinal and vertical direction were in good agreement with the monitoring results for most of the measuring points.

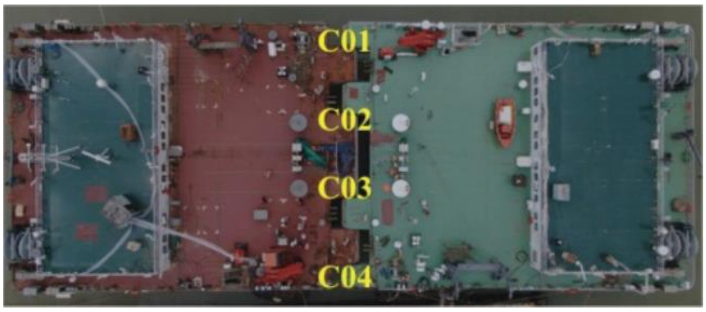


Figure 3.3: Top view of the Scientific Research & Demonstration Platform (SRDP) (Wu et al., 2021)

3.4.2 Dynamic response characteristics of connectors

Due to complicated loads induced by wind, waves and current, the connectors between the modules of very large floating structures are bearing large loads. Therefore, the dynamic response prediction of connectors plays an important role in connecting system design. The research on dynamic response of flexible connectors mainly focuses on the following two aspects:

Effect of sea conditions on connector loads (Wu, 1996)

This study included the dangerous wave direction range of the maximum connector load, the influence of wave direction and sea state on the connector loads, the analysis of the load response characteristics of the connector under different sea state levels and wave spectra. The conditions of unconnected, flexibly connected, and rigidly connected modules was compared.

Influence of connector stiffness on connector load

An early work done by Riggs et al. (1999) studied thirteen different connector stiffness cases, in which longitudinal and vertical stiffness varied and transverse stiffness was fixed at a large value. Xia et al. (1999) investigated the hydroelastic behavior of two-dimensional articulated plates connected by idealized connectors, which were treated as a series of flexural rotational springs and vertical linear springs. The effect of the stiffness of connectors on the hydroelastic response of floating modules were studied by Fu et al. (2007). Riyansyah et al. (2010) and Gao et al. (2011) investigated the effect of the location and rotational stiffness of the connector for reducing the hydroelastic response and resultant stresses of the VLFS. Additionally, Michailides et al. (2013) also found that the connectors' internal loads were affected directly by the connectors' rotational stiffness. Zhang et al. (2017) proposed three types of flexible connector configurations to represent anisotropic stiffness models. They investigated the effect of the different stiffness on the global stability of the multi-modular floating system with amplitude death mechanism (Zhang et al., 2015), where a preferred parameter domain for the stiffness and wave period was suggested. Zhao et al. (2019) proposed a general strategy for determining the stiffness configuration for flexible connectors according to specific requirements.

3.5 Structural response

As summarized by Suzuki et al. (2006), VLFS response in waves is dominated by elastic deformation of the structure. This elastic deformation can be due to the deformation of the floating bodies, or relative motions in their connectors, or combinations of these. For conventional VLFS for floating infrastructure applications, the vertical motions were found to be in the order of the incident wave height and the depth of the floating structure.

Nishigochi et al. (2020) proposed a method to analyze a Large-scale Floating Transposition Station (LFTS). They identified the occurrence of stress concentrations in the structural members of the LFTS by systematically changing the external force conditions such as the coal loading condition and wave load assumed during the operation and performing LFTS oscillation analysis as well as stress deformation analysis.

In the past, linear Kirchhoff plate theory was regularly employed to model the structural response of monolithic VLFS in various combinations with hydrodynamic models mentioned earlier in this section to address the hydroelastic problem. Considering larger deformations than permissible in linear plate theory, Chen et al. (2003 & 2006) formulated the nonlinear hydroelastic problem using Föppl-Von Kármán plate theory. They found that including nonlinear membrane stresses had little effect on the deformations, however increased the structure stress by 30%.

3.5.1 Physical and structural nonlinearity

Stronger nonlinear effects can be expected for floating membrane type of structures as considered by Trapani et al. (Trapani & Millar, 2016, 2013; Trapani et al., 2013) as well as Schreier & Jacobi (2020b, 2020a) for Offshore Floating Photovoltaic applications. For such structures with a depth of merely millimeters to centimeters, (Verhelst et al., 2019, 2020b) used a nonlinear plate model to describe wrinkling and buckling response. Further nonlinear effects can be due to material nonlinearities mainly in polymer materials (Verhelst et al., 2020a). Xu & Wellens (2022) presented a 2D nonlinear hydroelastic model of a floating membrane structure with third order treatment of waves and structure deflections.

Structural nonlinearity is discussed considering the influence of mooring systems and coupling between modules of the floating structures. Shimada & Miyajima (2002) conducted field measurements of elastic deflection and the mooring system to validate their nonlinear mooring simulation program. Their results demonstrated that their calculation code was useful for the design of VLFS mooring system.

Apart from large overall deformations, strong local deformations can also introduce nonlinear structural response, e.g., in the case of local structural failure. In this case, the structure can be modelled as several rigid or elastic bodies coupled by elasto-plastic hinges. The elasto-plastic deformation of marine structure including VLFS has been studied by Iijima et al. (2011, 2015) as well as Kimura et al. (2010) and termed hydro-elastoplasticity. Iijima & Fujikubo (2012) developed a mathematical model to describe the post-ultimate strength of a VLFS, considering the effects of hydroelasticity. The whole VLFS is modeled by two beams on an elastic foundation connected via a nonlinear rotational spring assuming that VLFS collapses at midship under severe bending moment, as shown Figure 3.4. The VLFS can be modeled as several elastic beams with an elasto-plastic hinge embedded at the connections (Iijima & Fujikubo, 2018). Iijima & Fujikubo (2019) carried out a parametric dependency study of the collapse extent of a VLFS under extreme vertical bending moments and developed a simple formula to predict the extent of collapse.

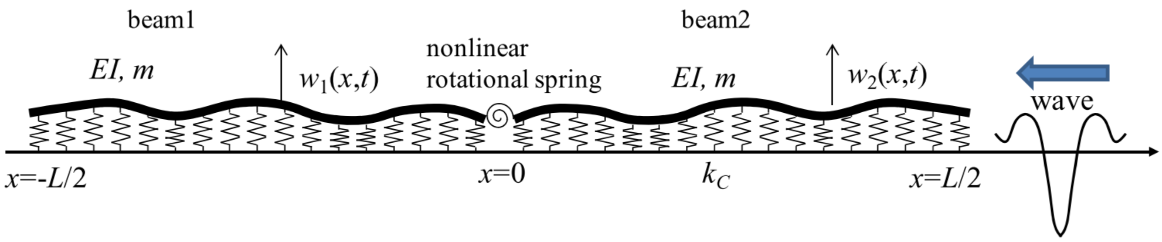


Figure 3.4: Two beams on elastic foundation with an elasto-plastic hinge at the connection. (Iijima & Fujikubo, 2012)

3.5.2 Reduction of structural response

With an eye on the purpose of VLFS as floating infrastructure or floating cities, several studies have been undertaken to reduce the structural response by means of breakwaters, use of submerged plates or special mooring arrangements. The mooring arrangements are discussed in Section 4. Here, the focus is on plates and breakwaters in combination with VLFS. As shown in Figure 3.5, Cheng et al. (2016b) investigated the fluid-structure interaction of oblique irregular waves with a pontoon-type VLFS edged with dual horizontal/inclined perforated plates in the context of direct time domain modal expansion theory. They employed analytical, numerical and experimental techniques in their study (Cheng et al., 2016b, 2014). The results showed that the contribution of dual inclined perforated plates in reducing the deflections is significant when the gap between two plates is not too narrow.

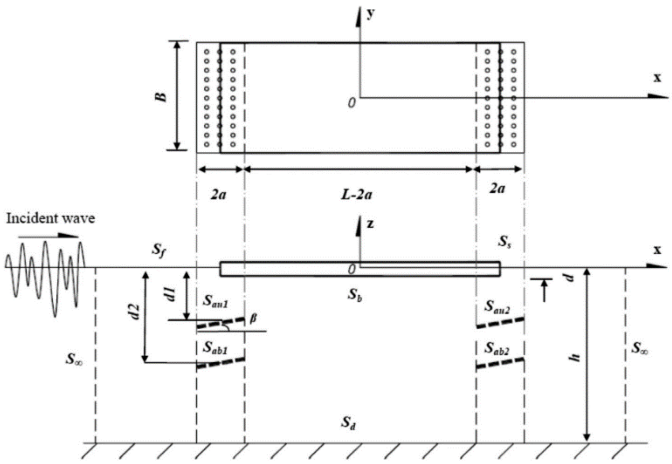


Figure 3.5: Schematic diagram of a rectangular VFLS with dual inclined perforated plates and the coordinate system (Cheng et al., 2016b).

Mohapatra & Guedes Soares (2016) investigated the effect of a submerged horizontal membrane on a moored floating plate. Earlier, Mohapatra & Sahoo (2014) developed the theoretical background for wave diffraction of a flexible floating structure in the presence of a flexible submerged structure based on Green's function. Feng et al. (2020) investigated the hydroelastic response of a VLFS with an attached submerged porous and solid plate, respectively, using Darcy's law and eigenfunction expansion-matching method for multiple domains. They found that a porous plate was more effective at low frequencies while a solid plate had greater effect at high frequencies.

The use of a modular raft Wave Energy Converter (WEC) attachment at the fore edge of a rectangular VLFS for extracting wave energy while reducing hydroelastic responses of the VLFS under wave action was investigated by Nguyen et al. (2019).

Khabakhpasheva & Korobkin (2002) found that an auxiliary floating plate or vertical mooring lines connected to the main structure can be optimally designed to significantly reduce deflections of a floating plate. The same problem of a spring connected to the floating plate was studied by Zhao et al. (2007) using the Wiener–Hopf technique.

Van Kessel (2010) explored an alternative way and investigated aircushion supported VLFS using linear potential theory and adiabatic modelling of the aircushion. He found that aircushions significantly influenced the behavior of the floating structure and reduced the structural loads.

3.6 Other technologies in design and analysis

3.6.1 Basin experiment technology

Basin experimental technology has always been playing an important role in the investigation of nonlinear dynamic responses of naval architecture and offshore structures as well as ocean space utilization structures. When conducting basin experiment of very large floating structures, the scaling ratio selection is a challenging task, because it requires a compromise among the model scantlings and basin size limitation.

Latest contributions to basin experimental investigations for ocean space utilization are the experiments conducted at the Maritime Research Institute Netherlands (MARIN) within the project Space@Sea (Fig.3.7). The newly proposed concept of a modular floating island with low ecological impact was tested experimentally, and the results were presented in the plenary lecture at the OMAE2019 conference.

Figure 3.7: Modular floatign island basin experiments conducted at MARIN
(The blue future:Horizon 2020 project Space@Sea, 2018)

New results and knowledge were reported by Haneda et al. (2016) from model experiments in the towing tank of the National Maritime Research Institute of Japan (NMRI) using a 1:200 scale model of an underwater platform to stabilize e.g. offshore floating wind turbines.

Another experiment was carried out at Dalian University of Technology to investigate the hydroelastic responses of a rectangular VLFS edged with dual horizontal/inclined perforated plates (Cheng et al., 2016a) (Figure 3.8).

Figure 3.8: The VLFS model used in the experiment of Cheng et al. (2016a).

A basin experiment for a semi-submersible VLFS with scale ratio 1:100 was conducted in the State Key Laboratory of Coastal and Offshore Engineering of Dalian University of Technology (Ding et al., 2017). Also, a model of a 3-module semi-submersible VLFS with 5 transverse lower hulls in each module was tested in the same basin (see Figure 3.9) by Wu et al. (2017b). Later, a model test with scale ratio 1:100 of an 8-module semi-submersible-type VLFS (see Figure 3.10) was tested in Deepwater Offshore Basin at Shanghai Jiao Tong University to verify the software THAFTS-IHIW, which was established to estimate the hydroelastic responses of VLFS in the inhomogeneous waves (Ding et al., 2019). Ding et al. (2017) also established a direct coupled method based on Boussinesq equations and Rankine source method to analyze the vertical bending moment of floating bodies near islands and reefs. The earlier experiment was carried out in the State Key Laboratory of Coastal and Offshore Engineering at Dalian University of Technology, as shown in Figure 3.11.

Figure 3.9: Model test of 3-module semisubmersible platform in the basin at Dalian University of Technology (Ding et al., 2017; Wu et al., 2017b)

Figure 3.10: Model test of 8-module VLFS model in the basin at Shanghai Jiao Tong University (Ding et al., 2019)

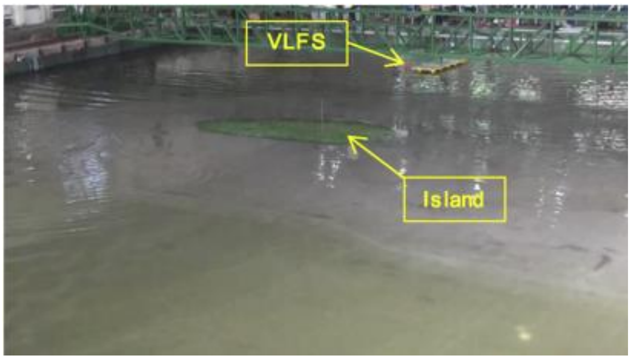


Figure 3.11: Model test of a semi-submersible VLFS in the head wave (Ding, 2015; Ding et al., 2017)

Comparisons between basin experimental results and the numerical analysis results are also conducted to validate the numerical tools. The numerical procedures were verified and validated by comparisons of the predictions and the model test results of a 3-module VLFS and an 8-module semi-submersible platform in shallow sea regions with seabed topography (Wu et al., 2017b). From the comparison of pitch and connector force, see Figure 3.12, it can be pointed out that in most wave frequencies the amplitudes of motions and connecting forces with uneven seabed are larger than those with even seabed. The inhomogeneous waves induced by uneven seabed bathymetry should therefore be considered in the prediction of motions, loads, and structural responses of the multi-module floating structures.

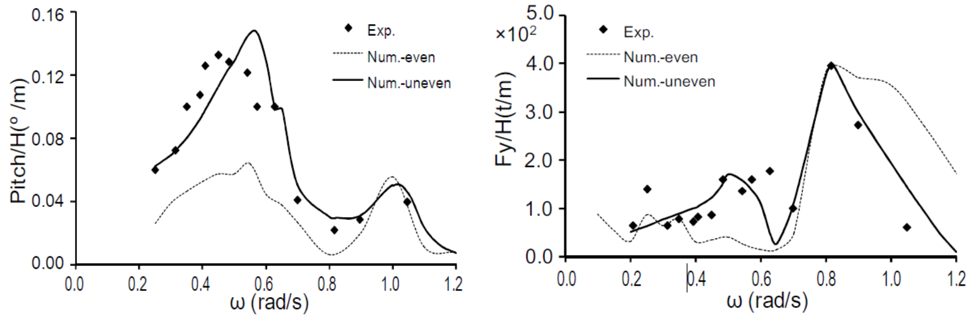


Figure 3.12: Influence of uneven seabed on heave motion and connector force

Schreier & Jacobi (2020b) conducted model tests with a thin flexible floating sheet in the towing tank of Delft University of Technology. They measured the structural deformation by Digital Image Correlation (DIC) and found that the flexible sheet followed the wave elevation of the longer waves in the experiment and showed significant hydroelastic interaction for shorter waves, see Figure 3.13.

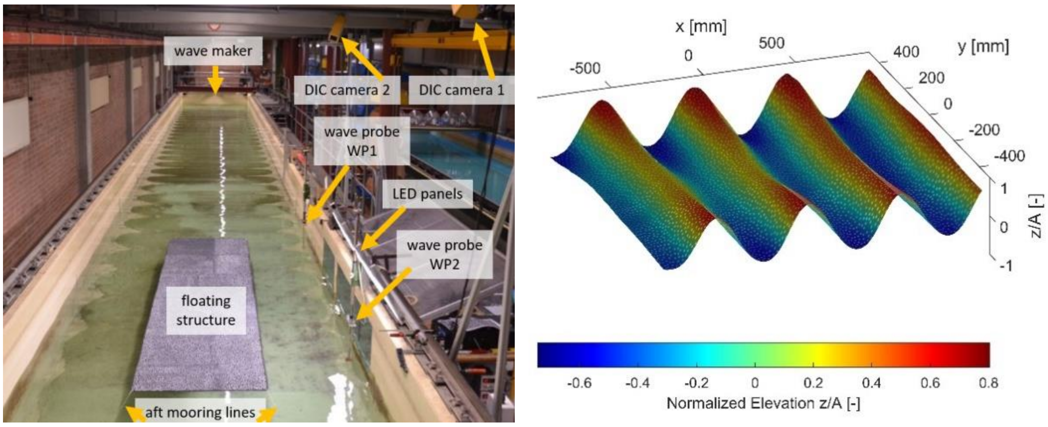


Figure 3.13: Digital Image Correlation measurements of thin flexible floating sheet (Schreier and Jacobi, 2020a). Left: experimental setup with model 4.95 m x 1.05 m. Right: structural elevation normalized by incoming wave amplitude over aft 1/3 of the structure

3.6.2 On-site testing technology

On-site testing, also named full-scale experiment, has always been a challenging task for the transducer installation and reliable data collection in long-term on-site testing. This section summarizes several recent on-site testing cases and the key technologies applied on VLFS structures.

Wu et al. (2021) and J. Ding et al. (2021a) deployed a scaled two-module semi-submersible VLFS near an island and reefs, as shown in Figure 3.14. On the platform were six sub-systems measuring waves, structure response, connector force, mooring line force, anti-corrosion status, floating wave breaker efficiency, and WEC generated electricity. All the sub-system data were obtained automatically through an integrated monitoring surveillance system. R. Ding et al. (2021) made an application of network modelling method to this demonstration platform.

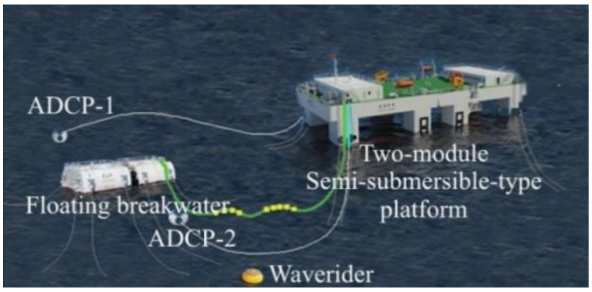


Figure 3.14: Diagrammatic sketch of the SRDP (Wu et al., 2021)

On-site tests were also conducted for floating protective barriers. Floating protective barriers provide essential protection to critical governmental, commercial, and private assets. The seaworthiness of the Triton® barrier design developed by HALO Maritime Defense Systems (US) was investigated through a combination of field deployment, physical testing, and numerical simulations. The full-scale Triton® barrier, deployed and inspected near Isles of Shoals, New Hampshire provided important information on its dynamic behavior and the overall structural integrity under monitored environmental conditions (Knysh et al., 2021).

W2POWER is an on-site testing project ("Pelagic Power as W2Power") and its platform is integrated with wave energy devices (McTiernan and Sharman, 2020).

Large fish cages can also be regarded as large floating offshore structures and some on-site testing and monitoring has been conducted. There are many fish cages on-site, such as Havfarm (a steel frame for 6 cages measuring 50 m × 50 m on the surface, with open nets at 60 m depth), Pisbarca (a hexagonal steel structure with 7 cages built by a Spanish company, with a total volume of 10,000 m^3, (Scott, 2000)), Ocean Farm 1, Shenlan 1, Shenlan 2 (a closed containment tank using concrete material for offshore farming (Olsen, 2020)), and Guangzhou Institute of Energy Conversion's semi-submersible wave powered aquaculture cage with seawater desalination plant on board and solar panel roof (Chu et al., 2020).

For large flexible fish cage structures, net deformation is an interesting problem. Moe-Føre et al. (2016) studied the hydrodynamic loads acting on high solidity net cage models subjected to high uniform flow velocities and the corresponding deformation of the net cages. Model tests of net cylinders with various solidities were performed in a flume tank with a simulated current. The drag force acting on the net cage and flow velocities as well as turbulence characteristics inside and downstream of the net cage were investigated by Bi et al. (2020). They found that biomass, flow speed, net cage configuration, and net deformation have various effects on the drag force and fluid flow.

3.6.3 Cost-effective design

OSU structures are commonly very large floating structures and require investments in the range of billions of dollars for full-scale applications. These costs could be reduced by saving construction material. Many researchers have proposed some ways to reduce wave-induced loads and hydroelastic responses of the VLFS. This is expected to reduce cost of the structures. The conventional approach of enhancing integral rigidity of the VLFS is impractical as larger structural stiffness leads to high demand of construction material. Therefore, this method is not easily applied to an existing VLFS. Another common approach is to employ the breakwaters surrounding the VLFS to reduce the environmental loads, such as bottom-founded breakwaters (Ohmatsu, 2001), or floating breakwaters (Hong & Hong, 2007; Tay et al., 2009). It is expected that the inclusion of breakwater surrounding VLFS can lead to feasible cost-effective designs.

Besides, cost-effective design of ocean engineering facility could be achieved by sharing the cost. Wave and wind energy converters were combined in hybrid semi-submersible platforms with the objective of taking advantage of synergetic effects to reduce the levelized cost of energy and to increase the quality of the delivered power to the grid (Kamarlouei et al., 2020;

Pérez-Collazo et al., 2015; Sarmiento et al., 2019; Zhu et al., 2020). Ikoma et al. (2020) applied an in-house program based on linear potential theory to calculate hydrodynamic performance of an Oscillating Water Column (OWC) and elastic motion behavior of a large floating structure equipped with multi-OWC devices shown in Figure 3.15. They also discussed damping effects on vertical displacement and bending moments.

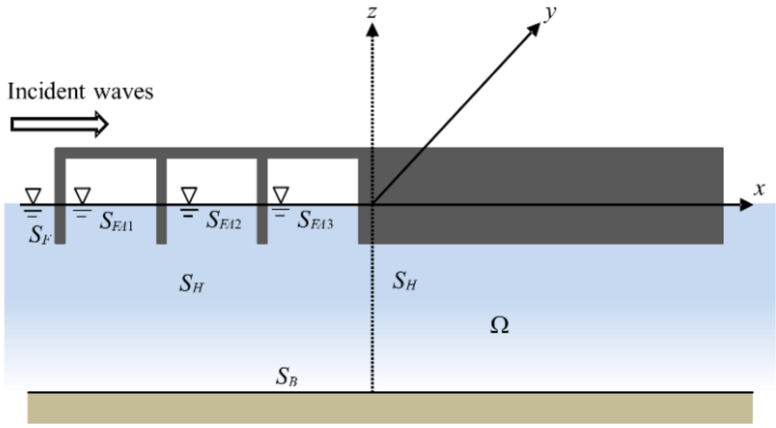


Figure 3.15: Sketch of large floating structure equipped with multi-Oscillating Water Column (OWC) devices (Ikoma et al., 2020)

3.7 Challenges and future trends

The most critical challenge for the analysis of global motions and structural responses of VLFS is the hydroelastic multi-body characteristic, which leads to many nonlinear issues on environmental loads, global motions, and structural responses. This brings along considerable challenges for analysis methods and calculation programs. In addition, the demand for accurate predictions of dynamic responses of VLFS under complex environmental conditions such as inhomogeneous wave, complicated seabed topology and finite water depth, contributes more challenges to the research of VLFS. This section not only presented the application of traditional 3D hydroelasticity theory, analysis method, programs, and experiments, but also summarized the latest research results of hydroelastic analysis of VLFS under complex environmental conditions in recent years.

In developing engineering application of VLFS, four key challenges are summarized as below.

- Effective nonlinear time domain hydroelasticity theories need to be developed to achieve more accurate dynamic response analysis of VLFS under complex sea states.
- Model testing technology for VLFS structures is to be improved by overcoming the challenges of similarity laws and complex boundary conditions due to large scale ratios, in order to provide a reliable verification basis for the development of newly proposed theories.
- Simplified methods for preliminary design and analysis of VLFS are to be developed. This is particularly important for conceptual designs of VLFS in engineering practice.
- With the proposal of more flexible floating structures for Offshore Floating PV applications, efficient numerical tools need to be developed to consider nonlinear effects of large deformations and wrinkling.

4. POSITIONING & MOORING

4.1 Classification of station keeping systems

Most floating OSU structures are intended for operation at a predetermined position. Therefore, a station keeping system acting against drift forces due to wind, waves, and currents is an integral part of the structures' design to keep the structure at its required position. These station keeping systems may be grouped into three main types: (1) caisson or pile-type dolphins with rubber fender system, (2) mooring lines, and (3) dynamic positioning (DP). The selection among the three main types depends on the design requirements.

4.1.1 Dolphins

Dolphins are structures fixed to the seabed and extending above the free surface. This solution is used when there are strict requirements in terms of maximum horizontal motions of the floater and the water depth is small. Loads on dolphins, or piles, are driven by the environmental horizontal forces on the floating system. It is important to note that the station keeping system needs to sustain the relatively large first order wave loads. Second, the system should be designed with natural frequencies of the horizontal modes above the wave frequency range to avoid resonance.

The rubber fender-dolphin mooring system was adopted for the two floating oil storage bases at Kamigoto and Shirashima islands in Japan (Wang & Tay, 2011). This kind of mooring system has since been used for other facilities such as floating piers, floating terminals, floating exhibition halls, floating emergency bases, and floating bridges. As the large size rubber fenders can undergo large deformations (of up to approximately one-third of their lengths), a considerable amount of the kinetic energy of the floating structure can be absorbed.

The mega-float is an example of a floating structure aimed for ocean space utilization, which has been constructed by Japan as a pontoon type VLFS test model for floating airport terminals and airstrips in the Tokyo Bay. The mega-float had an assumed deck area of 5 km^2 and was moored by more than 30 dolphins (Suzuki, 2005). In this case, for progressive failures of the mooring system, the collapse behavior of a single dolphin was investigated by a push-over analysis, i.e., a static method to investigate how far into the inelastic range a structure can go before it is on the verge of a total or a partial collapse. The effects of an earthquake on the floating structure moored by the dolphin system were also investigated. The horizontal motion of the sea bottom due to an earthquake is transmitted through the mooring dolphins and rubber fenders to the floating structure. Results showed that the floating structure is practically isolated from the effects of an earthquake and the impact of the earthquake was generally limited to the mooring system.

4.1.2 Mooring lines

Systems based on catenary lines are the most common solution for station keeping. These are also called soft mooring systems because the horizontal motion natural frequencies are significantly lower than the range of wave frequencies. For this reason, the mooring system is compliant with the first order wave loads. On the other hand, the floating structure experiences a mean horizontal offset due to the mean environmental loads and it also responds dynamically to the low frequency wave drift loads and wind loads.

The mooring lines are typically composed of several segments of the same material or combinations of different materials. Materials of line segments include chains, steel wire ropes, and synthetic ropes. These mooring systems can be used for a wide diversity of floating structures operating in all water depths, from shallow up to a few thousands of meters. See Ma et al. (2019) for a contemporary overview of offshore mooring systems.

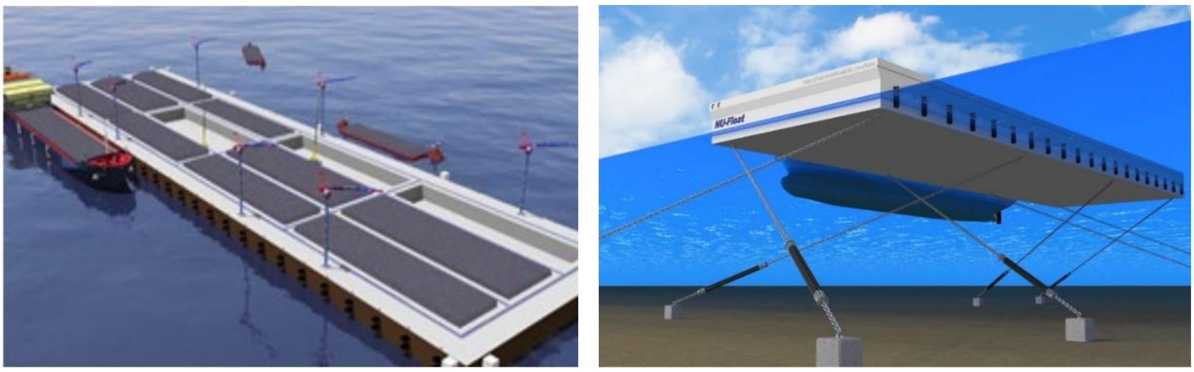
The tension leg platform (TLP) concept may be considered a special class within the "mooring line type" and it consists of vertical tethers or tendons under tension that are fixed to the seabed. Stability is mostly provided by the mooring system, which is designed to achieve natural frequencies of the vertical motions above the wave frequency regime. On the other hand, the system is susceptible to vibrations due to sum frequency wave excitation. The horizontal motions are excited by the low frequency wave drift and wind loads since the related natural frequencies are low. The TLP solution may be considered when the vertical floater motions need to be minimized. In practice it has been implemented in a small percentage of the existing offshore oil and gas platforms. The same concept has been proposed for floating wind turbines with different geometries in depths varying from 50 to 320 m (Shin et al., 2014; Shin et al., 2013).

While the reports of ISSC Loads Committee provide a general overview of the advances related to calculation of mooring line loads, the following paragraphs focus on studies and methods applied to OSU.

Wang et al. (2018) presented a detailed analysis of a nonlinear two-dimensional moored floating structure using the extended Hamilton principle. They studied the influence of the sag-to-span ratio and inclination angle of the mooring cables on the response of the floating structure.

Weller et al. (2018) demonstrated that the mooring and foundation module of open source DTOcean (Optimal Design tools for ocean energy arrays) is able to provide wave energy device and/or site developers with rapid mooring and foundation design solutions to meet appropriate design criteria. S.-H. Yang et al. (2018) performed an experimental and numerical investigation of a taut-moored wave energy converter system with a point-absorber type converter. A numerical model at scale ratio of 1:20 was developed to simulate coupled hydrodynamic and structural response of the wave energy converter system, primarily using potential flow theory and Morison equation. The study showed that the simulation model could satisfactorily predict the dynamic motion responses of the wave energy converter system at non-resonant conditions, while at resonant conditions, additional calibration was needed to capture the damping present in the experiment.

Ganesan & Sen (2015) computed nonlinear load-excursion curves using catenary theory to determine linear and nonlinear line stiffness and obtain the horizontal tension for each individual mooring line. Eto et al. (2020) made an attempt to use an elastic mooring line as a mooring system for a Large-Scale Floating Coal Transshipment Station (LFTS) as shown in Figure 4.1. Even if the mooring lines attached to the LFTS moved up and down, an appropriate tension acted on the elastic mooring lines, such that the lines were expected to suppress the oscillation of the floating body and prevent the mooring lines from breaking due to excessive tension. It was understood that the elastic mooring system can be applied as a mooring system for large structures.



(a) (b)

Figure 4.1: Image of LFTS system (a) and elastic mooring system (b) (Eto et al., 2020)

Xu et al. (2019) presented a detailed review of floating Wave Energy Converter (WEC) projects in the world, including the wave energy capturing technology, development history, main dimensions, mooring system design, and tested sea sites. The study showed that an elastic synthetic rope had great potential in the application of WEC mooring systems, and that the hybrid mooring system, including clump weights and buoys, could be a good solution for WEC station keeping.

Trubat et al. (2020) studied the influence of wave hydrodynamic loads on the lines of a catenary mooring system of floating wind turbines. Simulations for the DeepCWind and the OC3 Hywind platform using FLoaWDyn aero-servo-hydro-elastic model in different sea states showed an increase of the tension standard deviation between 2 and 4 %, with a consequent increase of the fatigue damage.

4.1.3 Dynamic positioning

Dynamic Positioning (DP) systems are applied in connection to operations, which require precise positioning and minimal horizontal motions. Frequent changes of the operation site, like in mineral exploitation, may also require DP capabilities. The aim of the DP system is to counteract the environmental mean horizontal loads and reduce the low frequency horizontal motions. More rarely, the system may aim at controlling roll/pitch motions. Wave frequency motions are not controlled. In some cases, the positioning system combines mooring lines with assistance from DP. One should note that, until the present date, DP has rarely been considered for positioning of OSU structures of the type discussed in the present report.

As an example of a new ocean space utilization concept, the Mobile Offshore Base (MOB) is a multi-module platform proposed by the US Navy, which was designed to be able to accommodate conventional take-off and landing of long-range cargo aircraft (Palo, 2005). This multi-unit structure comprised several self-propelled, semi-submersible modules. These modules were lined-up and the alignment was maintained by means of DP thrusters or DP connectors or a combination of both (Lamas-Pardo et al., 2015). A Multi-Module Control Dynamic Positioning System (MMCDPS) was developed to keep each module properly oriented. In turn, the thrusters would serve to propel the module in transit. Tests and simulations with physical models, along with virtual tank tests, had shown good performance with this system.

4.1.4 Novel mooring technologies and arrangements

Practical solutions have been introduced for different mooring arrangements promising to reduce operational loads, initial and operational costs, and environmental impact, namely:

- Load reduction devices that are attached on the mooring line and rotate in response to the movement of a floating unit and mooring line loads. These devices mainly use a buoyancy/weight element, which rotates under loading to reduce line tension (Doyle et al., 2021).
- Integrated tension monitoring systems where a mooring line connector directly measures actual line tension with secondary readings on angle and rotation. These devices will provide a better understanding in integrity management.
- High strength ropes manufactured from ultra-high molecular weight polyethylene fibers with superior mechanical properties at breaking point, making them ideal for shock absorption and dynamic load applications (Bastos and Silva, 2020).
- Shared station keeping, where multiple units can be moored in position in a network of mooring lines. In this arrangement a shared anchor is a point in the mooring system connected to multiple mooring lines that reduce the overall number of needed anchors (Dimkin, 2019).

4.2 Special problems of mooring analysis for OSU

There are some challenges related to the mooring system design for ocean space utilization, which are related to establishing the design loads and responses for non-conventional and complex structures. These include:

- Representing the hydroelastic response of flexible structures, e.g. VLFS (Nguyen et al., 2018b; Ni et al., 2018), fish cages (Shen et al., 2018), floating bridges and submerged tunnels (Dai et al., 2021; Jin & Kim, 2020), floating solar islands (Kristiansen & Borvik, 2018).
- Considering complex coupling effects on the mooring loads analysis, which can be hydrodynamic or mechanical, e.g., for arrays of fish cages (Tang et al., 2020), the influence of fish in a fish cage (He et al., 2018), dynamics of submerged tunnels (Jin & Kim, 2020), or sloshing effects in closed cages (Su et al., 2021).
- Identification of hydrodynamic coefficients and related loads for fish cages composed of slender elements and nets, often subjected to large deformation (e.g., Cifuentes &

Kim, 2017; Jin et al., 2021; Shen et al., 2018). For structures consisting of an assembly of slender elements, dependency of the drag coefficient on the Reynolds number and Keulegan-Carpenter number in oscillatory flows with varying amplitudes and periods in irregular waves needs to be taken into account.

- Considering inhomogeneous wave loads, which may be relevant for very long structures installed near shore (e.g., Dai et al., 2021).
- Considering changing bathymetry, both in terms of finite water depth hydrodynamic effects and in terms of mooring configuration (Wang et al., 2019).

Some of the recent relevant works are described and discussed in the following sub-sections.

4.2.1 Hydro-elastic responses

The conventional mooring analysis considers the motion of the floater as a rigid body. However, many structures intended for ocean space utilization are designed as Very Large Floating Structures (VLFS) to adapt to special use. As the dimension of the floater increases, the elastic deflection of the floater become significant, which can have an impact on mooring tensions.

Ni et al. (2018) established a coupled numerical analysis method for a VLFS and mooring system based on the three-dimensional hydroelasticity and quasi-static mooring analysis method. The elastic deflection amplitudes and phases of various modes of a VLFS were first computed in regular waves in frequency domain. These were then converted into time series for the specified real sea state, and time domain simulations for the vessel motion and mooring tension were performed. In the time domain simulation, the displacements at mooring connection points on the vessel included both the rigid body motion and elastic deflection of the vessel. A single VLFS module was analyzed together with a mooring system to demonstrate the procedure of the analysis. A second case study consisted of three modules with a mooring system. The calculation results matched well with the data from model tests. The elastic deflections at the mooring points were small, however, due to the high frequency, the related loads may contribute to fatigue damage.

Nguyen et al. (2018) proposed the use of vertical elastic mooring lines to reduce the hydroelastic responses of a pontoon-type VLFS. The mooring lines were connected at the fore and aft edges of the VLFS and used in addition to the dolphin-rubber fender mooring system that was used to restrict the horizontal motions of the structure. The rectangular shaped VLFS was modelled as a Mindlin plate floating on an ideal fluid, for which linear potential theory was applied. The hydroelastic analysis was performed in frequency domain using a hybrid finite element–boundary element (FE-BE) method. The stiffnesses of the mooring lines were optimized for maximum reduction in the hydroelastic response using the Differential Evolution algorithm. It was found that hydroelastic responses of VLFS could be significantly reduced by using vertical elastic mooring lines with optimal stiffnesses.

Kristiansen & Borvik (2018) presented an investigation of a new concept for a floating solar photovoltaic island. The system comprised a circular elastic collar covered with an aircushion supported membrane deck. The numerical model was based on potential theory combined with a Euler beam model for the collar and an aircushion model for the vertical loads on the membrane. Point loads due to moorings attached to the floating collar were considered by the beam model. A modal approach was followed to represent the motions. The investigation included model tests where the model was moored with a horizontal system composed of four lines with prescribed stiffness. A reasonably good agreement was achieved for the vertical motions. However, the authors stated that the agreement of mooring line loads for the flexible island with a simplified model including surge were not satisfactory.

Wan et al. (2018) proposed a modular floating concept for oil storage, which was composed of modular floating tanks and barges. An innovative mooring system consisting of several mooring lines besides the fender system was proposed and investigated.

4.2.2 Coupling effects

Multi-body hydrodynamics were considered for the mooring system design of aquaculture net cages. Tang et al. (2020) investigated the dynamic responses of a net-cage system using a time-domain numerical model based on Morison equation and a lumped-mass scheme. The cages were arranged in a row along the flow direction. In order to simulate the shielding effect, which decreased the water particle speed at the downstream net panel due to the previous cages, a reduction factor of 0.85 by each previous net cage was introduced to the water particle velocity of the waves and current. The effects of mooring system failure were further investigated for this multi-cage case. With the same number of cages attached, the maximum mooring line tension on the remaining anchor always increased after the failure. In addition, the maximum line tension under the failure state increased with the number of cages; however, the tension ratio relative to that under the normal state remained almost constant.

A Submerged Floating Tunnel (SFT) was proposed as an effective alternative to conventional bridges and underground/immersed tunnels for passing through deep water. Jin & Kim (2020) developed a time domain coupled hydroelastic dynamic model to solve the tunnel-mooring-train interaction under wave excitations. The equations of motion for a tunnel and mooring lines were based on FE (finite element) rod theory with Galerkin formulations. The tunnel was coupled with mooring lines through a specially devised connection method with linear and rotational springs. Wave induced hydrodynamic loads were estimated by Morison equation for a moving object. The train was modeled using a multi-rigid-body dynamic method, in which a train element was composed of seven constituent rigid sub-bodies. The interaction between the tunnel and the train was taken into consideration based on the correspondence assumption and the simplified Kalker linear creep theory. The safety requirements were evaluated under moderately rough wave conditions and track irregularity.

The influence of fish on the mooring loads of a floating net cage was studied numerically and experimentally by He et al. (2018). Two experimental series were conducted with fish occupying a total of 2.5% of the fish cage volume. In the first experiment, they used nine rigid fish models, which were placed inside the net cage without touching the net and towed with the net cage. The other case employed live fish (more than 800 salmons of 16 cm length) in conditions with waves and current. The flow-displacement effect of a rigid fish in current was simulated by a potential-flow slender-body theory. Viscous wake effects were added. The displacement flow was clearly more important than the viscous wake flow. Both the numerical simulations and the model tests with rigid fish in current showed that the fish influence on the mooring loads of the fish cage was less than 3% of the mooring load without fish. However, the measured mooring loads with live fish in current were between 10% and 28% larger than without fish. The reason was contact between the fish and the net cage. Accounting for the latter fact in the numerical model by changing the local solidity ratio of the net in the contact area gave reasonable numerical predictions. The experiments in waves and combined waves and current also showed a non-negligible influence of the fish on the mooring loads. The waves influenced the behavior of the fish and some of the fish went to the net bottom possibly because they were uncomfortable in the wave zone.

Su et al. (2021) applied a frequency domain and a time domain numerical model for calculation of closed rigid fish cages in waves. The coupled time domain solution employed potential flow hydrodynamic coefficients for the wave-structure interactions, a cable model for the mooring lines representing gravity and hydrodynamic loads and a weakly nonlinear multi-modal method to simulate the sloshing inside the cage. The analysis showed that sloshing had a large influence on the coupled heave and pitch motion of the cage, as well as on the wave drift forces and therefore on the mooring line loads.

Liang et al. (2019) presented a mooring system design methodology combining the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) with the vessel mooring coupled model. The method was applied to design the mooring system for a semi-submersible VLFS. The study concluded that the accurate dynamic responses of vessel and mooring system could be used as objective function.

Coupled mooring analysis was also discussed in the literature for more generic mooring problems. Barrera et al. (2020) presented the importance of mooring design parametrization on the dynamic behavior of mooring loads. The dynamic numerical model showed a good accuracy with the experimental tests at the fairlead of the mooring system. Jiang et al. (2020) discussed the standard design procedures and simulation tools for marine structures used for offshore oil and gas installations. The validation was performed for the dynamic mooring system analysis technique that coupled the dynamic mooring model with a RANS equation solver. Hermawan & Furukawa (2020) proposed a coupled dynamics model of multi-component mooring lines to analyze the motion of an offshore structure. The study suggested that three-dimensional mooring line treatment needs to be considered as lateral mooring line motion had considerable impact on mooring line tension.

4.2.3 Hydrodynamics of fish cages with nets

Shen et al. (2018) investigated the wave induced responses on a fish farm system comprising a flexible floating collar and flexible net cage, which were moored by a system with bridle lines, frame lines and anchor lines supported by buoys. The investigations combined numerical modelling with model testing and included survival conditions. Hydroelasticity was considered for the floating collar and sinker tube, while a truss model represented the net cage where the hydrodynamic loads were predicted by a screen model. The Morison force model was applied to represent the hydrodynamic loads on the mooring lines. The numerical model was validated by comparisons with test data. The results showed that the bridle lines experience larger loads than the mooring lines. The flow reduction factor in the rear part of the net was the most important parameter for the mooring line loads. Regarding survival conditions, the authors concluded that the existing mooring system could be applied for offshore conditions, as long as the bridle lines were designed accordingly. However, reduction in volume of the net cage might be a problem.

A complete analysis of the hydrodynamic response of a single fish cage under current, regular waves, regular waves/current, and irregular waves/current loading condition was presented by Cifuentes & Kim (2017). The comparison between the results of wave-only and the collinear combination of regular waves and current loading showed a significant effect of current on the mooring load. In waves only, the tension on the mooring lines was greatly influenced by the wave height. As for the combined wave/current case, the tendency of mooring line tension varied almost linearly with wavelength and the influence of wave height was less pronounced. The slope of the tension curves was less steep in the combined case than for waves only. Under irregular waves and currents, the spectra for the mooring line tension showed peaks at the wave frequencies and low frequencies. The low-frequency peak was generated by the nonlinear viscous drag load over the cage. For strong currents, the effect of current and wave loading was of similar importance for mooring line tension.

Jin et al., (2021) presented a numerical model to calculate the motion responses and mooring line loads on the Ocean Farm 1 fish farm offshore structure. Ocean Farm 1 consisted of a quasi-rigid frame structure that supported the net to form an enclosed volume for the fish. The numerical model combined potential flow hydrodynamics for the frame elements, drag coefficients for the slender elements, and a screen model for the net panels. The mooring line hydrodynamics was represented by a finite element model and Morison load model. Since low frequency motions were important for the mooring loads, the wave drift forces were represented by full quadratic transfer functions. The fully coupled responses were calculated in the time domain for conditions with waves and current. Numerical predictions were systematically compared with model test data. The results showed reasonable to good agreement of wave frequency responses. However, prediction of low frequency motions was more challenging, and significant differences were observed between tests and predictions.

4.2.4 Inhomogeneous wave conditions

Dai et al. (2021) studied the mooring lines for a floating bridge under the action of wave loads. The bridge considered in the study was a 4.6 km long straight and side-anchored floating pontoon bridge for crossing the Bjørnafjord. Inhomogeneous wave field was taken into account due to the large span of the crossing and a complex topography. Thus, in the numerical studies, one homogeneous wave condition, typically an annual maximum sea state, and two modified inhomogeneous wave conditions accounting for different spatial variations of wave characteristics (H_s, T_p and θ_p), were considered. Time domain simulations showed that the extreme values of the mooring line tensions were mainly governed by the pretension and thus they were virtually unaffected by the inhomogeneity of the wave conditions. However, inhomogeneous wave loads had a considerable effect on the standard deviations of mooring line tension, which characterized the dynamic components of the responses.

4.2.5 Seabed effects

Seabed features such as the slope and bottom friction may have an influence on mooring system design, depending on the water depth.

Wang et al. (2019) proposed a new catenary-taut-tendon hybrid mooring system used in a semisubmersible type VLFS (floating runaway) over uneven seabed. The motion response of a single module (SMOD) in a coastal region was investigated via time-domain approach and validated against model tests. Hydrodynamic coefficients of the SMOD were obtained using a conventional panel method and mooring tensions were simulated using a lumped mass method. Catenary mooring lines with considerable anchor radius were deployed on the deep-water side of the SMOD and taut mooring lines on the other side. A tendon system was also applied to meet the strict heave motion requirement of the floating runway. The analysis indicated that both mooring system and seabed topography have significant influence on the SMOD motion responses in the coastal region. The influences of tendon and taut mooring stiffness on the SMOD motions and mooring safety were further studied by sensitivity analyses. The results revealed that the SMOD with larger tendon and taut line stiffness have smaller sway and roll motion responses in severe environmental condition.

Huang et al. (2019) assessed several mooring systems designed for floating wave energy converters (WECs) in deep water locations with a steep sloping seabed (ocean cliffs). Considering the manufacturing and installation costs and the bathymetrical features as well as the technical requirements, the study considered three kinds of mooring systems: catenary mooring system, synthetic cable (polyester) taut mooring system, and suspended anchoring point mooring system. The latter consisted of a hanging heavy block, which was suspended over the very steep cliff. The angle of the seabed slope ranged from 30° to 90°. The numerical results showed that both chain catenary and synthetic rope taut mooring system were fit for purpose for mooring of a WEC in deep water with the seabed slope angle around 30°, and the catenary mooring system was more suitable considering economic costs and system feasibility. When the angle of the slope increased further, the suspended anchor point solution became the sound and economical scheme. The hanging heavy block moored on seabed by an additional chain efficiently provided the necessary main restoring force, even in a high slope configuration.

To investigate the influence of different types of seabed friction on the mooring lines, two types of friction were considered in a series of experiments by Barrera et al. (2019). One of them simulated a non-deformable seabed, which can be assimilated to a rocky bottom. The other configuration simulated a deformable bottom of a sandy seabed, in which the ballast coefficient representing the elastic characteristic of seabed has higher influence than in the previous case. The results showed that the tension increased in the sandy bottom due to the sand-chain friction by burial and footprints in the seabed. It also increased the vertical distance between the anchor and fairlead increasing the loads on the mooring lines as well. The authors observed differences between 4 and 15%.

4.3 Challenges and future trends

The station keeping system of floating structures aimed for ocean space utilization may be grouped into three main types: (1) caisson or pile-type dolphins with rubber fender system, used when there are strict requirements in terms of maximum horizontal motions of the floater and the water depth is small. (2) mooring lines, which is the most common solution for station keeping. (3) dynamic positioning (DP), which is applied in connection to operations requiring precise positioning and minimal horizontal motions. DP has rarely been considered for positioning of OSU structures of the type discussed in the present report.

The knowledge and best practices used by the traditional offshore oil and gas sector can in great part be transferred and applied to design mooring systems for more general ocean space utilization. However, the financial constrains are different, as well as several of the technical challenges. Relevant practical solutions have been introduced to reduce the initial and operational costs, the operational loads, and the environmental impact, as described in the text.

Regarding the existing design tools and recommended practices, they can in general address the challenges involved with the mooring system design for OSU, but in several cases with quite large uncertainties involved. This means that using the existing tools often implies oversimplifying physical phenomena, which are specific to the OSU structure under analysis. There is therefore a need for new developments and improvements of numerical modelling. The challenges are related to establishing design loads and responses for non-conventional structures and they include: correct representation of hydroelastic responses of flexible structures and their effects on mooring loads, considering complex coupling effects both hydrodynamic and mechanical, use of correct force models for slender structures and fish net panels, as well as considering complex bathymetries both in terms of hydrodynamic effects and mooring system configuration. Advances have been achieved over the recent years as described herein.

5. RULES, REGULATIONS, BEST PRACTICE

Rules and regulations have been a topic covered by ISSC for years. Historically, ISSC has a focus on ships and offshore oil and gas industries. As the industry broadens and becomes involved in emerging markets, this Ocean Space Utilization Committee addressed a few emerging markets that offer opportunities for naval architects to advance research and development.

5.1 Complex regime of rules and regulations

Rules and regulations for man-made structures at sea are very complex and hard to understand to many. A proven regime has been established for ships and offshore oil and gas industry, which has been evolving over time. For the broader applications in the field of Ocean Space Utilization, this established regime can provide a starting point. However, e.g., for floating cities, the legal framework for selling houses on a floating property does not even exist, yet. This section summarizes the existing rules and regulations with respect to Ocean Space Utilization. The rules and regulations may be categorized into (1) Regulations, (2) Industrial standards and 3) Classification rules as described below.

Regulations

- International regulations. The United Nations' International Maritime Organization (IMO) has been playing the central role in protecting life at sea and in preventing pollution to marine environment. IMO's regulations such as SOLAS, MARPOL, ICLL are still the corner stones for all human activities at seas. Since 1982, the United Nations Convention on the Law of the Seas (UNCLOS) provides a baseline legal framework for areas beyond national jurisdiction.
- Regional and state regulations. European Union (EU) has been very proactive. EU plays a pivotal role in maritime emission controls, which eventually become adopted by other regions and countries around the world.

- Country/state regulations. More and more countries are introducing their own regulations that are often more stringent than international regulations. Being mostly stationed in one location within the jurisdiction of a country, the man-made structures for Ocean Space Utilization are heavily influenced by the requirements of the coastal state.

Industry standards such as API, NORSOK, IEC, ISO

- Take API as an example. API Codes are widely used in designing and operating structures at seas. Though established mainly for offshore oil and gas industry, the API codes are also the starting point when one wants to design innovative structures for a new/unique application. Similarly, NORSOK is becoming more and more applied.
- IEC plays a central role in guiding offshore wind turbine design, including the design of the support structures for the wind turbines. The platforms of wind turbines are considered the foundation supporting the sophisticated wind turbine; they are designed to serve the purposes. The class rules developed for these platforms all started with load cases adopted from IEC Code.

Rules of classification societies

- Class rules may be considered as best practice guidelines, because class rules were initially intended to be formalized requirements established based on long-standing good practice. Over time, especially since design based on analysis came into existence, class rules may come first before the industry has built up enough experiences. Take offshore wind substructure as an example, classification societies have been proactive in writing rules for guiding the structural designs ahead of many actual projects. This is helpful to the industry on one hand as the rules mature together with the growth of actual application. It also implies that there is tremendous room for the class rules to advance and refine.

Table 5.1 shows some examples of rules and regulations for Ocean Space Utilization applications. This table is not a comprehensive list by any means, but it is intended to show the areas where expertise and knowledge of naval architects become increasingly relevant. The other intent of this table is to show, in a very simplistic manner, the links between regulations and industrial best practice.

It is important to note that rules and regulations are far less matured in these emerging applications. This means an opportunity for naval architects and offshore engineers to support rule development for regulatory bodies and classification societies.

Table 5.1: Example Rules, Regulations and Best Practices

Needs	1. Regulation (International, Regional & State)	2. Industrial standard	3. Class rules
Offshore Wind Turbine	UK, USA, Norway, … (DNVGL 2020)	IEC 61400-3Design requirements for offshore wind turbines IEC PT 61400-3-2 Design requirements for floating offshore wind turbines	DNVGL-RU-OU-0512 Floating offshore wind turbine installations DNVGL-ST-0119 Floating wind turbine structures ABS Guide for Floating offshore wind turbine installations ABS Guide for Bottom-founded Offshore Wind Turbines ClassNK Guideline for Offshore Floating Wind Turbine Structures BV Guidance Note for Classification and Certification of Floating Offshore Wind Turbines RINA Guide for Certification of Floating Wind Turbine Installation CCS Guidelines for Floating Wind Platform (draft)
Deepsea minerals mining, ROV, AUV	UNCLOS, International Marine Minerals Society (IMMS) Code for Environmental Management of Marine Mining, International Seabed Authority (ISA) Mining Code	NORSOK U-102 Remotely operated vehicle (ROV) services	ABS Rules for building and classing underwater vehicles, systems and hyperbaric facilities, 2017 CCS Rules for building and classing underwater vehicles, 2018 DNV Rules for classification underwater technology, Part 5 types of UWT systems Chapter 9 underwater working machines and systems
Marine aquaculture	EU Norway Aquaculture Stewardship Council Salmon standard NS9415-2009 on "Marine fish farms requirements for site survey, risk analyses, design, dimensioning, production, installation and operation"	…	DNVGL-RU-OU-0503 Offshore Fish Farming Units and Installations ABS Guide for Building and Classing Offshore Fish Farming Installations

5.2 *Influences of other industries*

An important aspect is that the markets covered by this Ocean Space Utilization Committee are normally led and driven by other industries. The rules and regulations for ships and/or floating platforms (offshore oil and gas industries) need to be customized to accommodate the unique needs for OSU.

Take offshore wind turbines (OWT) as an example. Designs of OWT are heavily influenced by the International Electrotechnical Commission (IEC). IEC is the association that is dominated by the wind turbine manufacturers. The IEC Code 61400-series was developed mostly by the wind turbine industry, based on the experiences and practices of onshore wind turbine (Wang, 2021). The classification societies DNV and ABS have adopted these IEC Codes and have revised their rules for OWT following the moves in IEC. Expectedly, over time, more and more experience will be gained, and the OWT industry along with the classification societies will understand and identify gaps in rules and regulations. See also Hopstad et al. (2020) for an overview of government requirements, standards, guidelines, and other certification requirements within offshore wind for Norway and internationally.

An important revision common to both DNV and ABS rules is related to stability requirements. As shown in the following figure, which is extracted from the ABS Floating Offshore Wind Turbine (FOWT) Guide (American Bureau of Shipping, 2020), the stability curve of the FOWT takes a stepped shape, combining a segment for "power production" and another one for "rotor parked". This is a distinct feature, taking the operating characteristics of an FOWT into account that stops operation if its inclination becomes too large. This is different from many stability curves that are used in conventional offshore applications.

FIGURE 1
Intact Stability Curve for the RNA in Power Production

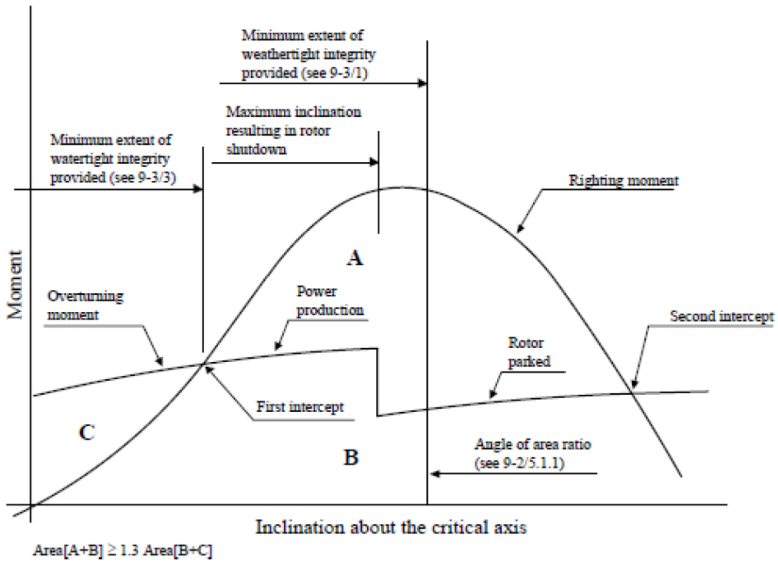


Figure 5.1: Intact Stability of Floating Offshore Wind Turbine (FOWT) (American Bureau of Shipping, 2020)

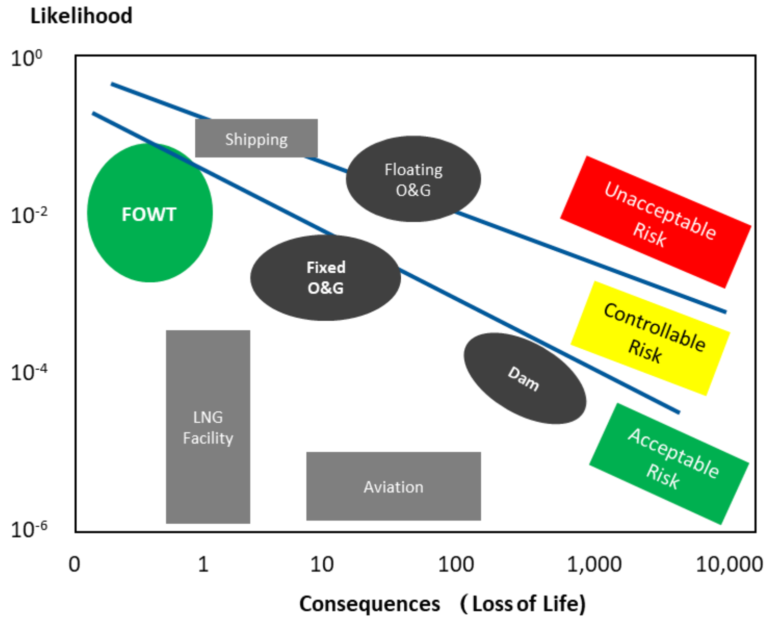


Figure 5.2. Risk of FOWT in comparison with other industries in the scale of Whitman (Wang, 2021)

A main driver of this unique stability curve is the demand for striking a balance between safety and commercial viability. An FOWT is unmanned, which is different from many offshore platforms in the oil and gas industries. Thus, the risk profile of an FOWT is quite different from that of a platform for oil or gas production, see the risk comparison in Fig. 5.2 (Wang, 2021) according to the scale of Whitman (1984). Therefore, FOWT industry needs a different way of managing the risks.

On a different note, floating offshore infrastructure projects and floating cities are intended for use by regular citizens, who, unlike personnel in the shipping as well as offshore oil and gas industry, are not trained for working and living on floating structures. For such projects, inspiration for stability, safety, and comfort regulations may need to be sought in the cruise shipping sector, where thousands of people rely on the safe design and operation of their ship.

Similarly, in deep-sea mining, the technology solutions require contributions in the areas of Remotely Operated (Underwater) Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), and deep-sea-going submersibles. The main challenges seem to be encountered by those bringing samples/minerals from the seabed to the surface. While there are class rules for guiding designs and operations, tremendous opportunities exist in advancing the technologies and rules related to underwater vehicles – manned and unmanned, remotely operated, autonomous or not.

Offshore aquaculture encompasses a broad range of production systems located in deep water marine environments (O'Shea et al., 2019). These operations are fully exposed to open-ocean conditions of wind, waves, storms, and currents. Concerns over limited nearshore sites, environmental sustainability, and food security have also led to new, state-sponsored development projects for offshore aquaculture. Class rules for aquacultures are mostly taken from the experiences in the offshore oil and gas industries. Where they are relevant for the most part, there are many technical challenges that arise from the needs of fishing industry. The structures are much more flexible, for which analysis tools are not necessarily fully tested.

5.3 Environmental concerns

Deep sea mining is an example of great public concerns over environmental impact (Pretlove and Blasiak, 2018). It is difficult to fully estimate the real environmental impact of deep-sea mining exploration and exploitation activities due to the fragility of these ecosystems, the unknown resilience of these systems, and the effectiveness of the anticipated efforts to assist natural recovery (Rademaekers et al., 2015). Nevertheless, it is predicted that these activities will have significant effects if not properly regulated. In terms of deep-sea mining, the most relevant social impacts will likely be associated with several key changes during the mining life cycle, which is potentially a long one (20 - 30 years) and may apply to different stakeholder groups at household, local, regional, national, and international level. Deep-sea mining has been attempted many times by many countries but remains sporadic experiments because of the concerns over environmental damages, the high costs involved, and because of the (im-)maturity of technologies.

It is therefore very relevant to naval architects and offshore engineers to be aware of the high environmental impacts due to the mining operations. With time passing, this environmental concern may introduce innovative technologies that would require redesigns or changes in the way structures for underwater use are designed and evaluated.

5.4 Some technical challenges

Obviously, many of the OSU topics covered in this Committee are new and their applications are few. And yet, some new challenges come into light. There is a need for naval architects and offshore engineers to collaborate with other industries as many of the newly identified challenges require cross disciplinary joint development efforts.

For example, as the offshore wind projects go further offshore, floating wind turbines become increasingly relevant. The offshore wind industry realizes that detailed engineering of an FOWT and accurate calculation of their motions has become a key in design of both the turbine and the support structures. In principle, sophisticated software is needed to simultaneously calculate the aerodynamics of the blades, the dynamics of the tower and floaters, the motion response of the floaters. However, for such a calculation tool to reach the maturity, it has to be developed by many engineers from a diverse range of industries. And this is an example showing the high demand for developing next generation calculation tools in some OSU fields.

6. RISK ASSESSMENT

Risk assessment is a process of risk identification, risk analysis, and risk evaluation, where risk is commonly understood as the likelihood that an (undesired) event occurs multiplied by the magnitude of the event's consequences. This general definition makes risk assessment a very wide field with many sub-topics that could be addressed individually. Table 6.1 gives an overview of the variety of risk assessment topics. In an attempt to order the field, the sub-topics are clustered in the three main categories (1) technological risk assessment, (2) socio-economic risk assessment, and (3) environmental risk assessment. However, this allocation is not exclusive since several sub-topics require considerations in more than one cluster. Table 6.1 lists the risk assessment domains that the committee finds relevant for OSU.

Table 6.1: Overview of risk assessment topics relevant for OSU

Technological Risk Assessment	**Socio-economic Risk Assessment**	**Environmental Risk Assessment**
• Design • Operational • Maintenance • Structural • System	• Marine (traffic and other operations) • Societal impact • Sustainability • Financial • Reputational • Political • Regulatory • Stranded asset • Health • Cyber security	• Climate • Ocean (acidification, hypoxia, marine pollution) • Ecological/Ecosystem • Environmental

There are different methodologies for assessing the risks: qualitative, quantitative, more complex semi-quantitative methods, and combinations those. For traditional marine industries (offshore oil and gas industry, shipping industry) it is common to adopt risk assessment methodologies and procedures from well-developed safety domains like nuclear industry, chemical industry, space industry, and aviation industry. However, for relatively new ocean space utilization activities, e.g., deep sea mining and renewable energy, the situation is more complex since industry practice and/or legislation regulating risk assessment is limited (if at all existing), see also Section 5. Existing frameworks for (marine) risk assessment tend to be sector specific (van Hoof et al., 2020). It is common to look at the risks from a single perspective (e.g., technical, environmental, social, economic) or from a single consequence viewpoint. However, holistic views on risk assessment are gaining momentum.

6.1 Known unknowns

New complex risks are being introduced to ocean ecosystems as industrialization of the world oceans increases. There is a need to account for potential interplay between technical, socio-economic, and environmental factors underlying development and management of the ocean resources. Research on risk is often conducted in distinct spheres (engineering research, social science, environmental science) by experts, whose focus is on narrow sources or outcomes of risk. For instance, some fisheries scientific community has developed a framework for ecological risk assessments based on modelling, statistics, and exposure-consequence method (O et al., 2015). These approaches presume that risk can be assessed objectively, is knowable, and that decision-making involves optimizing expected benefits against net losses. According to Phillips (2015), this interpretation of risk neglects societal perceptions of risk, which is a fundamental component of informed environmental management decisions and societal acceptance of new technology. Neglecting societal risk perception may be less relevant during the risk assessment itself, however, is all the more important before and after that. The following list summarizes some current challenges in risk assessment that are common across OSU fields.

- Large uncertainties of environmental conditions for offshore locations.
- New and unproven technologies without safety track-record.
- Definition of acceptable risk levels.
- Acceptable methods for risk assessment, evaluation, and mitigation.
- Subjectivity in measuring societal and environmental impacts.
- Current standards and regulations do not fit new concepts, e.g., in aquaculture sector.
- Commercial/societal challenges/societal acceptance.
- Interaction between OSU activities.

- Climate change and legislations, e.g., Article 234 of the United Nations Convention on the Law of the Sea.
- Inconsistent national rules and international recommendations, e.g., the Rules for Navigation in the Water Area of the Northern Sea Route and International Maritime Organization (Kim & Panchi, 2021).
- Standards are lagging and industry practice becomes a standard.

In the following subsections, three examples of risk assessment approach in different OSU fields are given. The examples are aquaculture in Norway, Offshore Floating Photovoltaics in the Dutch North Sea, and Offshore Wind Farming in UK coastal waters.

The focus of the examples is on identifying specific challenges in common practices and approaches and/or fundamental knowledge gaps.

6.2 Aquaculture (Norwegian perspective)

Risk assessments are mandatory by law in the Norwegian aquaculture industry and are controlled by the following five regulatory authorities: Directorate of Fisheries, Food Safety Authority, Norwegian Maritime Authority, Norwegian Labour Inspection Agency, and the County Administration. The relevant aquaculture legislation and regulations were described in Holmen et al. (2017). Their analysis of current practices showed that most efforts were put into the documentation of actions to mitigate environmental hazards, i.e., fish escapes (Føre & Thorvaldsen, 2021; Jensen et al., 2010; Thorvaldsen et al., 2015) and that the current practice for risk assessments deviates from regulatory requirements (Holmen et al., 2018, Tab. 3). The largest deviations were found in the planning phase and regarding the involvement of workers in the analysis phase, see e.g., (Thorvaldsen et al., 2020). Furthermore, there was lack of knowledge of risk factors during aquaculture operations. Several challenges were identified regarding risk assessment performance: (1) allocating sufficient time to gather all relevant personnel for risk assessments; (2) lack of motivation as the risk assessment was often seen as an unavoidable “exercise” to satisfy the demands of the authorities or their own management; (3) finalizing the risk documentation was regarded as more important than checking whether the significant risks were understood and mitigated; (4) broad scope of risk assessments; and (5) the follow-up work might not be prioritized. Recommendations on how risk assessment practice could be improved during planning, analysis, and evaluation steps as well as an overview of the risk influencing factors and safety indicators in fish farm operations can be found in (Holmen et al., 2018, Sec. 4; Utne et al., 2017) and (Holmen et al., 2021), respectively.

6.3 Offshore Floating Photovoltaics

In the Netherlands, Offshore Floating Photovoltaics (OFPV) is considered one possible pillar for future renewable energy supply (van ’t Wout, 2021). A first pilot project is already operational in Dutch coastal waters (Oceans of Energy, 2020). Against this background, an MSc thesis was conducted at TU Delft by Ivardi Daroen (2021) to identify the main challenges of an OFPV risk analysis and to propose an approach to handle these challenges. The focus of that study was placed on technological risks. The following challenges were identified.

- For OFPV there was no specific (or standard) risk assessment approaches for technological risks, which prevents a more consistent assessment (IEA, 2011). Only a limited amount of literature regarding OFPV risk assessments was found. The only risk assessments were performed by Gao et al. (2021) and Wu et al. (2019), both multivariate analyses performed in China. These studies covered mainly risk factors related to decision-making for investors and policymakers, including overviews of the PESTLE (Political, Economic, Social, Technological, Legal, Environmental (Kolios, et al., 2016)) risk factors. However, a clear gap was identified in literature assessing the technological risk factors associated with the performance of OFPV systems. This gap included all elements of risk assessment, i.e., the identification of events, risk cause analysis, risk consequence analysis and evaluation. Furthermore, current standards for risk assessment that were established for the offshore oil and gas industry were only applicable to a limited extent (Leimeister and Kolios, 2018). Since the main components of OFPV system included floating support structures, module connectors, PV module support frame, mooring system, and PV power system, the difference between the failure of the structural components and electrical components of the OFPV system needed to be considered.

- Lack of risk cause and quantitative reliability analyses performed for OFPV. For inland floating PV, a limited number of reliability studies was performed in the available literature, which were mainly qualitative. Both qualitative and quantitative risk cause analysis could contribute to risk assessment for OFPV at current development stages. Based on a literature review, Ranjbaran et al. (2019) also concluded that more research regarding the reliability of floating PV was necessary.
- A risk consequence analysis has not been performed for OFPV. For the modelling of scenarios due to an event, the event tree analysis was the most widely used method in literature. However, the physical consequences due to an initiating event and quantification of these consequences were less obvious. To account for the risk consequences, methods were proposed, which incorporated economic aspects and failure costs, such as a cost priority number (CPN) to compare different systems. However, the required additional cost parameters might form an obstacle for OFPV, given the current phase of concept developments and the design confidentiality.
- A multivariate analysis has not been performed for OFPV yet during the risk prioritization. Methods to evaluate the sensitivity of the results have been observed in literature, but these have not been executed yet for OFPV.
- Currently no probabilistic database specifically for OFPV, nor for floating PV in general, has been found in the literature. Leimeister & Kolios (2018) remarked that for novel offshore systems overall, lack of data, data confidentiality, costs, time, and computational efficiency challenged the risk and reliability assessment. The gap in literature regarding probabilistic OFPV data for the quantification of risk and reliability was significant. Note that the descriptive data for an OFPV system was available and sufficient to describe the main functions of the technology and to grade the subsystems and components accordingly. This data was adequate to assess the technical risks of OFPV qualitatively, supplemented by descriptive data for individual subsystems and components from comparable technologies, e.g., land-based PV, inland FPV, and offshore floating structures. However, due to confidentiality of the OFPV concepts currently developed, several design specifications were lacking. Other environmental descriptive data was widely available from the offshore industry and PV industry. When it is not feasible to obtain probabilistic data of an actual OFPV system, a valid way to deal with lacking data is to base failure rates on existing substitute databases from other technologies with more available information, such as the OREDA database. However, the application of substitute databases (from other technologies with more available information) presents another knowledge gap.

To address these challenges, Daroen (2021) first defined his research object as a generic, multi-modular floating OFPV installation situated between four bottom-founded offshore wind turbines in the Dutch North Sea. He conducted a preliminary hazard identification (HAZID) as well as failure mode and effect analysis (FMEA) and showed that these generic concepts were applicable to OFPV. Literature references from other fields were used to identify the possible hazards and failure mechanisms. For the subsequent system reliability analysis, a Fault Tree Analysis (FTA) according to Jonkman et al. (2015) was conducted and Minimum Cut Sets (MCS) were identified following the definition by Rausand & Hoyland (2004). As an example for an element reliability analysis, Daroen (2021) selected a mooring line of the system and applied a structural reliability analysis (see Nilsen et al., 1998) to quantify the failure rate of the element. Rosenblatt transformation was used to obtain normal distributions for the random variables in the limit state function from non-normal stochastic distributions. The normalized distributions were then used in a First Order Reliability Method (FORM). The process for the consequence analysis was outlined using Event Tree Analysis (ETA; Rausand & Haugen, 2020) and scenarios. Eventually, an exemplary risk evaluation based on the quantitative results of the previous steps was conducted using rating scales as proposed by Rausand & Haugen (2020) and Proskovics et al. (2016).

6.4 Floating Offshore Wind Turbines

The risk of Floating Offshore Wind Turbines (FOWT) was assessed and studied in terms of a dissertation research work of Gabriela Grasu (2021) in a joint master's program, MTEC, among Newcastle University, University of Southampton, and University College of London. The following literature review was extracted from her dissertation.

Research and developments of floating offshore wind technology have been performed since the beginning of this millennium and currently the FOWT are part of the long-term strategy of many international agencies and associations. To this date FOWT are still considered as an immature sector. In 2017, WindEurope within its statement "Floating Offshore Wind Vision Statement" (2017), presented the expected commissioning dates for the most advanced European FOWT projects at that time. Table 6.2 compares the initial estimation with their current status.

From Table 6.2, it is noticed that almost 50% of the initial projects were cancelled and only one project was delivered on time. The major factors were the financial support and the technical complexity for maintaining the asset integrity. Both, financial support and maintenance complexity are directly related to the existence of hazards associated with this technology. They are present through the entire life of the project, which starts at design phase and ends with its decommissioning.

Several international agencies, associations and institutions launched and financed research programs to overcome the challenges of FOWT and prepare the path towards commercialization. The International Energy Agency (IEA) facilitated the collaboration, between its member countries, under EU H2020 LIFES50+ project to address the offshore wind challenges by setting up several research tasks, which also included a bespoke risk assessment framework (Proskovics & Hutton, 2016).

The main function of a floating offshore wind turbine is to safely produce sustainable energy at a competitive cost. However, each system composing an FOWT plant will present its own set of specific hazards and associated risk scores, having a distinct impact on the FOWT overall performance. Wind turbine blade failure will trigger very high consequences, especially when occurring during operation. Based on the daily renewable energy newsletters ("Blade and Nacelle Failures," 2021), the most frequent blade failure modes were: blade became loose due to bonding failure of the blade root inserts, blade separated from the hub, blade broke or destroyed, and blade loss due to failure of blade internal structural member known as the shear web. Blade parts or an entire blade could affect the plant systems and/or the supporting sub-structures causing minor or major damage of their function. The same source ("Blade and Nacelle Failures," 2021) also indicated major equipment failure modes such as Rotor-Nacelle Assembly (RNA) collapse or nacelle fire. Failures of the FOWT were identified during the transportation phase, such as extreme heeling of the Floater Unit (Foster, 2016). Cases of capsize and sinkage of the prototypes have been recorded due to improper installation maneuvers or extreme weather conditions ("Extreme Weather Causes Floating Wind Turbine Prototype To Sink," 2011, "Saitec floating turbine capsizes off Spanish coast," 2020, "SKWID Sinks Off Japan," 2014).

Table 6.2: FOWT Project comparison (created in a MSc Dissertation (Grasu, 2021) based on a technical report (Wind Europe, 2017) by Wind Europe.

Project name	**Capacity**	**Country**	**Expected Commissioning date**	**Status (March 2021)**	**Reference**
Dounreay Tri	2x5 MW	Scotland	2018	Under Development with Hexicon	Russell (2020)
Gaelectic	30 MW	Ireland	2021	Cancelled	"4C Offshore, Gaelectric/Ideol Offshore Wind Farm: Project Details." (n.d.)
Hywind Scotland	30 MW	Scotland	2017	Operational since 2017	Equinor (2017)
Wind Float Atlantic	30 MW	Portugal	2018-2019	Fully operational 2020	Richard (2020)
Kincardine	48 MW	Scotland	From 2018	On-going manufacturing and Installation	Cruickshank (2021)
French pre-commercial farms	4x25 MW	France	2020	Newly estimated commission date 2023	Randall-Smith (n.d.)
Atlantis/Ideol project	100 MW	UK	2021	Cancelled	"4C Offshore, Ideol/atlantis Energy1.5 Floating Project Offshore Wind Farm: Project Details" (n.d.)

According to the particularities of each FOWT concept and the complex context of the market where they are deployed, the following conclusions can be drawn.

- The FOWT market specificity and selected concept will determine particular risk sets.
- Many risks related to the Bottom Fixed Offshore Wind are transferrable to the FOWT.
- New specific risks have arisen for FOWT structures and systems, such as capsizing and sinkage of the floating support structures.
- As unmanned structure with little to no hydrocarbons onboard, FOWT has a very different risk profile from offshore oil & gas platform. And as a result, great care needs to be taken when transferring expertise from offshore oil & gas industry to FOWT.
- Asset integrity and maintainability improvements should be achieved by a realistic and comprehensive risk understanding.
- The transparency of risks and their mitigations may encourage financial support.

Note that for all three activities considered above, the application in offshore environment may cause larger environmental loads, corrosion, humidity, icing and thus result in additional challenges related to the performance and safety of these systems including human personnel. In terms of structural safety, accidental collisions with ships should also be considered.

Current research trends in risk assessment domain include: (1) development of methods/tools and infrastructures for dynamic risk assessments; (2) increase of automation system approach to human error and multi-risk approaches; (3) greater involvement of users in the research community, however, this is rarely (if at all) applied in practice.

6.5 Mooring systems

One of the main obstacles for the quantitative risk assessment of the mooring line in Daroen's work (2021) on OFPV was finding the mooring loads. Ikhennicheu et al. (2021) summarized analytical methods to determine the environmental loads of floating PV systems in three reference cases including an offshore condition based on current industrial practice.

Considering external loads, such as wind, waves and current, Ohmatsu (2005) proposed a risk analysis method of the VLFS mooring system. Taking the slowly varying wave drift force and the friction drag component of wind and current load into account, the proposed risk analysis method was found suitable for VLFS with vast horizontal dimensions.

Sulaiman et al. (2013a) described a mooring system design for very large offshore aquaculture ocean plantation floating structure that accounted for forces and environmental loadings. An evaluation of optimum mooring performance in wave, wind and current loadings on mooring components was conducted. Besides, the authors also discussed the suitable safety factors and coefficients for the design of mooring systems for very large offshore aquaculture floating structures. Furthermore, Sulaiman et al. (2013b) conducted a qualitative risk analysis of a floating aquaculture plant with special emphasis on the mooring system. They conclude that “an integrated approach to risk analysis will assist the aquaculture sector in reducing risks to successful operations … and can similarly help to protect the environment, society and other resource users from adverse and often unpredicted impacts” Sulaiman et al. (2013b, p.16).

Hallowell et al. (2018) investigated the mooring system reliability of offshore floating wind farms using Monte-Carlo simulations. The study suggested that the reliability of a multiline system with multiple lines ending on a single anchor degraded significantly when the progressive failures were taken into consideration.

7. CONCLUSIONS & RECOMMENDATIONS

This Committee investigated and summarized the recent developments in the field of Ocean Space Utilization (OSU). After an inventory of current OSU projects and initiatives in various stages, floating infrastructure projects and floating aquaculture form the largest groups of OSU projects outside of the energy sector. For floating infrastructure projects, the focus is on large to Very Large Floating Structures (VLFS). Due to the large horizontal dimensions of these structures, the inhomogeneity of environmental conditions was specifically addressed. For the hydrodynamic loading, motions, and structural response of VLFS, this committee continued the work of the ISSC2006 committee on VLFS (Suzuki et al., 2006). Here the modelling approaches for hydroelastic response including nonlinearities and the treatment of the connectors for multi-modular floating structures were at the focus. Positioning and mooring systems of VLFS as well as other OSU structures were categorized and the current trends as well as challenges were investigated. A survey on existing and emerging rules, regulations, and best practices for OSU applications and risk assessment case studies on offshore aquaculture, offshore floating photovoltaics, and offshore wind turbines complete this report. The conclusions drawn from the individual sections are summarized in the following subsections.

7.1 Environmental conditions

From the overview of environmental conditions related to OSU and involved VLFS, it is concluded that models for the prediction of extreme ocean events on very large structures should take temporal and spatial variability into account.

Furthermore, wave scattering by the floating structures should be considered, as opposed to ships and conventional offshore structures, where this effect is commonly neglected. E.g., floating breakwaters are specifically designed to reduce the wave height on their leeward side, and artificial islands or floating cities of several square kilometers in size will also cause significant wave scattering that alters the wave conditions in their vicinity.

An additional aspect of environmental conditions specific to Offshore Floating Photovoltaics (OFPV) and some forms of aquaculture is the solar irradiation. This information is scarce for nearshore and offshore locations and can differ significantly from data obtained from nearby land-based stations.

Regarding the ecological impact of very large floating structures, the fact that these structures on the one hand block the sunlight entering the water and on the other hand provide hard substrate offering a new habitat for marine organisms should be considered.

7.2 Global loading, motions, and structural response

For the analysis of global loading, motions and structural response, hydroelasticity of monolithic and multi-modular structures introduces several nonlinear effects. These nonlinearities pose the most critical challenge for analysis methods and calculation programs. The inhomogeneity of environmental conditions and variable seabed bathymetry add to the complexity of the loading and response analysis.

The four key challenges for the development of engineering solution for VLFS are summarized below.

- Effective nonlinear time domain hydroelasticity theories need to be developed to achieve more accurate analysis results for dynamic responses of VLFS under complex sea states.
- Model testing technology for VLFS needs to be improved to meet the challenges of similarity law and complex boundary conditions associated with large model scale ratios to provide a reliable verification and validation basis for the development of newly proposed theories.
- Simplified methods for preliminary design and analysis of VLFS need to be developed. This is particularly important for conceptual designs of VLFS in engineering practice.
- With the proposal of more flexible floating structures for Offshore Floating PV applications, efficient numerical tools need to be developed to consider nonlinear effects of large deformations and wrinkling.

7.3 Positioning and mooring

Three main station keeping systems for OSU structures were identified. These are (1) caisson or pile-type dolphins with rubber fender systems for strict limitations on horizontal motions and shallow water depth; (2) mooring lines, which are the most common station keeping solution; and (3) dynamic positioning, which was rarely considered for the OSU structures covered in this report.

The knowledge and best practices from the conventional offshore oil & gas sector can in great part be transferred and applied to mooring design of more general OSU applications. However, the financial constraints and several of the technical challenges in OSU fields are different. Relevant practical solutions have been introduced to reduce the initial and operational costs, the operational loads, and the environmental impact.

The existing design tools and recommended practices can in general address the challenges involved with OSU mooring system design, however, with quite large uncertainties in several cases. Using the existing tools often implies over-simplifying physical phenomena, which are specific to the OSU structure under analysis. Therefore, there is a need for new developments and improvements on numerical modelling. The challenges related to establishing design loads and responses for non-conventional structures include

- Correct representation of hydroelastic responses of flexible structures and their effects on mooring loads.
- Considering complex coupling effects both hydrodynamic and mechanical.
- Using correct force models for slender structures and fish net panels.
- Considering complex bathymetries both in terms of hydrodynamic effects and mooring system configuration.

7.4 Rules, regulations, best practices

When considering the landscape of rules, regulations, and best practices for OSU applications, large uncertainties come to light. With most structures and projects under consideration being one-of-a-kind solutions, there is little by way of established rules and guidelines. However, classification societies and other regulating bodies strive to quickly develop guidelines derived from their experience in the conventional offshore industry as well as bottom-founded offshore wind turbines. Floating Offshore Wind Turbines currently receive much attention in the field of Offshore Renewable Energies. The complex interaction from aerodynamics via structural dynamics to hydrodynamics and mooring systems requires a holistic approach from many engineering disciplines and dedicated simulation software still needs to be developed.

Another challenge for widespread Ocean Space Utilization with floating infrastructure and even floating cities is the lack of governance models for such applications. Depending on the location, from coastal waters to the exclusive economic zone, different rules can be applicable even within the same country. International waters are again subject to another set of rules. Furthermore, most national laws do not foresee in floating structures being traded and used in the same way as real estate onshore. Here, social sciences and legal studies are required to develop the appropriate governance models.

7.5 Risk assessment

The risk assessment case studies on offshore aquaculture, offshore floating photovoltaics, and floating offshore wind turbines underlined that these are mainly new technologies, where there are no readily available methods for risk assessment and no empirical data to build on. The experience from the offshore oil and gas industry is not easily applicable to many OSU fields due to different risk picture as most OSU structures are either unmanned like OFPV, FOWT, or intended for use by many people like floating infrastructure. The experience of the established offshore industry provides a valuable starting point for the OSU risk assessment. However, a systematic risk assessment procedure needs to be developed to take the differences between the different industries into account.

7.6 Recommendations

Based on the literature review presented above and the conclusions, the following recommendations for future research related to Ocean Space Utilization are given.

Dedicated studies on inhomogeneity of environmental conditions in prospective locations for OSU with very large floating structures, e.g., the North Sea and Mediterranean Sea for large-scale OFPV applications should be conducted.

Efficient numerical tools for the coupled mooring analysis of very large and flexible floating structures should be developed, where the interaction of the mooring system and the flexible structures has a significant influence on the mooring loads and structural response. Furthermore, new numerical tools should be prepared for FOWT analysis that couple aerodynamics, hydrodynamics, structural responses, and mooring dynamics.

The aforementioned developments in the numerical field also require the development of experimental techniques and laboratory setups that allow for the correct scaling of all relevant parameters and effects, including aero- and hydrodynamic loads, structural and mooring stiffness, as well as nonlinear effects from multi-body interconnections.

For the development of industrial standards and best practice guides for design and operation of the broad spectrum of OSU applications, experience from those OSU fields that are further developed, e.g., offshore aquaculture and offshore wind, as well as from conventional offshore oil and gas industry should be gathered and taken into account. This cross-reference will aid greatly in the development of safe and cost-effective designs for other OSU applications.

In terms of governance, Ocean Space Utilization is mostly terra incognita. Therefore, dedicated studies on marine spatial planning, governance of the ocean, and international maritime legislation are recommended to develop a legal framework that enables a sustainable utilization of ocean space.

Overall, OSU projects require a holistic approach including technical, socio-economic, and environmental aspects. Engineers tend to focus on the technical aspects of a project, whereas the business case and the societal acceptance including environmental viability of a project are inevitable factors that determine the project’s success or failure.

Obviously, many of the OSU topics covered in this Committee are new and their applications are few. And yet, some new challenges came into light. There is a need for naval architects and offshore engineers, hydrodynamicists, and marine structural engineers to collaborate with other industries as many of the newly identified challenges require cross-disciplinary joint development efforts.

The utilization of ocean space by humans may have started millennia ago, now it is on the verge of a new era, in which industrial scale utilization has to be sustainable for generations to come.

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