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Toward the Realization of Concrete Floating Structures for Offshore Wind Power Generation in Japan

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Abstract. In this paper, an overview of the contents of the Design and Construction Guidelines for Concrete Floating Offshore Wind Power Facilities in Japan was provided. According to the guideline, a case study of a concrete floating structure supporting 10MW wind turbines was presented. The structural safety and durability were assessed based on stresses and strains obtained from nonlinear FE analysis even if the design load case applied in this study was limited. It is expected that further detailed examinations of concrete floating structures ultimately contribute to adoption and promotion of concrete floating structures in the world.

1 Introduction

The use of renewable energy is expanding worldwide. In Japan, there is a policy to increase offshore wind power generation, which is expected to be a key player in renewable energy, to 30 to 45 gigawatts (GW) by 20401). Particularly, Japan has relatively limited suitable land areas for onshore installations but ranks sixth in the world in terms of the exclusive economic zone (EEZ) including territorial waters. There is high anticipation for the installation of offshore wind power generation. It should be noted that in the case of bottom-fixed systems, technology development has advanced mainly in Europe. However, for floating systems, our country has had various experiences relatively early on in the world [1]. Due to the limited shallow coastal areas suitable for bottom-fixed systems along our coastline, considerations for the introduction of floating offshore wind power generation had been progressing. While attention tends to be focused on the scale and speed of floating offshore wind power projects overseas [2,3], the development of floating systems is currently a global competitive research field.

Now, let's consider the goals mentioned earlier by the government-industry council. Among the 45 GW of wind power generation targeted for 2040, assuming 24 GW for bottom-fixed offshore wind turbines and 21 GW for floating offshore wind turbines. When converted to the largest 10-megawatt (MW) turbines currently available, this would be equivalent to approximately 2,100 turbines. Even with the unrealistic assumption of constructing one wind power generator per day without breaks, it would take around six years to achieve this, and

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it is not a feasible number even if the existing shipbuilding-related industries were operating at full capacity.

Necessarily, we must consider utilizing the concrete industry, which can provide a wide base nationally and can complete everything from material sourcing to construction domestically, for floating platform construction. Here, in March 2023, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) released the Design and Construction Guidelines for Concrete Floating Offshore Wind Power Facilities [4] (referred to as the "Guidelines (Supplement)" hereafter). In this article, we provide an overview of the content within these Guidelines (Supplement) and discuss the current challenges in concrete floating platform design in our country, along with presenting a design study for a concrete floating platform intended for 10MW-class wind turbines.

2 Design and construction guidelines in Japan

2.1 Design Principals for Concrete Floaters based on the guidelines

The Guidelines (Supplement) is divided into Part 1, Part 2, and Reference Materials. In Part 1, the Guidelines (Supplement) are positioned as an appendix to the "Technical Standards and Safety Guidelines for Floating Offshore Wind Power Facilities (March 2023) [5] " (hereinafter referred to as the "Guidelines (Main Text) ", which were previously released by the Maritime Bureau of the Ministry of Land, Infrastructure, Transport and Tourism. The Guidelines (Main Text) provide common requirements for the design and construction of floating offshore wind power facilities, applicable not only to concrete but also to other materials.

In the Guidelines (Supplement), important points are outlined in Part 1 as premises, including statements such as: 'The design lifespan (design service life) must be set as the greater of the design specification-based service life of the wind power generation equipment to be installed or 20 years.' 'The required performance includes durability, safety, and usability, excluding recoverability.' Any content related to specific technologies or evaluations not included in Part 1 is documented in Part 2.

In the Part 2, in terms of performance requirements, the Japan Society of Civil Engineers (JSCE) and the International Electrotechnical Commission (IEC) have distinct standards. However, as a fundamental principle in the Guidelines (Supplement), it is stated that the wording from the JSCE Concrete Standard Specifications [Design] [6] should be adopted. The definition of limit states can be determined by to the JSCE Concrete Standard Specifications [Design]. In the limit state design, various partial safety factors are employed; material factors, structural analysis factors, and factors of members are to be consulted based on the JSCE Concrete Standard Specifications [Design], while other factors are to be referenced from the Guidelines (Main Text). It should be noted that the combinations of load cases to be considered in design and values of load factor are problematic to understand. However, for further insights, reference material is provided at the end of the Guidelines (Supplement), which offers a comparative analysis of load cases and load factors from the Guidelines (Main Text), the JSCE Concrete Standard Specifications [Design], and Det Norske Veritas and Germanischer Lloyd (DNVGL).

2.2 Verification for Safety, Durability and Serviceability of Concrete Floater

The modelling and analysis methods of members and structures to calculate the sectional forces or stresses acting on the floating body are always problematic. The calculation of sectional forces involves the fundamental approach of performing coupled analyses of the entire structural system consisting of the wind turbine, tower, floating body, and mooring system. Additionally, the Guidelines (Supplement) is stated as a standard requirement that dynamic response analysis methods in the time domain should be used. Unlike dynamic analyses performed for seismic design of onshore structures, there are specific conditions unique to floating bodies, such as setting boundary conditions considering buoyancy and mooring, modelling fluid resistance, and dealing with input values for wind and waves. These aspects can be complex to comprehend, but the Guidelines (Supplement) do not explicitly provide detailed information on these specific issues.

The verification of structural safety based on sectional forces and stresses is outlined in the Guidelines (Supplement). Essentially, it refers to the JSCE Concrete Standard Specifications [Design]. The guidelines specify that it is sufficient to conduct verifications for ultimate limit states and fatigue limit states. Regarding the examination of fatigue limit states, the guidelines state specific aspects unique to concrete floating structures. These include irregular dynamic loads, the resonance and damping of structural systems due to complex loads from wind and wave, and considerations for fatigue at the tower – floater joint and mooring equipment connections, taking into account the difference between dry and wet/submerged concrete. This difference is important to consider a potential reduction in the concrete's design fatigue strength.

The verification regarding durability also refers to the JSCE Concrete Standard Specifications [Design]. It includes inspections for steel corrosion due to carbonation and water infiltration, inspections for steel corrosion resulting from chloride ion penetration, and inspections for freeze damage. Additionally, appropriate measures are stipulated for the inhibition of alkali-silica reaction. However, criteria are specified specially for offshore wind floaters in the Guidelines (Supplement). For instance, in the verification of crack width concerning steel corrosion, the upper limit of the design threshold value is smaller, at 0.2mm, compared to the 0.5mm for typical structures determined in the JSCE Concrete Standard Specifications [Design]. Similarly, the chloride ion concentration on the concrete surface, in cases where data is unavailable, a value of 18.0 kg/m^3 is indicated. This value exceeds the maximum threshold (13.0 kg/m^3) established for structures used in coastal areas (ports or inland) determined in the JSCE Concrete Standard Specifications [Design]. As the number of installation cases in similar marine environments increases in the future and real-world data becomes available, it is expected that appropriate values will be set.

The verification of serviceability is briefly described as conducting a watertightness inspection and referring to the JSCE Concrete Standard Specifications [Design]. In the JSCE Concrete Standard Specifications [Design], the principle is to examine permeability as an indicator of watertightness. When considering service in environments with high hydrostatic pressure, such as spar-type structures, it is necessary to discuss in setting threshold values with special cautions on selected material.

3 Preliminary designs for 10MW wind turbine

3.1 Stability and motion analysis

Preliminary designs of concrete floaters for 10MW wind turbines by authors are shown in Fig. 1. The feasibility of multi-column semi-submersible type and spar type are mainly studied. The sensitivity analysis was performed to define a feasible geometry that, regardless of the mooring lines installed, must have sufficient hydrostatic stability as required by DNV's standard [7]. The selected spar geometry was coupled with the reference wind turbine IEA 10MW [8] and mooring lines to compute static stability properties, preparing for coupled dynamic analysis. Specifically, for spar type, structural response under wave action was evaluated by code “WAMIT” which computes wave loads and motions of floating structure in wave based on the linear and second-order potential theory [9]. The coupled dynamic analysis was performed by OpenFAST [10].

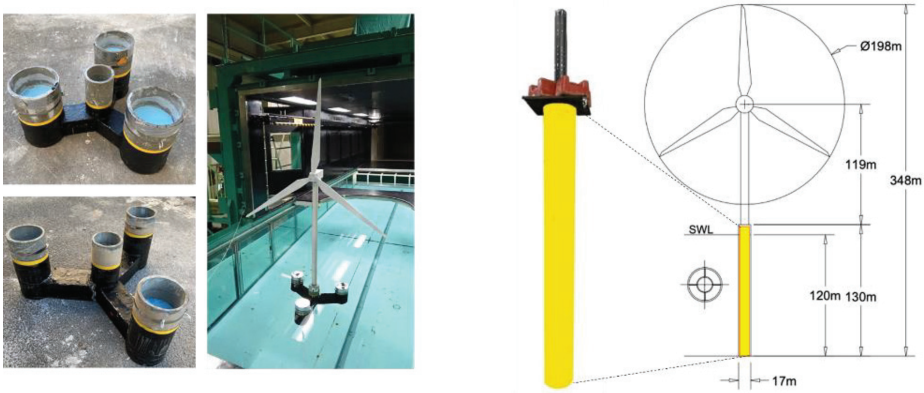
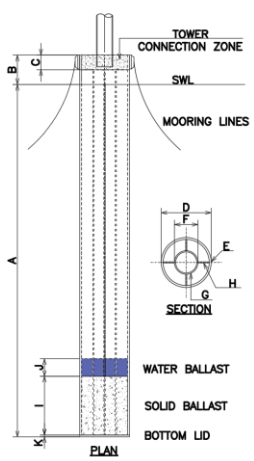


Fig. 1. Feasibility study of concrete floater for multi-column semi-submersible type and spar type

3.2 Design verification of concrete spar in terms of structural safety

The main dimension of the proposed spar is presented in Fig. 2. The spar has been developed considering the economic aspects of using regular concrete. The ballast control system was considered in the spar installation process to comprise solid ballast (black blast furnace slag with a unit weight of 28.00 kN/m^3) and seawater with a density of 10.26 kN/m^3. Three lines of R4 stud diameter of 0.095 m and unstretched length of 550 m, with each line at an angle of 120°, were applied as mooring lines [11].



LABEL	DESCRIPTIONS	[m]
A	DRAFT	120.00
B	AIR GAP	10.00
C	TOWER CONNECTION	5.00
D	EXTERNAL DIAMETER	17.00
E	HULL THICKNESS	0.60
F	INTERNAL TANK DIAMETER	8.00
G	INTERNAL TANK THICKNESS	0.40
H	INTERNAL WALL THICKNESS	0.40
I	FIXED BALLAST HEIGHT	10.50
J	WATER BALLAST HEIGHT	5.73
K	BOTTOM LID	0.60

Fig. 2. Main dimensions and variables of the concrete spar model

The forces transfer from the top part of the spar were obtained from time domain results of coupled dynamic analysis. For the static analysis, the highest forces were taken from each time domain, and the dominant load case, as shown in Table 1, was selected and applied to the FE model. Hydrodynamic pressure was extracted from the highest recorded pressure computed by WAMIT. Hydrostatic pressure can be defined using $P = \rho g h$, where g is gravitational acceleration, ρ represents the density of seawater, and h is the water depth.

Forces applied to the FE analysis were demonstrated in Fig. 3. The time-step monotonic static load ; forces composed of tower base reaction, mooring tension, water pressures, were applied in the FE analysis [11].

Table 1. Forces exerted from the top part applied in FE analysis

Fx [kN]	*Fy* [kN]	*Fz* [kN]	*Mx* [kN.m]	*My* [kN.m]	*Mz* [kN.m]	*T1* [kN]	*T2* [kN]	*T3* [kN]	Ø [degree]
2994	-372	-13537	47661	261,274	3160	7916	1231	1231	20.7

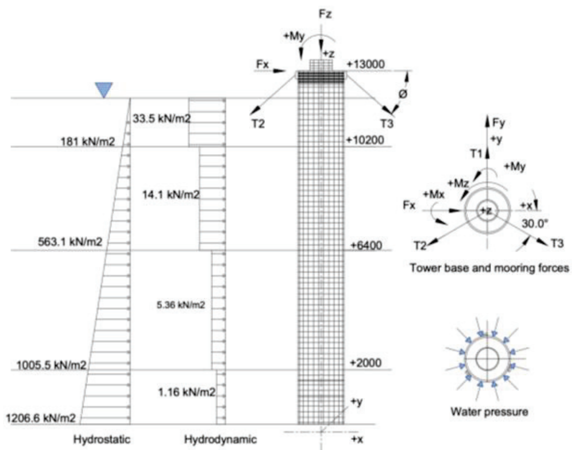
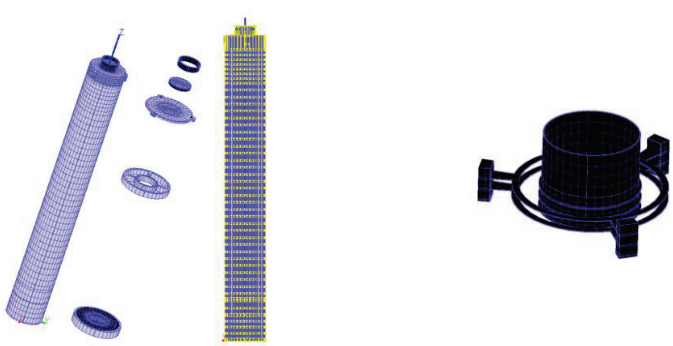


Fig. 3. Forces applied to FE analysis

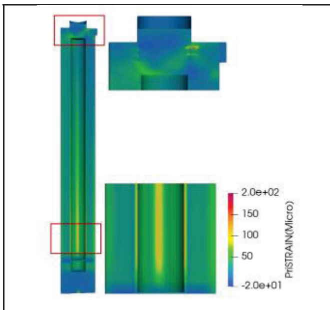
The FE model utilized a normal concrete compressive strength of 41MPa. The 0.2% and 0.15% reinforcement ratio were applied for vertical and horizontal reinforcing bars, respectively. Steel material class S355, with a yield strength of 355MPa, was employed for tower and fairlead connections. Under the assigned boundary conditions, the bottom end of the spar was constrained in the vertical direction, and the fairleads were restrained in the horizontal direction. A round-shaped steel with triple rip layers has been installed as a steel tower connection. The steel connection plate connected to steel rings has been utilized to resist large mooring tension for the fair lead connection. The overall model mesh based on the parametric design and preliminary tower connection, together with the fairlead connection, are shown in Fig. 4 [11].



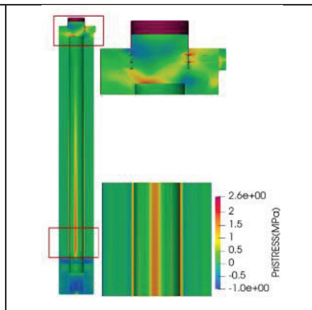
(a) Overall FE model (b) Tower and fairlead connections

Fig. 4. FE model with tower and fairlead connections

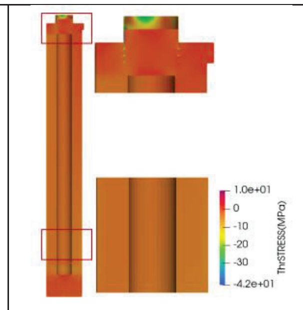
Localized stress and strain values of the proposed spar are presented in Fig. 5. The red-highlighted area in Fig. 5(a) means the tensile strain in concrete is over than the critical tensile strain 200με in which the microcrack starts to generate due to the material softening. In Fig. 5(a), a slightly red color only occurs at the tower connection. Although the structure is under significantly large water pressure, particularly at the bottom of Fig. 3, the analysis results suggest that the hull surface is under compression, as indicated by critical tensile strain in Fig. 5(a). This is attributed to the sufficient thickness of hull concrete. Fig. 5(b) presents tensile stress. The red color means the stress exceeded the concrete tensile strength (2.60MPa); however, this stress is generally resisted by reinforcing bars and prestressing tendons installed in concrete. Fig. 5(c) illustrates compressive stress, which generally is below 10MPa. Therefore, normal concrete with a compressive strength of 41MPa can be used to design the proposed concrete spar.



(a) Maximum principal strain



(b) Maximum principal stress



(c) Minimum principal stress

Fig. 5. Stress-strain localization and structural displacement obtained from the FEA

3.3 Design verification of concrete spar in terms of durability

Owing to the full prestressing design for main hull, tensile strain appeared only on the non-structural reinforced concrete members, i.e. internal partition wall which is designed for ballast control. The maximum tensile strain was at most 200 μ. However, it was decided to verify the crack width considering seawater use as ballast. The calculated maximum crack width based on the Guidelines (Supplement) with 80mm cover depth was 0.139mm. It was satisfied design limit value 0.200mm. The examination of the chloride ion concentration for the 41MPa concrete with water to cement ratio 0.36 was passed as well.

4 Conclusions

In this paper, we provided an overview of the contents of the Design and Construction Guidelines for Concrete Floating Offshore Wind Power Facilities in Japan and presented a case study of a concrete floating structure supporting 10MW wind turbines. However, the design load case applied in FE analysis was limited. The complete set of design load cases specified in the design standards should be applied in future studies. It is expected that further detailed examinations of concrete floating structures ultimately contribute to adoption and promotion of concrete floating structures in the world.

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