Comparison of concrete and steel semi-submersible floaters for 10MW wind turbines

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Abstract. Prestressed concrete floaters are gaining growing interest for floating wind turbines, while different material properties can affect the characteristics of floater motions and the range of suitable floater geometries. In this study, a basic geometry of a semi-submersible floater for 10MW is designed, based on which sensitivity study of the material property on floater design is conducted. It was found that minimum floater pitch angles achieved by selecting the optimum floater geometries were similar for the three types of material, while larger values of geometrical variables were required for concrete floaters than for steel floaters for a floater pitch limitation. If larger wall thickness was to be required for concrete structures due to, for example, corrosion protection and crack limitation, generally larger side column width and lower hull length were required for concrete floaters. As the sensitivity of pitch angle to the wall thickness was more affected by wind excitation than wave excitation for normal concrete, it is indicated that the design space for the length of hull can be widened by combining the design with the wind turbine controller methods in the treatment of the maximum thrust force. Lightweight concrete had advantages over normal concrete in the lower center of gravity. The raw material cost of lightweight concrete was higher than normal concrete but significantly lower than steel floaters.

1. Introduction
Prestressed concrete (PC) is gaining growing interest for floating wind turbines for advantages such as low material cost and flexibility of construction site. Concrete has different material properties compared to conventionally used steel. Steel has larger material density and higher strength, which usually result in smaller volume and lower total material weight. Concrete has lower material density and lower structural strength, which usually requires larger volume and larger weight. Another difference in the feature of the material properties between concrete and steel is that while steel has relatively constant material properties, that of concrete vary in wide range depending on the types of the cement and aggregates used in the composition. Different material properties may affect both the characteristics of floater motions and the range of suitable floater geometries. Investigation of these characteristics for concrete floaters in comparison with the widely used steel can give insights for future utilization of concrete for floating wind turbines.

Several designs of concrete floating platforms have been provided for wind turbines. Viselli et al. (2015) [1] and Yu et al. (2018) [2] proposed semi-submersible floaters, Campos et al. (2014) [3] designed a spar-type floater, and Walia et al. (2017) [4] studied TLP type floaters. In these studies, aspects of concrete floaters such as the floater motion, the cost leverages, and construction methods were studied. Results for direct comparison with steel floaters and consideration of variety of concrete structures are limited.
The objective of this study is to investigate the differences in the floater motion and floater geometries for different material properties. First, a basic geometry of a semi-submersible floater is designed with several geometrical variables. Three typical types of material, normal concrete, lightweight concrete, and steel are chosen to study the effect of material properties on the pitch motion and geometrical variables. Using the results from frequency domain analysis, the characteristics of concrete floater motions and design spaces are discussed. Finally, a simple comparison of raw material cost is conducted.

2. Design basis of the semi-submersible floater

2.1. Wind turbine and tower

DTU 10MW reference model\(^5\) was used for the wind turbine mounted on the floater. The mass, geometry and the controller of the wind turbine were the same as the definitions in reference [5]. The steel tower was newly designed for present floater, to avoid 3P and 9P of the blade rotation, and to withstand the ultimate strength for a spar type floater with the same wind turbine model. Details of the spar type floater and the coupled analysis performed for the tower design can be found in reference [6]. The basic properties of the wind turbine and the steel tower is summarized in Table 1.

| Table 1. Basic properties of the mounted wind turbine and the steel tower |
|-----------------------------------------------|
| Hub height | 119 m | Hub mass | 105,520 kg |
| Nacelle mass | 446,036 kg | Hub CG | (-7.073, 0, 119.0) |
| Nacelle CG | (2.687, 0, 118.08) | Tower mass | 780,900 kg |
| Blade mass (3 Blades) | 132148 kg | Tower CG | (0, 0, 60.58) |

2.2. Metocean conditions

The target site to install the semi-submersible floating wind turbine was set at the same location with the Fukushima FORWARD project. Metocean data for the site was investigated in references such as [7], and is summarized in Table 2. For the design load case, DLC1.6 of IEC61400-3-1 [8], which is the operational case in extreme condition, was considered in the sensitivity study conducted in this study.

| Table 2. Summary of the metocean condition |
|------------------------------------------|
| Water Depth | 120 m | Significant wave height, 50 years return period | 11.71 m |
| 10 min average wind speed, 50 years return period | 48.3 m/s (at 60 m height) | Significant wave period, 50 years return period | 13.0 s |

2.3. Material properties

Concrete structures have variety in the material properties depending on the types of the material and the ratio they are used in the composition. To represent the wide range of the material density, two types of typically used concrete were chosen. One is normal concrete, which is the commonly used in wide range of structures. The other is lightweight concrete, which use aggregate with lighter density in the composition to reduce the material density. This type of concrete is commonly used in structures such as bridges, where the dead weight has significant portion in the design load. The material density of normal concrete is approximately 2500 kg/m\(^3\), and that of lightweight concrete is approximately 1800 kg/m\(^3\).

Wall thickness of prestressed concrete structures is sometimes determined not only from the structural strength but also from the requirements such as covers for the steel, distance between the prestressing or reinforcing steel bars. These requirements also dependent on design parameters such as the type of cement and anticorrosion methods. To determine realistic range of wall thickness for concrete floaters, a simplified cross-section design was performed for a normal prestressed concrete based on the design standards from Architectural Institute of Japan [9], [10], and DNV GL [11], where the most
severe requirement of the three standards was used. The designed concrete cross section is shown in Figure 1, and the requirements considered in the design is summarized in Table 3. The distance between the PC sheaths were calculated assuming the maximum size of the coarse aggregate as 25 mm. It is seen from Figure 1 that the wall thickness was approximately 380 mm when the requirements shown in Table 3 were considered. Using this result as reference, the range of wall thickness to be used for the sensitivity study was determined as 350 mm to 550 mm.

For steel, material density of 7874 kg/m$^3$ was used. The wall thickness of steel structure usually depends on the required strength and the range was set as 16 to 40 mm for the sensitivity study. Water was used for ballasting considering the convenience of construction and maintenance. The material properties for the three types of material are summarized in Table 4.

![Figure 1. Designed cross section of a normal concrete structure](image)

Table 3. Summary of the requirements used for the cross section design

| Requirement                     | Value                  |
|---------------------------------|------------------------|
| Covering depth for PC steel     | $> 90$ mm              |
| Distance between PC sheaths     | $> 355$ mm             |
| Covering depth for reinforcing steel | $> 75$ mm         |
| Distance between reinforcing steel bars | $> 100$ mm   |

Table 4. Summary of the material properties for the sensitivity study

| Material Property                | Normal concrete | Lightweight concrete | Steel          |
|----------------------------------|-----------------|----------------------|----------------|
| Material density                 | 2500 kg/m$^3$   | 1800 kg/m$^3$        | 7874 kg/m$^3$  |
| Wall thickness, $C_t$            | 0.35 – 0.55 m   | 0.35 – 0.55 m        | 0.021 – 0.040 m|
| Ballast density (water)          | 1025 kg/m$^3$   | 1025 kg/m$^3$        | 1025 kg/m$^3$  |

3. Parametric design of the semi-submersible floater

3.1. Basic floater geometry

A semi-submersible floater was designed as shown in Figure 2. The floater consists of three side-columns, three lower hulls, three upper hulls and one main column. Square and rectangular cross-sections were used in this study. To limit the number of variables, several geometrical parameters that usually have smaller freedom in the design process were fixed. Draft was fixed to 20 m. The height of the location of the upper hull, which is usually determined from the requirement for air gap, was fixed to 10 m. Considering that smaller upper hull height is expected to lower total center of gravity (CG) while sufficient structural strength as a beam is required, the height of the upper hull was fixed to 3.5 m. Then, three geometrical variables, $L_{sc}$, which is the length of the side column, $L_{arm}$, which is the length of the lower hull, and $H_{lb}$, which is the height of the lower hull are the remaining variables required to be defined for the designed semi-submersible floater. Optimum geometries of the semi-submersible floater were studied for these three variables for the three types of material defined in Table 4. The
sensitivity study conducted in this study was simplified where the two geometrical variables were fixed when one variable was studied.

Figure 2. Basic geometry of the designed semi-submersible floater

Figure 3. Sensitivity of the total center of gravity to the geometrical variables

3.2. Effect of geometrical parameters on rigid body properties

The center of gravity and the pitch natural period are two of the properties of the total rigid body system that affect the pitch motion. Sensitivities of the two parameters to the geometrical variables were studied for the three types of material. Typical results of the dependence of the center of gravity on the geometrical variables are shown in Figure 3 for the three types of material. Here $L_{sc}$ was fixed to 13 m, $L_{arm}$ was fixed to 36 m, and $H_{th}$ was fixed to 7 m when one variable was being studied. $C_t$ denotes the wall thickness. It is seen from the figure that for all the geometrical variables, when the value of the parameter was increased, the height of the center of gravity generally decreased for all material types. For the same geometry, lightweight concrete and steel had lower center of gravity compared to normal concrete. This is because of the smaller total material weight requiring larger ballast in the hull that
lowers the center of gravity. An example of the results of the dependence of the pitch natural period on the geometrical variable are shown in Figure 4 for normal concrete. As can be seen from the figure, only $L_{sc}$ and $L_{arm}$ was contributing to the change in the pitch natural frequency, and the effect of $H_{th}$ was limited. While the effect of wall thickness was visible for the center of gravity as shown in Figure 3, the effect was limited for the pitch natural frequency. The same trend of the dependence of the pitch natural frequency on the geometrical variables was also seen for lightweight concrete and steel.

3.3. Outline of the frequency-domain analysis

Floater response in extreme condition was estimated to study possible design range of the semi-submersible floater. For the load case, DLC1.6 in IEC 61400-3-1 was used, which is the load case of wind turbine operation in extreme environmental condition. As the responses of many combinations of the geometrical variables were to be calculated, the floater motion was approximately obtained using frequency domain analysis, where the wave excited motion and wind excited motion were calculated separately. First, wave excited floater motion $u_{G}$ was obtained using the equation of motion shown in Eq.1. Here $u_{G} = (x, z, \theta)$, where $x$ is surge displacement, $z$ is heave displacement, and $\theta$ is pitch displacement in the global coordinate system.

$$M_{G}\ddot{u}_{G} + C_{G}\dot{u}_{G} + K_{G}u_{G} = F_{hydro} \quad (1)$$

where $M_{G}$, $C_{G}$, and $K_{G}$ is the mass, damping and stiffness matrix of the total system respectively, and $F_{hydro}$ is the wave excitation force. These matrices were obtained by summing the matrices for all the floater members; the side column, lower hull, upper hull, and main column, using the coordinate transformation matrix $T_i$ for i-th member as shown in Eq. 2 and Eq. 3.

$$M_{G} = \sum_{i} T_{i}^{T}(M_{i} + M_{a,l})T_{i}, \quad C_{G} = \sum_{i} T_{i}^{T}C_{i}T_{i}, \quad K_{G} = \sum_{i} T_{i}^{T}K_{i}T_{i} \quad (2)$$

$$F_{hydro} = \sum_{i} T_{i}^{T}f_{hydro,i} \quad (3)$$

where $M_{i}$, $C_{i}$, and $K_{i}$ is the mass, damping and stiffness matrix for the i-th member respectively defined in the member coordinate system with origin at the center of gravity of the member. $M_{a,l}$ is the added mass, and $f_{hydro,i}$ is the wave excitation force for i-th member. Wave was modelled with Airy wave theory as shown in Eq. 4.

$$\eta = \text{acos}(\kappa X - \omega t), \quad \varphi = \text{cae}^{kz}\sin(\kappa X - \omega t) \quad (4)$$

where $\eta$ is the instantaneous wave height, $a$ is the wave height, $\kappa$ is the wave number, $\varphi$ is the velocity potential, and $c$ is the phase velocity. The vertical wave excitation force was approximated with the summation of the fluctuating buoyancy, the Froude-Krylov force, and the diffraction force as shown in Eq. 5.

$$f_{hydro,i} = \rho g A_{w}\eta + \int_{-z_{0}}^{z} (\rho A_{w} + m_{az})\frac{\partial^{2} \varphi}{\partial z^{2}} dz \quad (5)$$
where $A_w$ is the cross-sectional area, $m_{az}$ is the added mass in the vertical direction, $z_0$ is the z coordinate of the bottom of the floater member, $z_1$ is distance between the center of gravity of the member and the bottom of the member, and $z_2$ is the distance between still water level and the center of gravity of the member. The frequency domain analysis was verified using an in-house time-domain coupled analysis tool NKUTWin [12], in which the hydrodynamic force is calculated with Morison’s equation. The results of a verification case where $L_{sc} = 12$ m, $L_{arm} = 35$ m, $H_{th} = 7$ m, $C_{ax} = 1.1$, and $C_{az} = 0.5$ are shown in Figure 5. Figure 5 (a) and (b) show the comparison of the response amplitude operators for heave and pitch respectively, and Figure 5 (c) shows the pitch response under irregular wave of $T_s = 13.0$ s and $H_s = 11.3$ m. It is seen from the figures that the results from frequency domain analysis gave similar results with the time domain analysis.

![Figure 5](image_url)

**Figure 5.** Comparison of (a) heave RAO, (b) pitch RAO and (c) irregular wave response for frequency domain and time domain analysis

Inverse FFT was applied to the frequency domain response to obtain the maximum floater pitch angle excited by irregular wave. To take the effect of random phases into account, 12 seeds of random vector were generated for the inverse FFT, and the average of the 12 results were used as the final pitch angle. As can be inferred from the results shown in Figure 5 (a), waveless point, which is the wave period where the sum of the fluctuating buoyancy, the Froude-Krylov force, and the diffraction force becomes zero, is likely to occur between 10 to 20 sec, which is the range coincide with the input wave periods. Since the waveless point is determined from the floater geometry, the sensitivity study can be strongly affected by the setting of the significant wave period of the irregular wave. To limit this effect, wave excitation was calculated for significant wave periods of 12sec, 13sec, and 14sec, and the maximum pitch angle obtained from the three cases was used for the sensitivity study.

For the wind response, the floater pitch angle was calculated using static equilibrium of the thrust force and the restoring moment. The instantaneous maximum of the thrust force of the onshore DTU10MW wind turbine was used for the thrust force. Finally, the total pitch angle of the floater was estimated by adding the wave excited pitch and the wind excited pitch.

4. **Structural design of the prestressed-concrete floater**

4.1. **General trend of effects of geometrical variables on floater motions**

General trend of the effects of the geometrical variables on floater pitch response was investigated. Figure 6 shows the sensitivity of the wave excited pitch and wind excited pitch to the geometrical variable $L_{sc}$ for normal concrete, where $L_{arm} = 36$ and $H_{th} = 7$. It is seen from the figure that wave excited pitch increased while wind excited pitch decreased with the increase of $L_{sc}$. For wind excited pitch, this is because restoring force increases with the increase of $L_{sc}$. For wave excited pitch the increase in $L_{sc}$ cause the increase in wave excitation force and the decreased pitch natural frequency as shown in Figure 4. Effect of wall thickness was visible in Figure 6 for both wave excited and wind excited pitch where larger wall thickness required larger value of $L_{sc}$ for the same pitch angle. This can be attributed to the
decrease of GM of the floater for wind excited pitch, and to the elevation of the height of the center of gravity for wave excited pitch with the increase of $L_{sc}$.

Figure 7 shows the sensitivity of wave excited pitch and wind excited pitch to $L_{arm}$ for normal concrete where $L_{sc}=13$ and $H_{lh}=7$. It is seen from the figure that $L_{arm}$ had similar effect with $L_{sc}$ on floater motions as the wave excited pitch increased while wind excited pitch decreased with the increase of $L_{arm}$. This can be attributed to the features that, similar to the effect of $L_{sc}$, the increase in $L_{arm}$ results in increased restoring moment, increased wave excitation forces, and decreased pitch natural period as shown in Figure 4.

For $H_{lh}$, however, the effect of the geometrical parameter on floater pitch response was limited as shown in Figure 8, where $L_{sc}=13$, and $L_{arm}=36$. One explanation for $H_{lh}$ not affecting the wave response is that the sensitivity of the wave period was considered in the wave response calculation. As the lower hull height mainly contributes to the position of the waveless point, when the maximum of the response for 12s, 13s, 14s is considered, the effect of $H_{lh}$ can be somehow buried inside the range of the wave period.

Though only the results for normal concrete were shown in this section, the same trends of the effect of the geometrical variables on the floater motions were also similarly seen for both lightweight concrete and steel.

Figure 6. Sensitivity of (a) wind excited pitch and (b) wave excited pitch to $L_{sc}$ for normal concrete

Figure 7. Sensitivity of (a) wind excited pitch and (b) wave excited pitch to $L_{arm}$ for normal concrete

Figure 8. Sensitivity of (a) wind excited pitch and (b) wave excited pitch to $H_{lh}$ for normal concrete
4.2. Comparison of optimum side-column width

The optimum side-column width with respect to the pitch motion was studied in this section. Figure 9 shows the dependence of the total pitch angle on $L_{sc}$ for normal concrete, lightweight concrete and steel, where $L_{arm}=36\,\text{m}$ and $H_{th}=7\,\text{m}$. It is seen from the figure that the total pitch angle became large for smaller $L_{sc}$ due to the wind excitation and for larger $L_{sc}$ due to the wave excitation, and the $L_{sc}$ values in the middle of the range gave smaller pitch motion. The minimum pitch angle achieved by selecting the optimum $L_{sc}$ was similar for all types of materials. In other words, the difference in the maximum pitch angle between different types of material could be limited if optimum design is to be performed. It can also be seen from the figure that the values of $L_{sc}$ that give small pitch angle were more dependent on the wall thickness for normal concrete than the $L_{sc}$ for lightweight concrete and steel. Table 5 summarizes the range of the side column width when the threshold of the design pitch angle was set as 10 degrees. It is seen from the table that larger side column width was required for normal concrete compared to lightweight concrete and steel. It is indicated from these results that if larger wall thickness is required for concrete structures due to, for example, corrosion protection and crack limitation, generally larger side column width compared to steel will be required to achieve the limitation of pitch angle. If lightweight concrete is used instead of normal concrete, the required side column width can be decreased as well as the effect of the wall thickness on the floater motion.

![Figure 9. Dependence of the total pitch angle on $L_{sc}$ for (a) normal concrete (b) lightweight concrete and (c) steel](image)

| Table 5. Summary of the range of $L_{sc}$ to satisfy floater pitch < 10 deg |
|---------------------------------------------------------------|
| Min wall thickness | Normal concrete: 12.0 m < $L_{sc}$ < 14.5 m | Lightweight concrete: 11.5 m < $L_{sc}$ < 14.5 m | Steel: 11.0 m < $L_{sc}$ < 14.5 m |
| Max wall thickness | Normal concrete: 13.5 m < $L_{sc}$ < 16.0 m | Lightweight concrete: 11.0 m < $L_{sc}$ < 44.0 m | Steel: 11.0 m < $L_{sc}$ < 14.5 m |

4.3. Comparison of optimum lower hull length

The optimum lower hull length with respect to the pitch motion was studied in this section. Figure 10 shows the change of the total pitch angle with the variable $L_{arm}$ for normal concrete, lightweight concrete and steel, where $L_{sc}=13\,\text{m}$ and $H_{th}=7\,\text{m}$. It is seen from the figure that total pitch angle became large for smaller $L_{arm}$ due to the wind excitation and for larger $L_{arm}$ due to the wave excitation, and the $L_{arm}$ values in the middle range gave smaller pitch angle. The minimum pitch angle achieved by using the optimum $L_{arm}$ was similar for all three types of material. It is seen from the Figure 10 (a) that for normal concrete, the effect of wall thickness was larger for smaller $L_{arm}$ where wind excitation is dominant, than in larger $L_{arm}$ where wave excitation is dominant. For normal concrete, this resulted in the narrowed range of $L_{arm}$ that satisfies pitch limitation for larger wall thickness. As the pitch angle was more affected by wind excitation for normal concrete, it is indicated from the results that the design space of a semi-submersible floater can be narrowed or widened depending on the treatment of the maximum thrust force in wind turbine controllers.

Table 6 summarizes the range of the hull length when the design limitation of floater pitch angle is set at 10 deg. It is seen from the table that normal concrete floaters required longer hull length compared to steel floaters for the same pitch limitation. While there was little effect of wall thickness for steel, the
required hull length increased with the increase of wall thickness for normal concrete and lightweight concrete. When lightweight concrete or normal concrete with small wall thickness is used, the optimum horizontal hull length could be similar with that of steel floaters to satisfy the pitch limitation.

![Figure 10](image1.png)

**Figure 10.** Dependence of the total pitch angle on $L_{arm}$ for (a) normal concrete (b) lightweight concrete and (c) steel

| Table 6. Summary of the range of $L_{arm}$ to satisfy floater pitch < 10 deg |
|------------------|------------------|------------------|
| **Min wall thickness** | Normal concrete | Lightweight concrete | Steel |
| 31 m $< L_{arm}$ $< 42$ m | 30 m $< L_{arm}$ $< 41$ m | 28 m $< L_{arm}$ $< 40$ m |
| **Max wall thickness** | 37 m $< L_{arm}$ $< 46$ m | 32 m $< L_{arm}$ $< 44$ m | 28 m $< L_{arm}$ $< 40$ m |

4.4. Comparison of material cost

Finally, a simple cost calculation was conducted for the three types of material. Figure 11 shows the total material weight for possible design combinations that gives total pitch angle lower than 11 degrees. Table 7 summarize the range of material weight and corresponding raw material cost for the three types of material. The unit cost was approximated values for raw material investigated on providers’ website. It is seen from the table that the pure material cost of floaters made of normal concrete is approximately one-fifteenth of that of steel floaters. If lightweight concrete is used, the cost becomes twice that of the normal concrete, but still can be significantly lower than steel floaters.

![Figure 11](image2.png)

**Figure 11.** Floater pitch vs total material weight for (a) normal concrete, (b) lightweight concrete and (c) steel

| Table 7. Range of the material cost for possible floater designs |
|------------------|------------------|------------------|
| **Material weight** | Unit material cost | Total material cost |
| Normal concrete | 1.2e+7 $\sim$ 2.0e+7 kg | 30,000 yen/m³ (230€/m³) | 144,000,000 - 240,000,000 yen (1,110,000 - 1,850,000 €) |
| Lightweight concrete | 0.8e+7 $\sim$ 1.5e+7 kg | 60,000 yen/m³ (460€/m³) | 267,000,000 - 500,000,000 yen (2,050,000 - 3,850,000 €) |
| Steel | 2.0e+6 $\sim$ 4.5e+6 kg | 90,000 yen/ton (690€/ton) | 1,800,000,000 - 4,050,000,000 yen (13,800,000 - 31,200,000 €) |
5. Conclusion

In this study, the characteristics of response of a semi-submersible floater for 10 MW wind turbine were studied for concrete and steel, and following conclusions were obtained:

1. Minimum floater pitch angles achieved by selecting the optimum floater geometries were similar for the three types of material, while larger values of geometrical variables were required for concrete floaters than for steel floaters for a floater pitch limitation.
2. If larger wall thickness was to be required for concrete structures due to, for example, corrosion protection and crack limitation, generally larger side column width and lower hull length were required for concrete floaters.
3. As the sensitivity of pitch angle to the wall thickness was more affected by wind excitation than wave excitation for normal concrete, it is indicated that the design space for the length of hull can be widened by combining the design with the wind turbine controller methods in the treatment of the maximum thrust force.
4. Lightweight concrete had advantages over normal concrete in the lower center of gravity. The raw material cost of lightweight concrete was higher than normal concrete but significantly lower than steel floaters.

Only floater pitch motion was considered in the comparison conducted in this study. Further study needs to be conducted on structural feasibility considering the material stiffness.

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