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

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Introduction

Prestressed concrete (PC) is gaining interest as an alternative to steels for FOWTs for following advantages:

- Lower material cost
- Possible contribution to local contents
- Possible construction flexibility

Concrete

- Lighter material density compared to steel.
- Larger wall thickness than steel.
- Various types of concrete with various material properties. Design parameters such as wall thickness sometimes dependent on design philosophy such as crack control and corrosion protection methods rather than required strength.

Steel

- Larger material density compared to concrete
- Lighter total material weight compared to concrete
- Relatively constant material property

How much effect the differences in the material properties for concrete and steel can have on floater responses and floater geometries?
Is there any types of concrete more suitable for FOWTs?

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Objective

1. Design a basic geometry of semi-submersible type floater with several geometrical variables to conduct sensitivity study.

2. Chose typical material properties for concrete and steel, and study the characteristics of the pitch response and suitable floater geometry for each material.

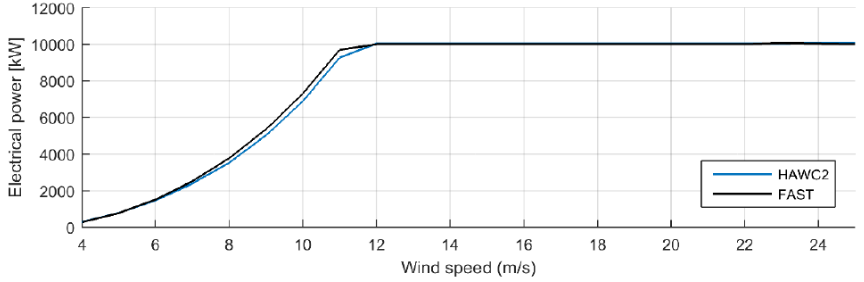
3. Estimate possible material cost range for the three types of material

Design basis – Wind turbine & Tower

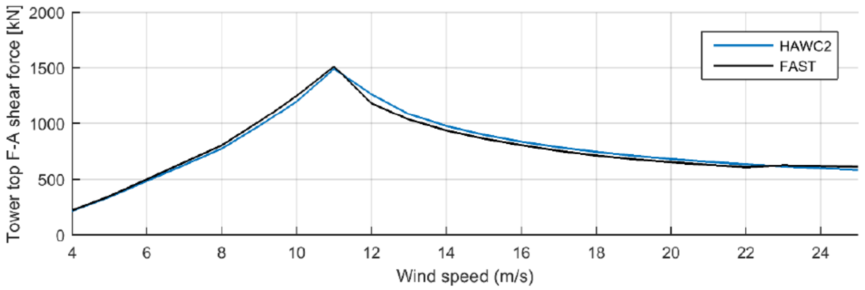
- Mounted Wind Turbine

	DTU 10MW WT
Hub height	118.5 m
Rated wind speed	11 m/s
Nacelle mass	446,036 kg
Nacelle CoG	(2.687, 0, 118.08)
Hub mass	105,520 kg
Hub CoG	(-7.073, 0, 119.0)
Blade mass	44,049 kg

Generated Power (kW)



Thrust Force (kN)



- Tower Design

	Density	Stiffness	Diameter - bottom	Tower mass	CoG
Tower (steel)	8.50E+3 kg/m3	2.10E+11 N/m2	12 m	780900 kg	(0, 0, 60.58)

Design basis – Metocean conditions

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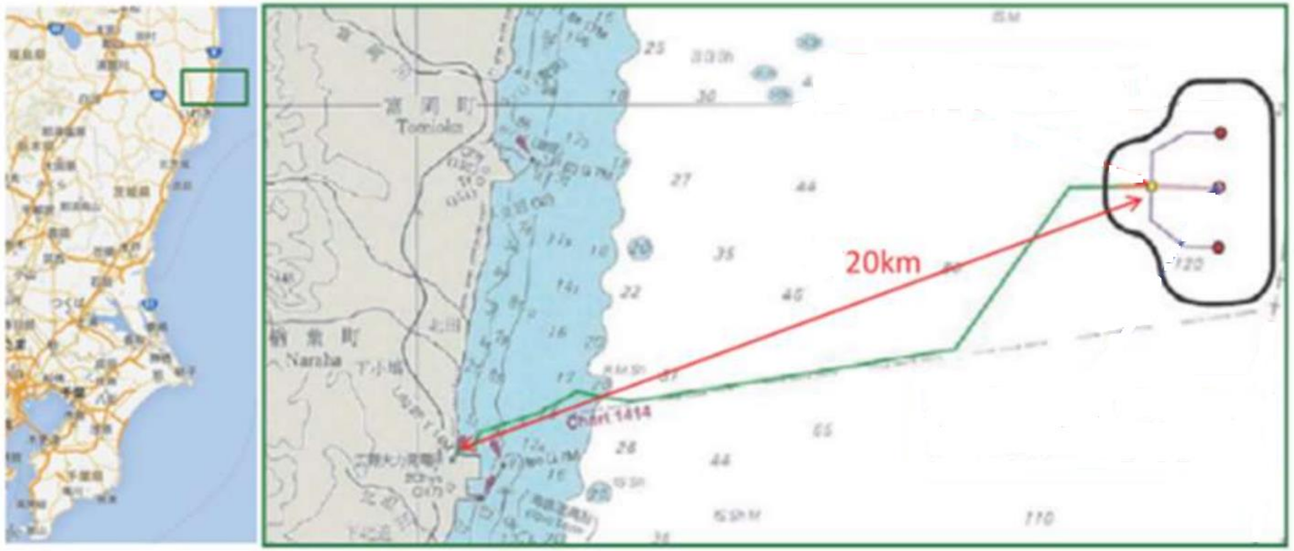
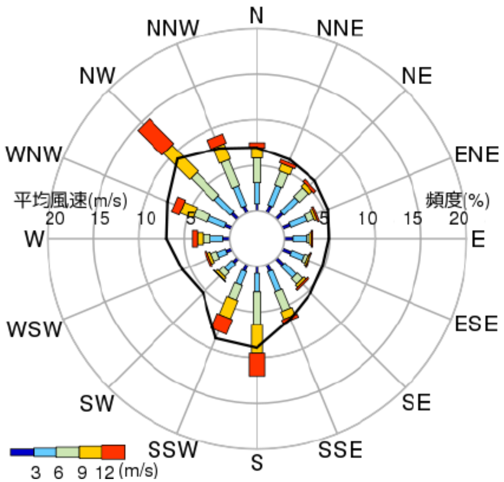
➤ Target site

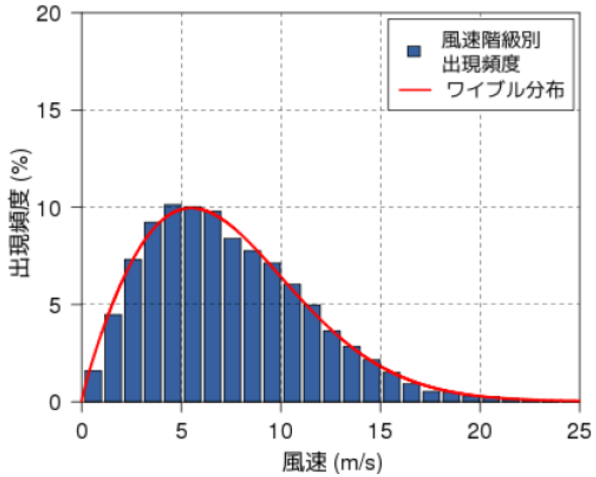


➤ Ultimate conditions

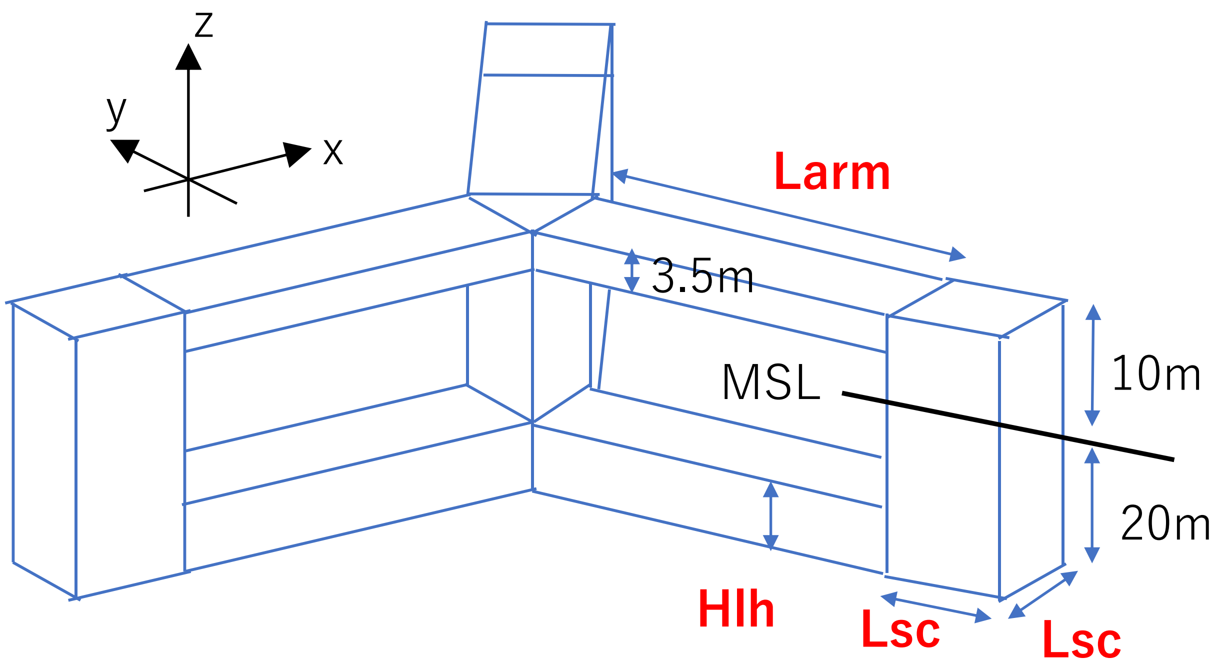
10 min mean wind speed （50 years，60 m height）	48.3 m/s
Wind shear in ultimate condition	0.1
Reference turbulence intensity	0.12%
Significant wave height (50 years)	11.71 m
Significant wave height (50 years)	13.0 s
Max. tidal level	C.D.L. + 2.77 m

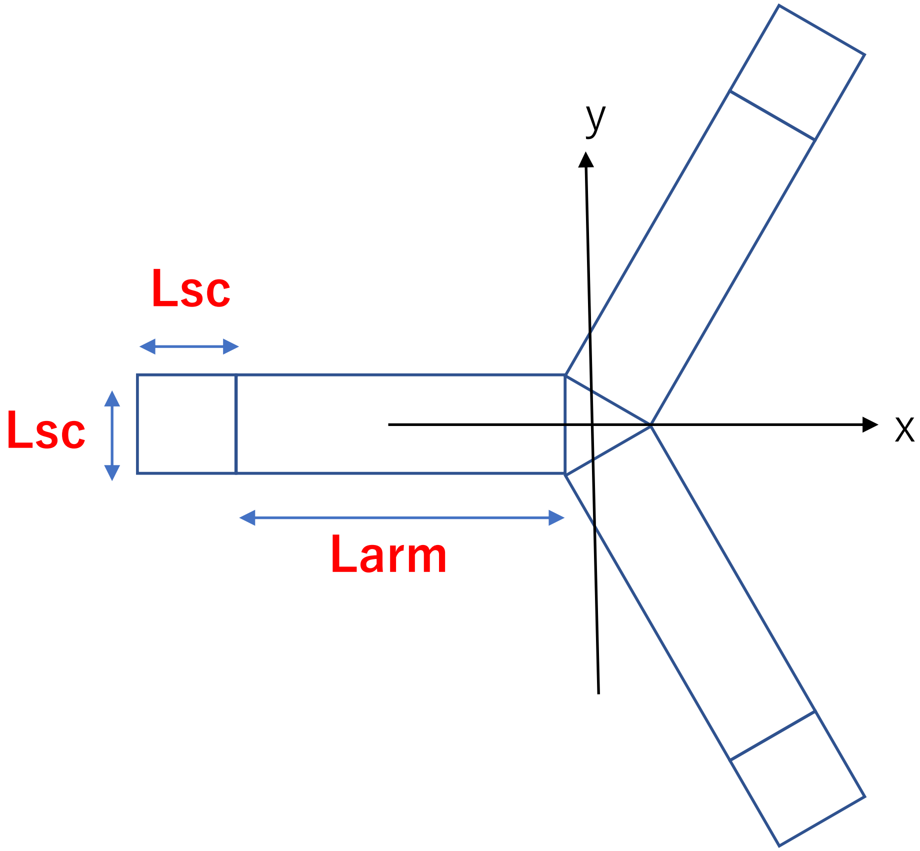
➤ Fatigue conditions





Basic geometry of the semi-sub floater





Basic geometry was designed considering:

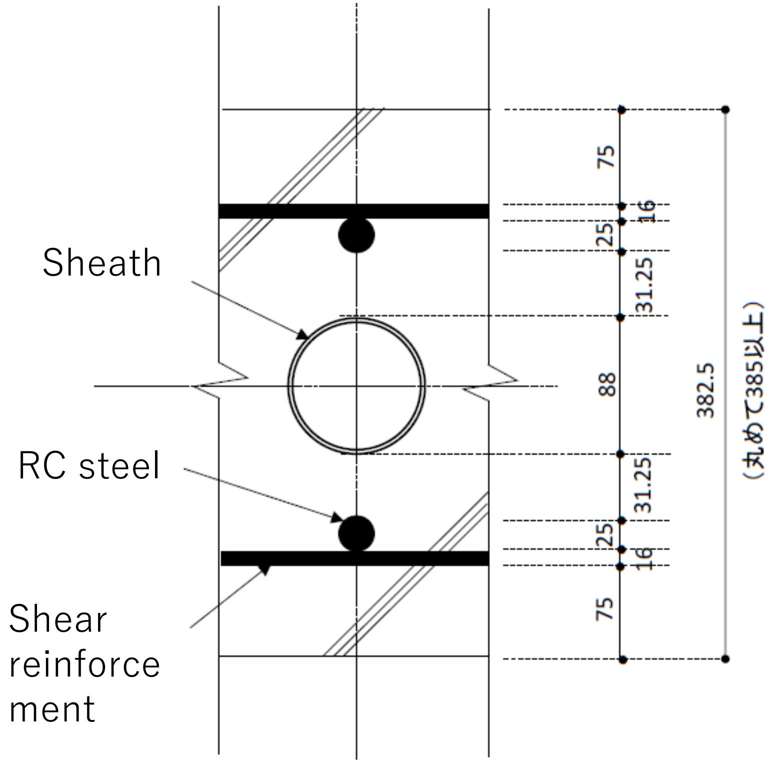
- Simplicity of the structural and hydrodynamic modelling
- Easier to install/model prestressed steel

Floater geometric variables for sensitivity study:

- Side column width (Lsc)
- Hull length (Larm)
- Lower hull height (Hlh)

Design basis – Material properties

	Normal Concrete	Lightweight Concrete	Steel
Material Density	2500 kg/m^3	1800 kg/m^3	7874kg/m^3
Wall thickness	350 - 550 mm	350 - 550 mm	16 – 40 mm
Ballast density (Water)	1025 kg/m^3	1025 kg/m^3	1025 kg/m^3



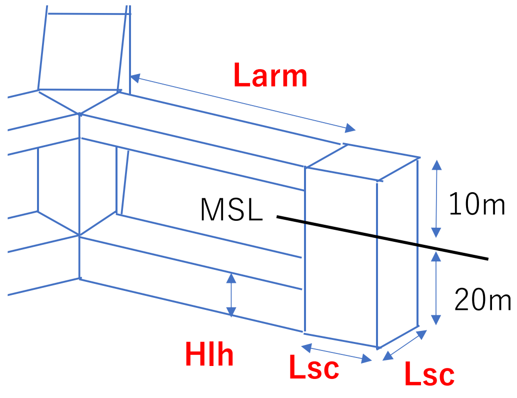
Simplified initial design based on Standard for Structural Design and Construction of Prestressed Concrete Structures, Architectural Institute of Japan (1998)

Parameters contributing to concrete wall thickness

・RC/PC Steel cover
・Minimum distance between PC sheath and RC steel
・Minimum distance between RC steels
..etc

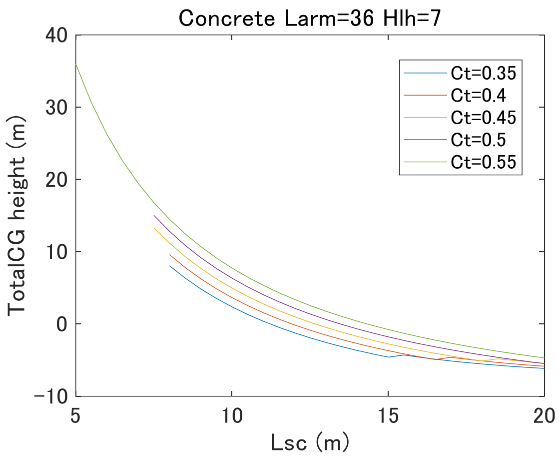
which are affected by concrete material type, anticorrosion methods, control of cracks etc.

CoG of the total system

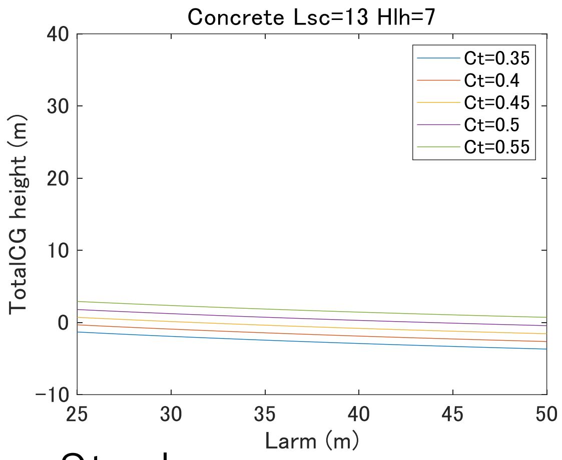


Normal Concrete

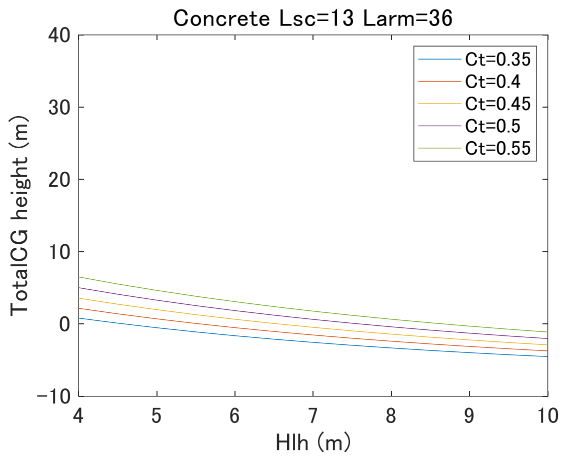
Lsc



Larm

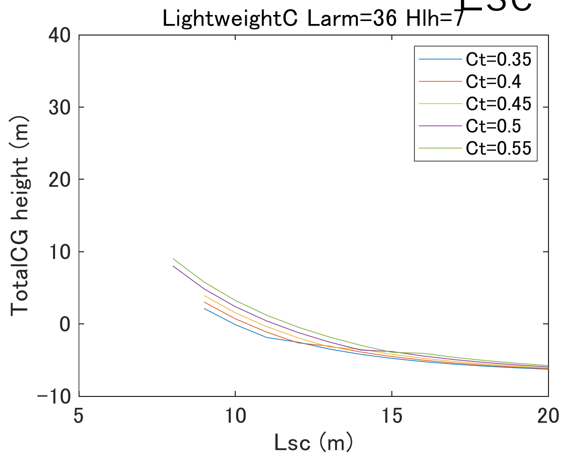


Hlh

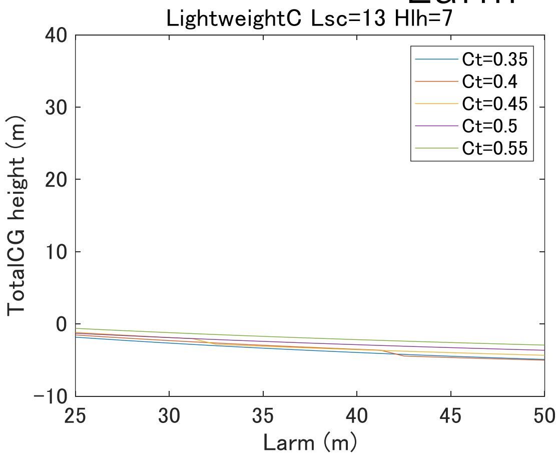


Lightweight Concrete

Lsc

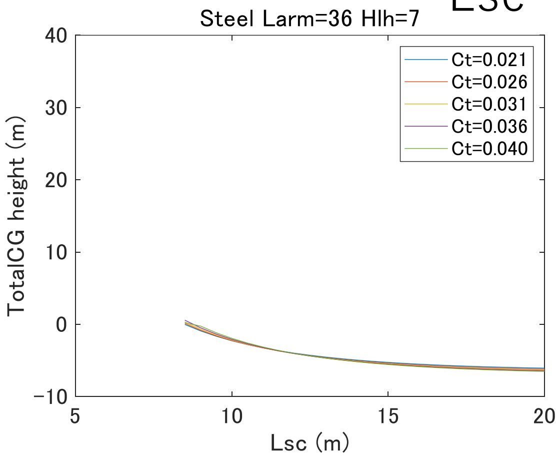


Larm

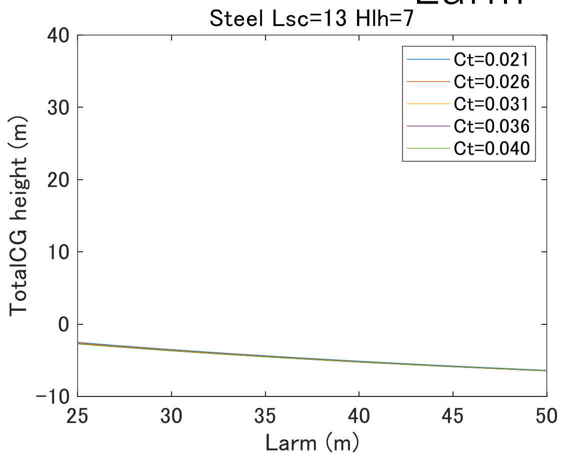


Steel

Lsc

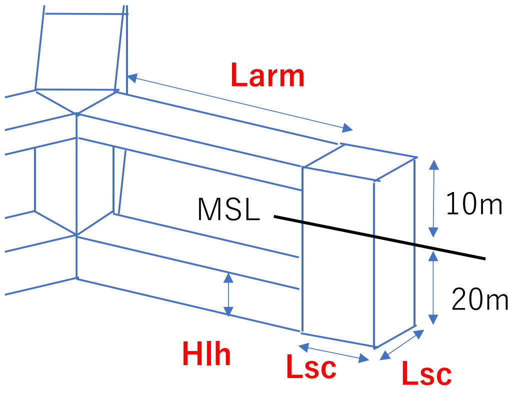


Larm

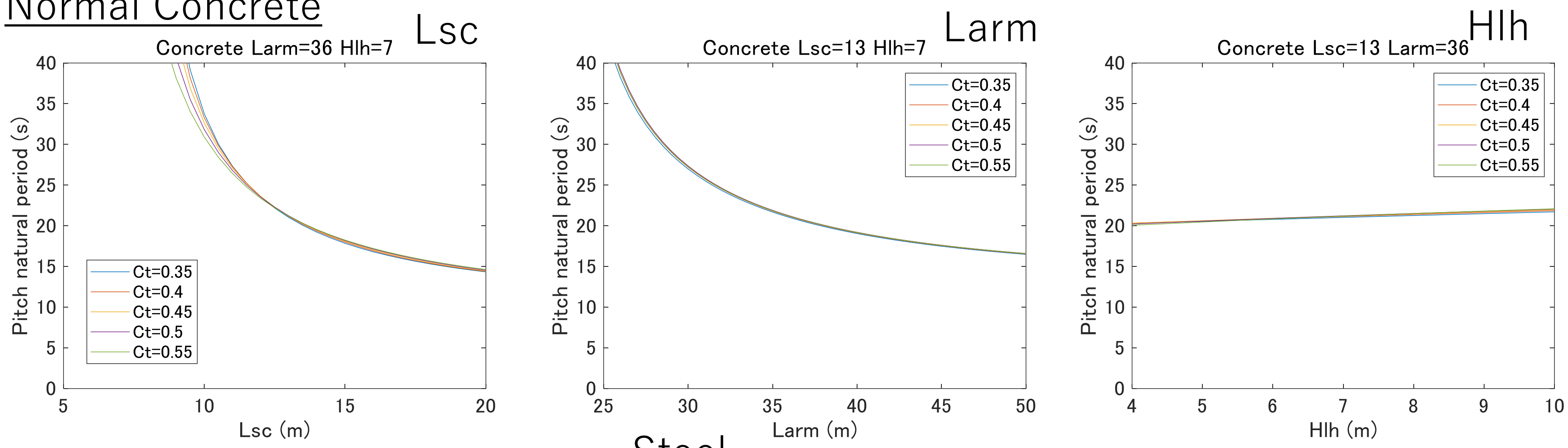


- Larger values for Lsc, Larm and Hlh result in lower total CoG for all material types.
- Lightweight concrete and steel give lower total CoG compared to normal concrete.

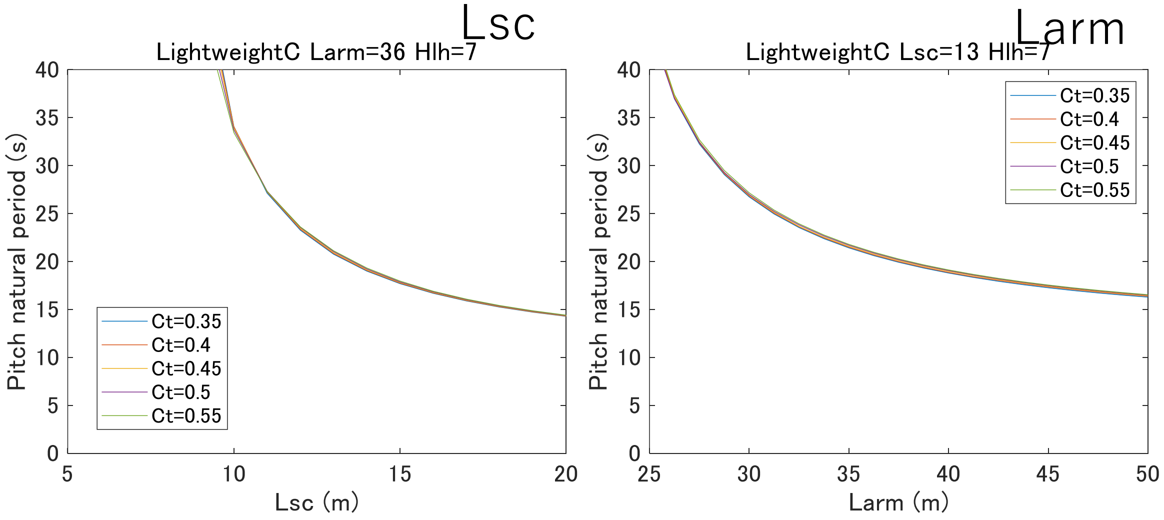
Pitch natural period



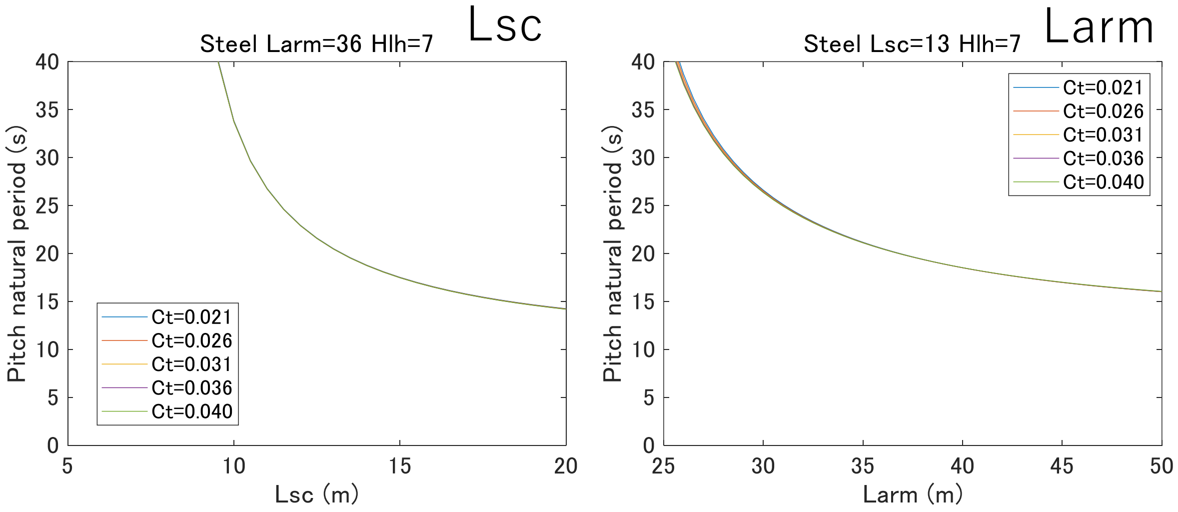
Normal Concrete



Lightweight Concrete



Steel



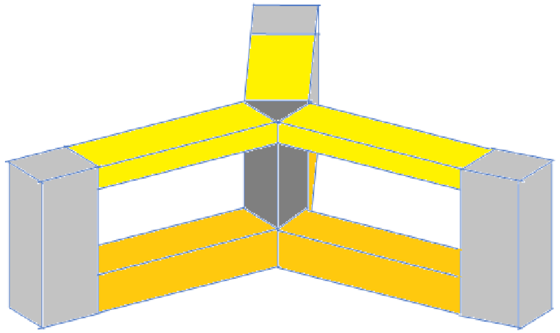
- Lsc and Larm has significant effect on pitch natural frequency, while effect of Hlh is limited.
- Dependence of pitch natural frequency on wall thickness is limited for all material types.

Frequency domain analysis

- Wave response ($Pitch_{wave}$)

<u>Equation of motion</u>

$$M_G \ddot{u_G} + C_G \dot{u_G} + K_G u_G = F_{hdro}$$

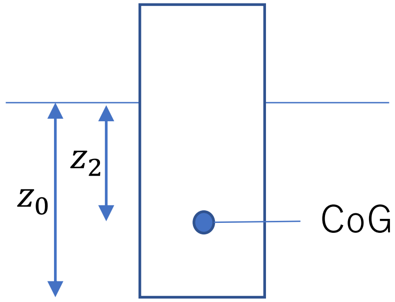


$$M_G = \sum_i T_i^T (M_i + M_{a,i}) T_i \qquad F_{hydro} = \sum_i T_i^T f_{hydro,i}$$

Coordinate transformation matrix for i-th member

<u>Wave excitation force</u>

i-th Member



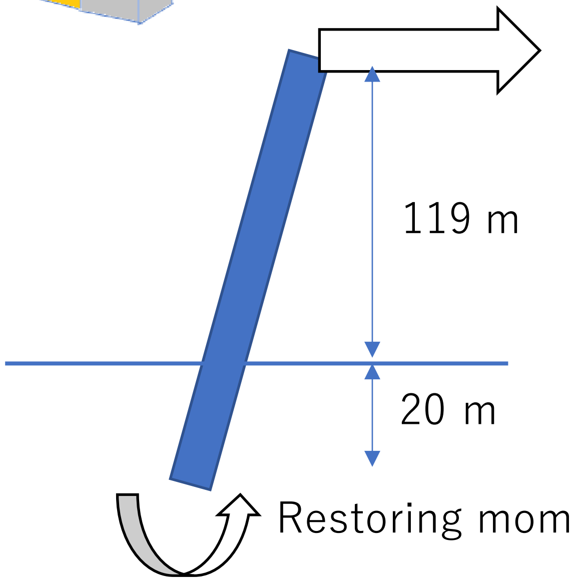
Airy wave theory

$$\eta = a\cos(\kappa X - \omega t) \qquad \varphi = cae^{kz}\sin(\kappa X - \omega t)$$

$$f_{hydro,i} \approx \rho g A_w \eta + \int_{-(z_0 - z_2)}^{z_2} (\rho A_w + m_{az}) \frac{\partial^2 \varphi}{\partial t \partial z} dz$$

- Wind response($Pitch_{wind}$)

Thrust force
1824.36kN（Onshore max)



Restoring moment: $M_G \cdot GM$

$$Pitch_{wave} = \max[Pitch_{wave}(T_s = 12.0s), Pitch_{wave}(T_s = 13.0s), Pitch_{wave}(T_s = 14.0s)]$$

$$\underline{Pitch_{total} = Pitch_{wave} + Pitch_{wind}}$$

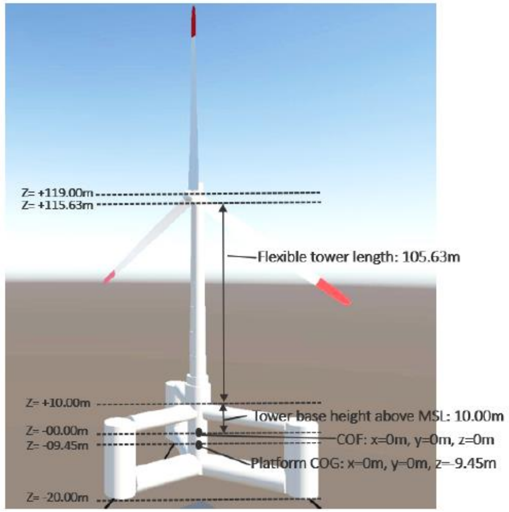
Verification of frequency domain analysis

■ *Time domain analysis*

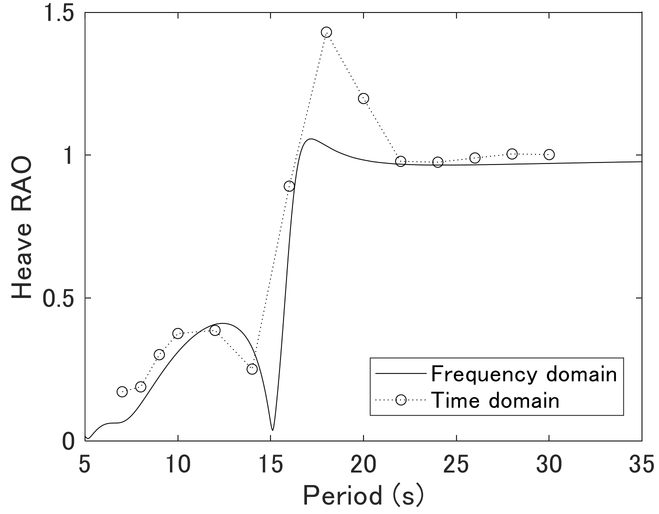
$$M\ddot{u} + C\dot{u} + Ku = F^{hydro} + F^{lines} + F^{buoyancy} + F^{aero}$$

$$F^{hydro} = \rho\frac{\pi D^2}{4}\ddot{u} + C_m\rho\frac{\pi D^2}{4}(\ddot{u} - \ddot{x}) + C_D\frac{1}{2}\rho D(\dot{u} - \dot{x})|\dot{u} - \dot{x}|$$

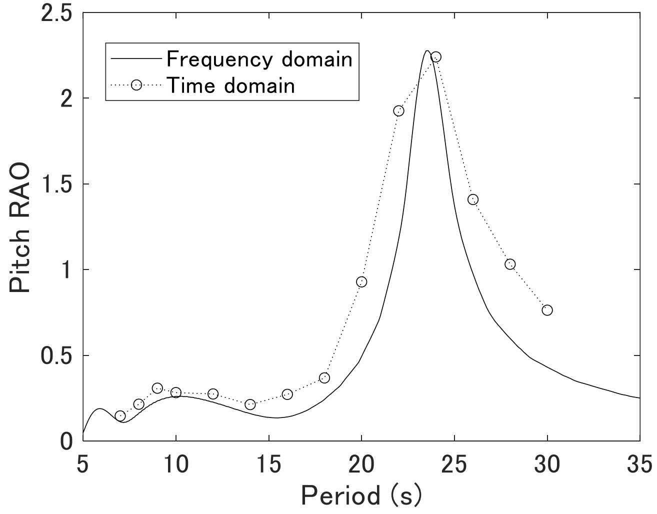
Verification case;
<u>Lsc=12m, Larm=36m, Hlh=7m, Hs=11.3m, Ts=14.3s, Cax=1.1, Caz=0.5</u>



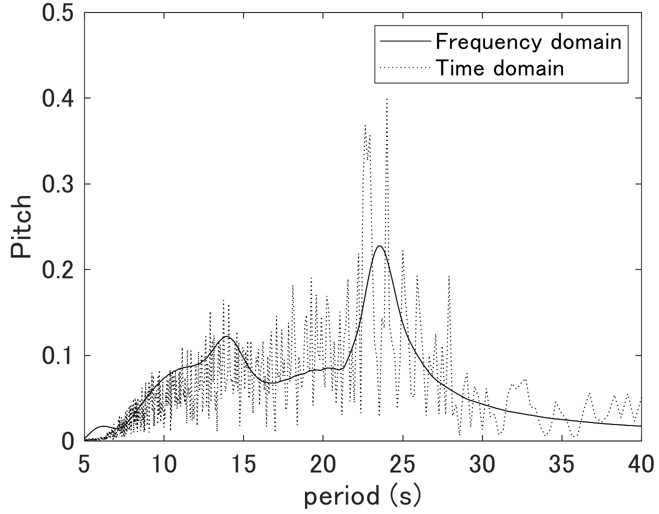
Heave RAO



Pitch RAO



Pitch Irregular wave response



Effect of floater geometries on pitch response

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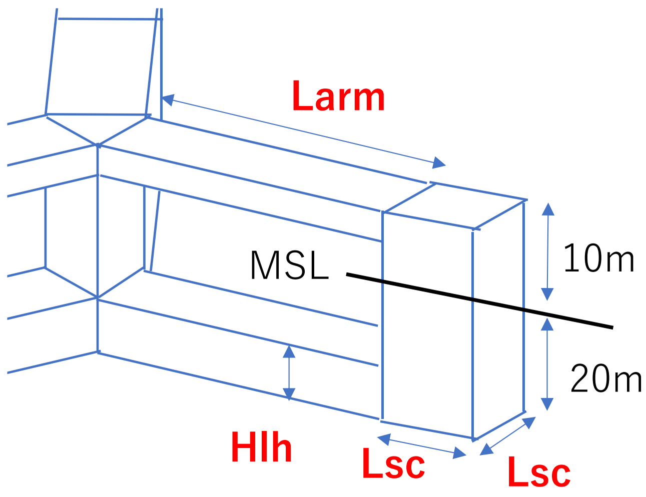

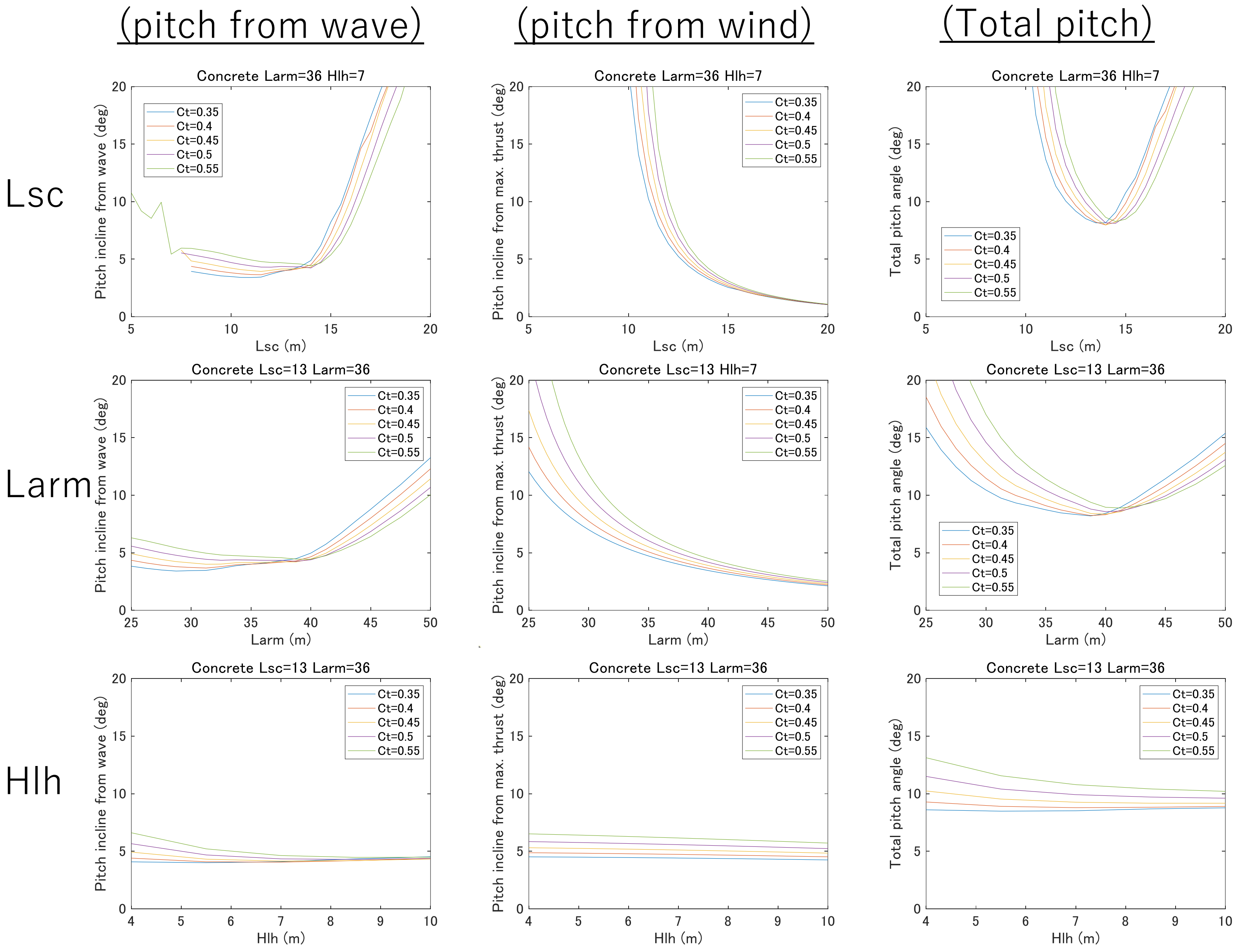

- Pitch response from wave excitation increased with the increase of Lsc and Larm, while response from wind thrust decreased with the increase of Lsc and Larm.
- Effect of Hlh on pitch responses from both wave and wind were limited.

Pitch responses for Side Column Widths (Lsc)

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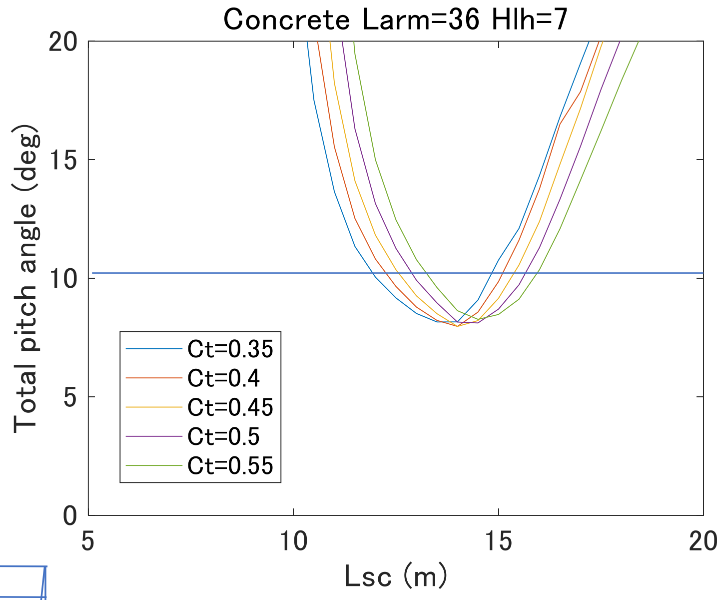
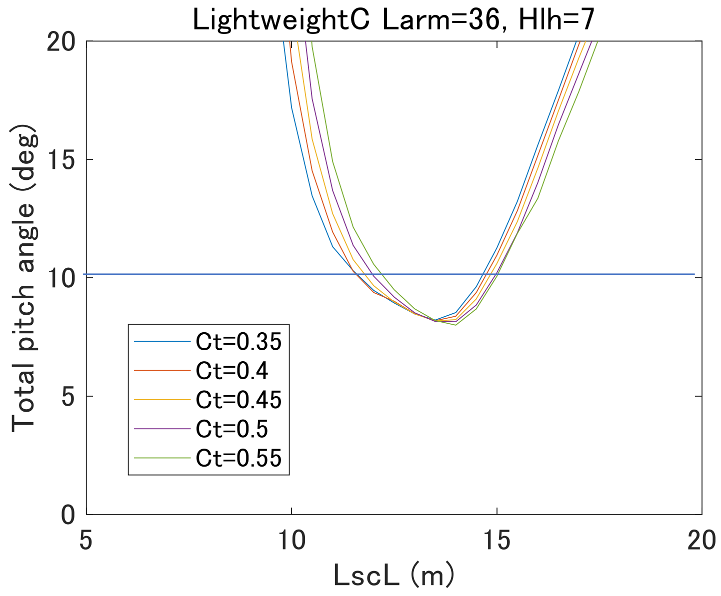
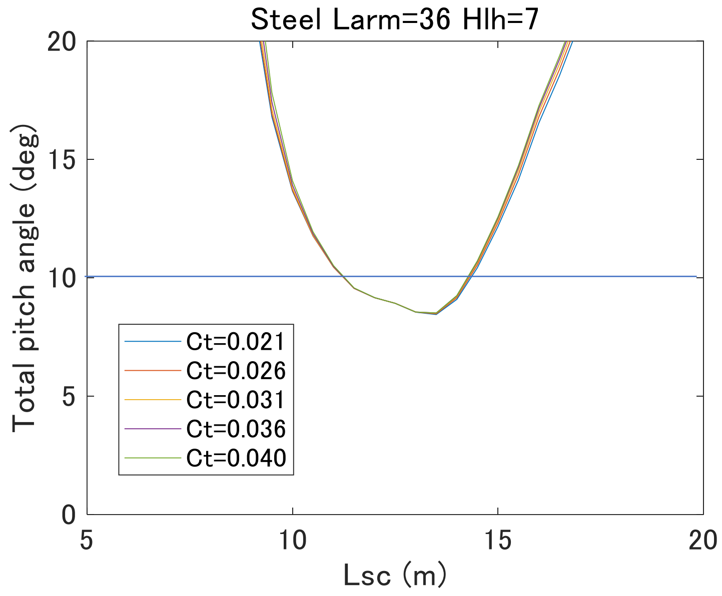
Normal Concrete



Lightweight Concrete



Steel



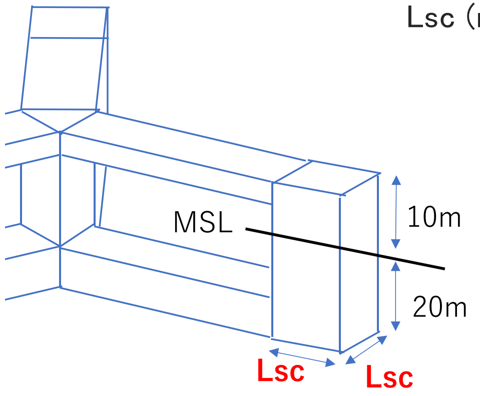
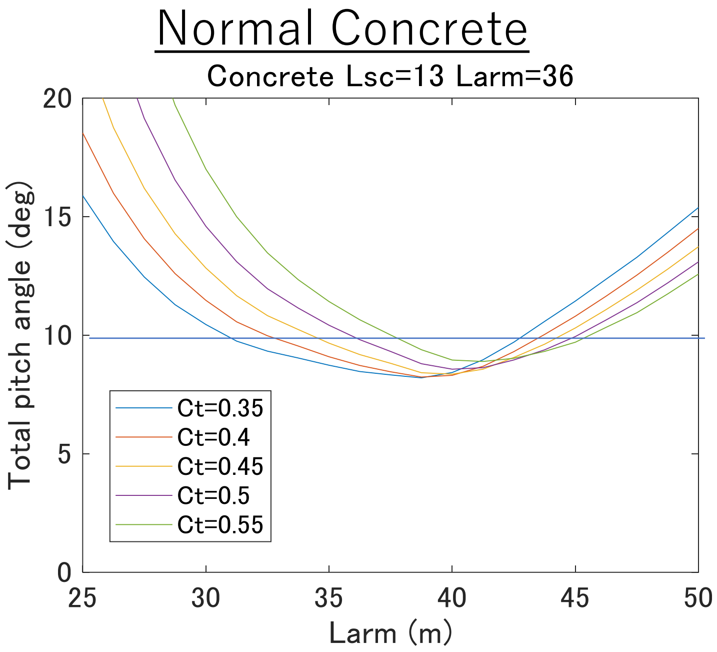


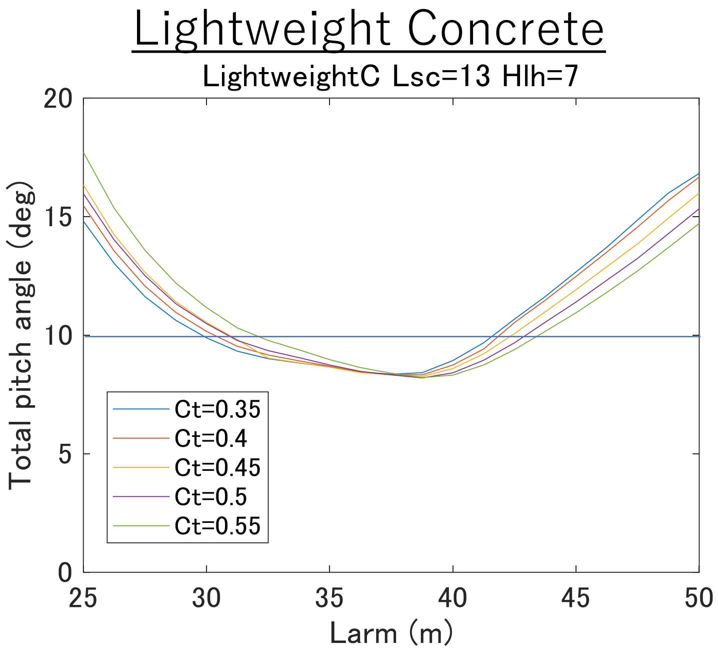
Table. Lsc values required for Max. Pitch < 10deg

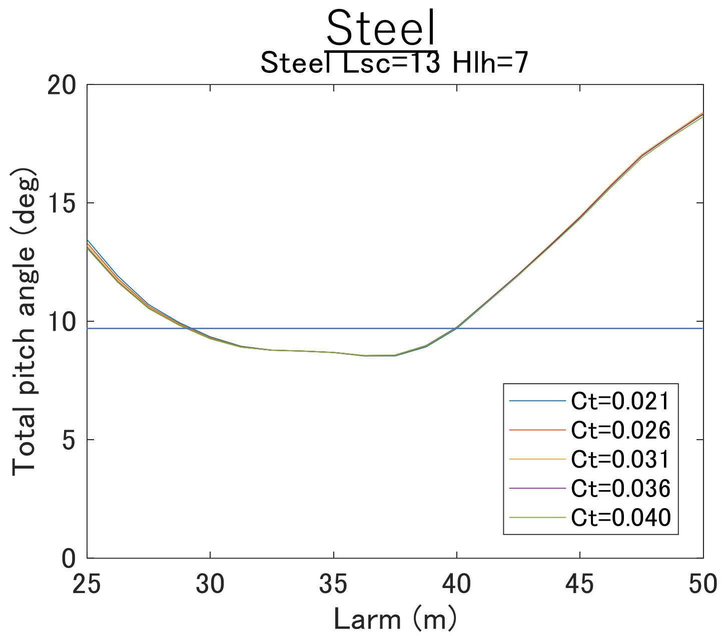
	Normal concrete	Lightweight concrete	Steel
Min wall thickness	12m<Lsc<14.5m	11.5m <Lsc<14.5m	11m <Lsc<14.5m
Max wall thickness	13.5m<Lsc<16m	11m <Lsc<15m	11m <Lsc<14.5m

- Minimum maximum pitch angle was similar for all material types
- Steel and lightweight concrete requires smaller Lsc than normal concrete for total pitch angle < 10 deg. Due to the lower center of gravity?
- Effect of wall thickness was larger for normal concrete due to the lower center of gravity?

Pitch responses for Hull Lengths (Larm)







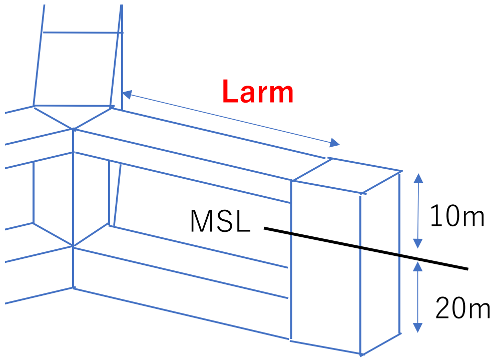


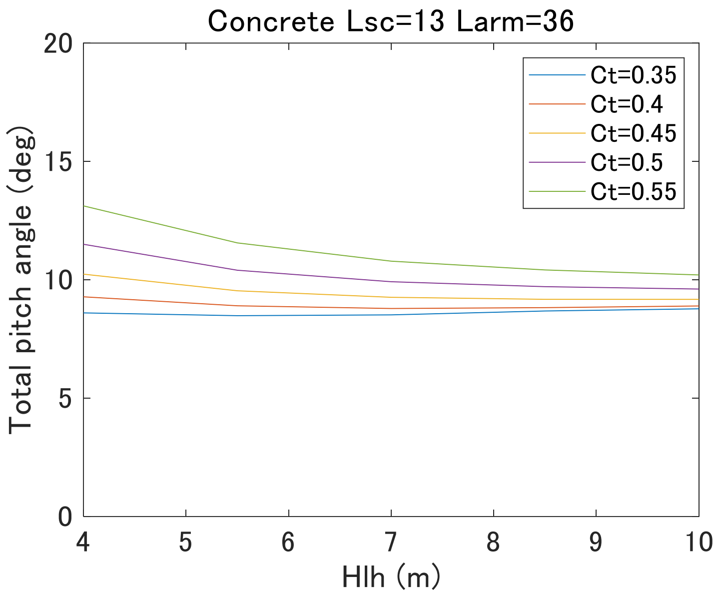
Table. Larm values required for Max. Pitch < 10deg

	Normal concrete	Lightweight concrete	Steel
Min wall thickness	31m <Larm<42m	30m <Larm<41m	28m<Larm<40m
Max wall thickness	37m <Larm<46m	32m <Larm<44m	28m<Larm<40m

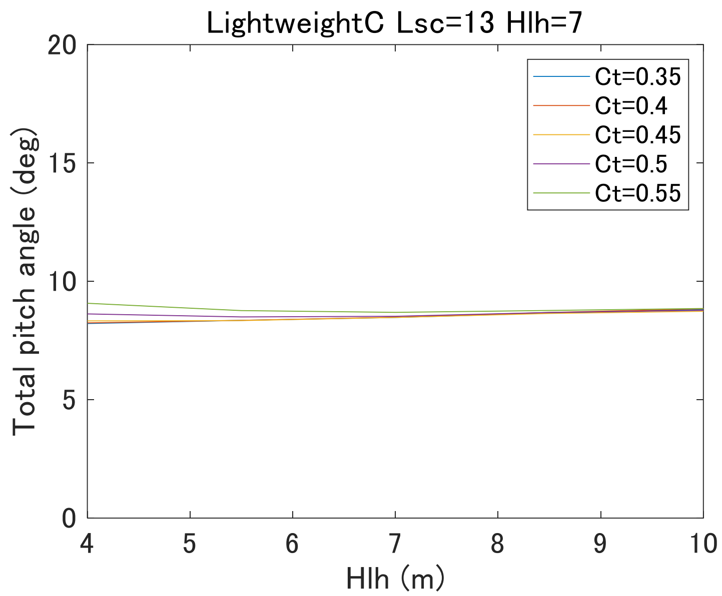
- Minimum maximum pitch angle was similar for all material types
- Steel requires smaller Larm than normal concrete for total pitch angle < 10 deg.
- Effect of wall thickness was large for normal concrete but limited for steel floaters

Pitch responses for Hull Heights (Hlh)

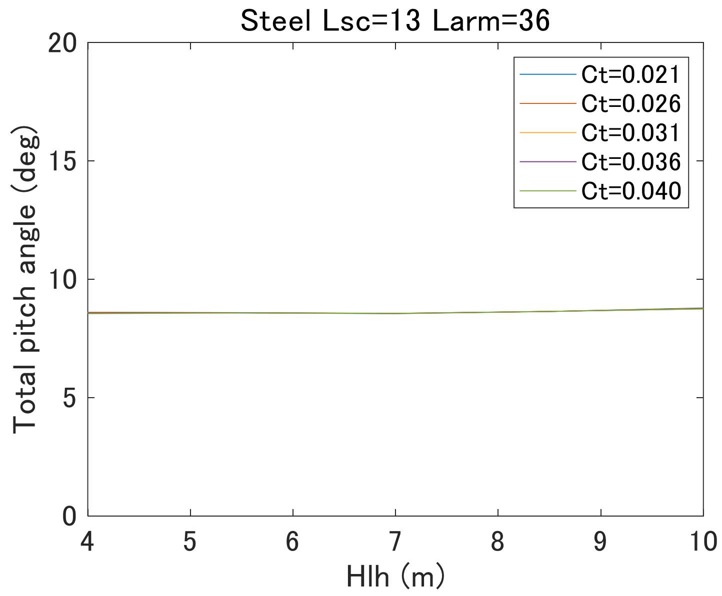
Normal Concrete

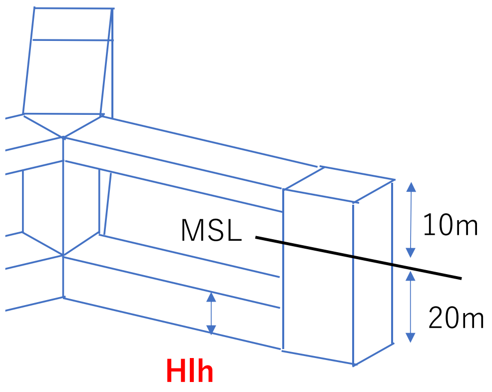


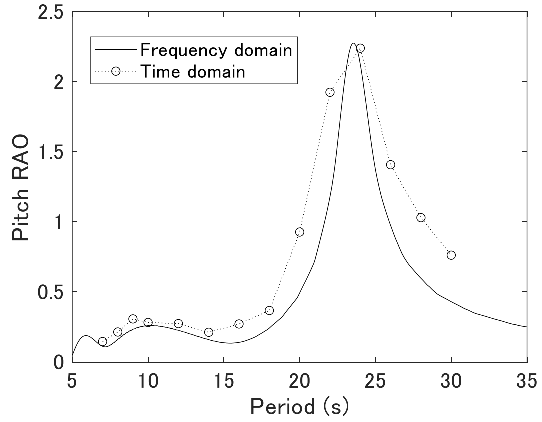
Lightweight Concrete



Steel







- Effect of Hlh is limited for all material types
- Consideration of the three wave periods can limit the effect of the position of the waveless point

$$Pitch_{wave} = \max[Pitch_{wave}(T_s = 12.0s), Pitch_{wave}(T_s = 13.0s), Pitch_{wave}(T_s = 14.0s)]$$

Material costs for possible designs

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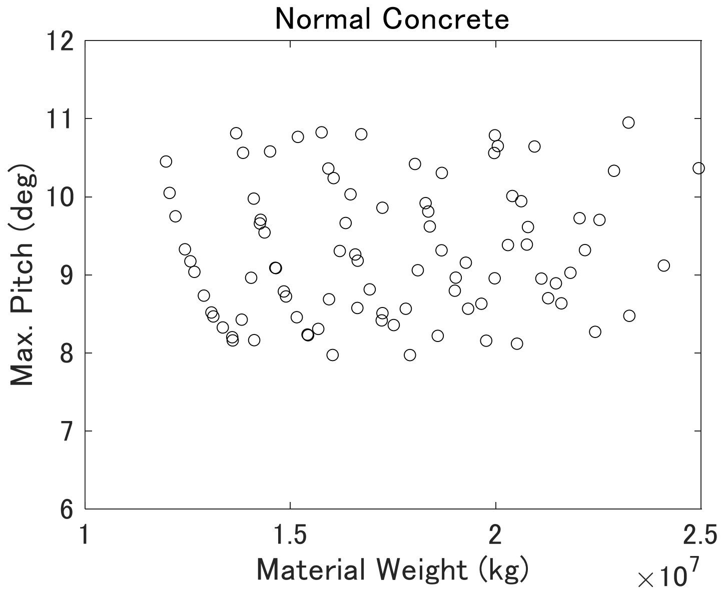
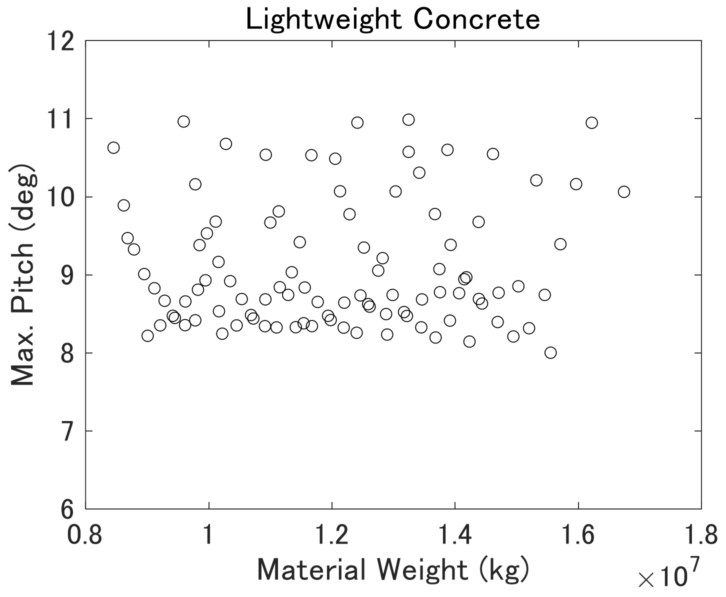
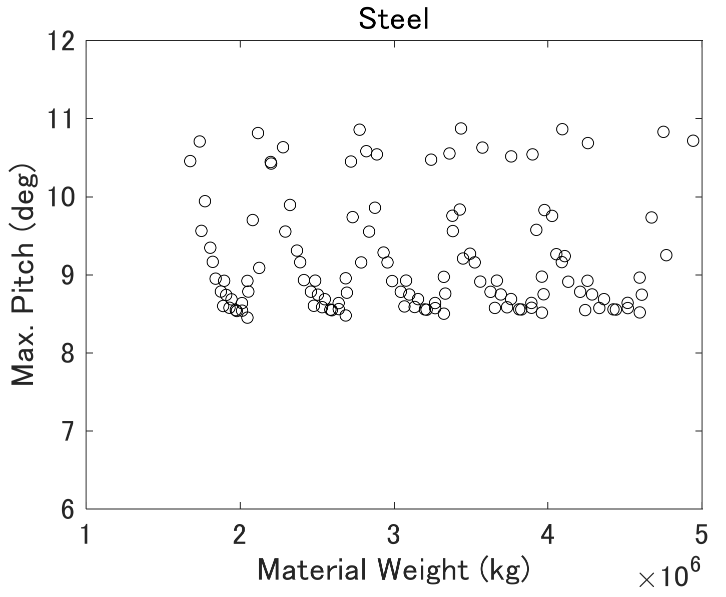
Normal Concrete



Lightweight Concrete



Steel



	Material weight	Unit material cost	Total material cost
Normal Concrete ($2500 kg/m^3$)	1.2e+7 ～2.0e+7 kg	30,000 yen/m^3 (230€/m^3)	144,000,000 - 240,000,000 yen (1,110,000 - 1,850,000 €)
Lightweight Concrete ($1800 kg/m^3$)	0.8e+7 ～1.5e+7 kg	60,000 yen/m^3 (460€/m^3)	267,000,000 - 500,000,000 yen (2,050,000 - 3,850,000 €)
Steel ($7874 kg/m^3$)	2.0e+6 ～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 €)

Conclusion

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

1. Minimum maximum pitch angles was similar for all material types

2. The optimum hull length and column widths for steel floaters is generally smaller than those for concrete floaters, which is mainly due the lighter material weight that result in lower center of gravity. The optimum hull length and column widths for light-weight concrete floaters were smaller than normal concrete floaters.

3. Effect of wall thickness on floater pitch response was the largest for normal concrete among the three material types. This is mainly due to the amount of contribution of the wall thickness on the weight and height of the water ballast. Larger wall thickness resulted in larger optimum hull length and column widths for normal and lightweight concrete floaters.

4. When max pitch<10 deg is used as design index, the material cost for concrete floaters is about one-tenth of the cost for steel floaters.

The comparison conducted in this study only considered floater pitch motion. Further study need to be conducted on structural feasibility considering the material stiffness.