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PROJECTE O TESINA D'ESPECIALITAT

Títol

STRUCTURAL DYNAMIC BEHAVIOUR OF A FLOATING PLATFORM FOR OFFSHORE WIND TURBINES

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To my sister Leyre, because you make me
smile even in the worst moments.
Thanks for your never ending happiness.

ACRONIMS AND ABREVIATIONS

r_1	External radius
r_2	Internal radius
r_D	Radius of dome
$r_{D.int}$	Radius of internal dome
r_C	Radius of cylinder
$r_{C.int}$	Radius of internal cylinder
r_L	Radius of lid
$r_{L.int}$	Radius of internal lid
$r_{T.top}$	Radius of tower top
$r_{T.bottom}$	Radius of tower bottom = Radius of frustum top
$r_{F.SwL}$	Radius of frustum at still water level
$r_{F.bottom}$	Radius of frustum at bottom
$h_{D.}$	Height of dome
$h_{D.int}$	Height of internal dome
h_C	Height of cylinder
h_B	Height of ballast inside structure
h_L	Height of lid
$h_{sub.F}$	Height of submerged frustum
$h_{Em.}$	Emerged height
e_D	Thickness of dome walls
e_C	Thickness of cylinder walls
e_F	Thickness of frustum walls
e_T	Thickness of tower
$V_{D.ext}$	Volume of external dome
$V_{D.int}$	Volume of internal dome
$V_{D.Conc.}$	Volume of concrete dome
$V_{C.ext}$	Volume of external cylinder
$V_{C.int}$	Volume of internal cylinder
V_L	Volume of lid
$V_{Sub.T.Ext.}$	Displaced volume by submerged frustum
V_{Sub}	Displaced water volume
V_{Min}	Minimum volume to assure floatability
$M_{D.Conc.}$	Mass of concrete dome
$M._{D.Up.\ Conc.}$	Mass of upper part of concrete dome
$M._{D.Low.\ Conc.}$	Mass of lower part of concrete dome
$M_{D.B}$	Mass of ballast on dome
$M_{D.w}$	Mass of displaced water by dome
$M_{C.Conc.}$	Mass of concrete cylinder
$M_{C.B}$	Mass of ballast on cylinder
$M_{C.w}$	Mass of displaced water by cylinder
$M_{L.Conc.}$	Mass of concrete lid
$M_{L.w}$	Mass of displaced water by lid
$M_{Sub.F.}$	Mass of concrete submerged frustum
$M_{Sub.F.w}$	Mass of displaced water by submerged frustum
$M_{T.Conc.}$	Mass of concrete tower
$M._{Plat.}$	Platform mass
$M_{Plat.Conc.}$	Concrete platform mass
$M_{Struc.}$	Structure mass

$M_{Struc.Conc.}$	Concrete structure mass
$M._{Mooring}$	Mooring lines mass
$C.M._{D.Int}$	Center of mass of internal dome, it is used for bal last
$C.M._{D.Ext}$	Center of mass of external dome, it is used to get the center of buoyancy
$C.M._{D.Conc.}$	Center of mass of concrete dome
$C.M._{C}$	Center of mass of cylinder
$C.M._{L}$	Center of mass of lid
$C.M._{F}$	Center of mass of frustum
$C.M._{F.Ext}$	Center of mass of external frustum
$C.M._{Tower}$	Center of mass of tower
$C.M._{Rotor\ from\ SwL}$	Center of mass of rotor
$C.M._{Up.M.}$	Center of mass of upper mass
$C.M._{Platform}$	Center of mass of platform
$C.M._{Struc.}$	Center of mass of structure
C.O.B	Center of buoyancy
I_X	Inertia in "*X axis*" [Global axis]
I_x	Inertia in "*x axis*" [Local axis]
I_Y	Inertia in "*Y axis*" [Global axis]
I_y	Inertia in "*y axis*" [Local axis]
I_Z	Inertia in "*Z axis*" [Global axis]
I_z	Inertia in "*z axis*" [Local axis]
$I_{D.low.conc.}$	Inertia of lower part of concrete dome
$I_{D.Up.Conc.}$	Inertia of upper concrete dome
$I_{D..Conc.}$	Inertia of concrete dome
$I_{C..Conc.}$	Inertia of concrete cylinder
$I_{C..Conc.}$	Inertia of concrete cylinder
$I_{L..Conc.}$	Inertia of concrete cylinder
$I_{F..Conc.}$	Inertia of concrete frustum
$I_{T..Conc.}$	Inertia of concrete tower
$I_{D.B.}$	Inertia of ballast on dome
$I_{C.B.}$	Inertia of ballast on cylinder
I_B	Inertia of ballast
$I_{D.Ad.M}$	Added mass inertia of dome
$I_{C.Ad.M}$	Added mass inertia of cylinder
$I_{L.Ad.M}$	Added mass inertia of lid
$I._{F.Sub.Ad.M}$	Added mass inertia of submerged frustum
I_{xx}	Second moment of inertia of the water plane area
C_{33}	Term from hydrostatic matrix on 3^{th} column and 3^{th} row (Heave)
C_{44}	Term from hydrostatic matrix on 4^{th} column and 4^{th} row (Roll)
C_{55}	Term from hydrostatic matrix on 5^{th} column and 5^{th} row (Pitch)
ρ_B	Ballast density
$\rho_{Conc.}$	Concrete density
ρ_w	Water density
$Draft_{Plat}$	Platform draft
F_{Thrust}	Wind force

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Apart from the academic circle, the people that brought me here were my parents, who taught me with their example ever since I was young the very necessary self-improvement and effort values. I thank you and I thank my whole family for believing in me and constantly supporting me.

Finally I wish to dedicate this thesis to my friends from university for all those days, weeks and months of endless study and mutual support as well as my friends from Barbastro, Barcelona and Stuttgart because I may have missed many important moments because of studying, but the ones I have been able to enjoy have been great and I thank you for that.

ABSTRACT: Structural Dynamic behaviour of a floating platform for offshore wind turbines

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Key words: wind, floating, sea, concrete, offshore

Offshore wind energy industry needs to install wind farms in waters increasingly deeper and further from coast because is there where the wind blows stronger and longer.

Nowadays bottom fixed foundations does not offer an answer economical enough to solve that problem. Therefore floating platforms are seen as the answer. These floating platforms need not only provide floatability but also enough stability to assure that wind turbines will be able to work as long as possible.
Until now, a handful of steel floating platforms have been built and tested. However their resistance to corrosion and fatigue for long term is a major concern apart from their construction and maintenance costs.

In this minor thesis, the use of concrete as material for floating wind platforms is proposed as an alternative that can provide, great resistance to corrosion and virtually non maintenance.

After selecting the best suitable floating platform type for shallow waters a static analysis is done in order to choose the geometry and dimensions that best fits the needs expressed.
Then with the selected model, a dynamic analysis is performed in order to check the platform interaction with waves. Finally a basic description of loads affecting the platform and the displacements and efforts distribution on it is shown.

Conclusions show that the use of concrete as material for shallow waters platforms is a real alternative and that there is a lack of software and calculation methodologies adequate and accessible.

Resumen: Comportamiento estructural dinámico de una plataforma flotante para un aerogenerador en alta mar.

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Palabras clave: viento, flotante, mar, hormigón, alta mar.

La industria de aerogeneradores instalados en el mar necesita instalar parques eólicos en aguas cada vez más profundas y más alejadas de la costa puesto que es allí donde el viento sopla con más intensidad y regularidad.

Actualmente los sistemas de cimentación al fondo no ofrecen una respuesta suficientemente económica para resolver ese problema. Por tanto las plataformas flotantes son vistas como la solución. Estas plataformas flotantes no solo necesitan proporcionar flotabilidad sino también la suficiente estabilidad como para asegurar que el aerogenerador podrá trabajar el mayor tiempo posible. Hasta ahora un puñado de plataformas flotantes de acero han sido construidas y probadas. Sin embargo su resistencia a la corrosión y fatiga a largo plazo está en dudo además de sus costes de construcción y mantenimiento.

En esta tesina como alternativa se propone el uso de hormigón como material para las plataformas flotantes en alta mar dada su gran resistencia a la corrosión y su prácticamente nula necesidad de mantenimiento como principales ventajas.

Tras seleccionar el tipo de plataforma flotante que mejor se adapta a las aguas poco profundas se realiza un análisis estático para escoger la geometría y dimensiones que mejor se adaptan a las necesidades requeridas. Posteriormente y con el modelo seleccionado se realiza un análisis dinámico comprobando su interacción con las olas.
Finalmente una descripción básica de las cargas que afectan a la plataforma y la obtención de los desplazamientos que en ella se ocasionan así como los esfuerzos que en ella provocan es mostrada.

Las conclusiones muestran como a pesar de que la utilización del hormigón como material para plataformas en aguas poco profundas es realista, existe todavía una falta de herramientas y metodologías adecuadas y accesibles.

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CHAPTER 1: INTRODUCTION AND OBJECTIVES

1.1. Introduction

Renewable energies have become a strategic sector in many countries around Europe, U.S.A and Asia [8]. They provide energy independence from unstable countries and a great amount of job and high tech technologies [5]. In the spring of 2008 the European heads of states enacted an environment and energy package which entails that 20% of the European energy consumption by 2020 must come from renewable energy. Also, the need to increase energy efficiency is part of the triple goal of the *'20-20-20' initiative* for 2020, which means a saving of 20% of the Union's primary energy consumption and greenhouse gas emissions, as well as the inclusion of 20% of renewable energies in energy consumption. [5] To get that objective, new technologies are been developed with a special focus in wind energy. [2]

In this field one of the aspects being developed is the searching of new locations for wind turbines. That includes since low wind speed zones to hard locations sites as ocean.

One of the objectives of the wind industry is to harvest the great wind energy of oceans [6] but to arrive to that point it is necessary to solve the foundation defy. Other industries as Oil&Gas have installed platforms even in 2000 meters deep waters [34].

On this thesis a floating foundation solution using concrete will be developed to meet shallow waters requirements unable by now for bottom fixed solutions. The use of concrete as material is one of the main differences with other floating platforms design developed around the world.

1.2. Motivation

Since years ago wind industry is looking to the oceans potential. Now that the bottom-founded offshore problems have been enough solved the next step is conquer greater depths using floating platforms.
Due the huge potential of this technology for Europe energy independence it has been decided to understand and try the concepts and tools up to date available through the design of a prototype.

1.3. Objectives

Several objectives have been defined:

- Environmental loads: To understand and valuate the environmental actions acting over this kind of structure on real sea conditions.
- Dynamic behavior: To check the dynamic behavior of the structure and its usefulness to support wind turbines.

- Concrete possibilities: To assess the capacity of concrete to fulfill the structural requirements for this structure and the possibilities of using it as a cheaper alternative to steel.
- Resulting forces: To get the forces acting on a floating platform structure to allow its checking.

1.4. Contents of the thesis

On this minor thesis after a state of the art describing current offshore platforms for oil & gas and the existing floating wind platforms prototypes, a description of the basic theoretical concepts for designing floating platforms is presented.
Then main requirements for floating platforms are explained and implemented in a prototype selection using static analysis and a subsequent dynamic analysis with the most suitable of these prototypes.

Finally, loads acting on the structure and the resulting displacements and forces are presented.

The minor thesis ends with a conclusions summary.

There are also three annexes relative to the structure properties calculations, the dynamic analysis results and the loads analysis.

CHAPTER 2: WIND ENERGY

2.1. Introduction

From navigation to agriculture wind energy has provide energy to human being since first civilizations. Culture in Mediterranean Sea was expanded through Phoenicians, pharaohs sailed Nile thanks to wind and Chinese empire based its irrigation and transportation system through channels and machinery impulse by wind. [24]

Nowadays wind energy is transformed in electricity providing clean and renewable energy to consumers around the world.

2.2. Wind energy

Wind power is produced by converting the kinetic energy of wind into electrical or mechanical power and if looking to statistics it does allowing grow and development; just in 2011 this industry employed 670.000 people around the world [1]

The key advantages of wind power are:
-It is a renewable, free, abundant and distributed energy.
-It is already competitive in optimum locations as opposed to traditional energy sources without any kind of state or subsidies support.
-It is relatively quick to install thanks to its modular components.
-It helps to assure national or regional energy independency from fossil energy.
-It has a relatively low environmental and land use impact.

As any technology in its developing phase there are problems to be solved; the main one is the necessity of more power grid reinforcement and interconnection to improve security of supply due to the natural unreliability of wind energy.

Since Kyoto's Protocol [2] the policies of nearly the entire world are moving into a new deal based in changing the nonrenewable resources (oil, gas, coal) to renewable ones like wind, solar energy, hydroelectricity…
The reason for that is the high consumption of nonrenewable or fossil resources, some of them, as in the case of oil, have may be already reached their peak. Another reason is the necessity to reduce greenhouse gases: CO_2, CH_4… which have a decisive impact on global warming.

Those green policies are boosting the green energy industry making an intense progress and becoming a strong I+D+I sector, especially in the wind energy sector.

The world's power capacity of renewable energies can be seen in table 1 as well as their inversion.

Table 1:"World power capacity of renewable energies and inversion on them realized" [2]

SELECTED INDICATORS		2008	→	2009	→	2010
Global new investment in renewable energy (annual)	*billion USD*	130	→	160	→	211
Renewables power capacity (existing, not including hydro)	*GW*	200	→	250	→	312
Renewables power capacity (existing, including hydro)	*GW*	1,150	→	1,230	→	1,320
Hydropower capacity (existing)	*GW*	950	→	980	→	1,010
Wind power capacity (existing)	*GW*	121	→	159	→	198
Solar PV capacity (existing)	*GW*	16	→	23	→	40
Solar PV cell production (annual)	*GW*	6.9	→	11	→	24
Solar hot water capacity (existing)	*GW_{th}*	130	→	160	→	185

As can be seen, wind energy and thermal solar energy are the major sectors of investments; the reason being its relatively low energy costs which makes it affordable and practically competitive against traditional energy sources.

Table 2: "Power generation sources and costs" [2]

POWER GENERATION	Typical Characteristics	Capital Costs (USD/kW)	Typical Energy Costs (US cents/kWh)
Biomass Power Stoker boiler/steam turbine Circulating fluidised bed	Plant size: 25–100 MW Conversion efficiency: 27% Capacity factor: 70–80%	3,030–4,660	7.9–17.6
Geothermal Power	Plant size: 1–100 MW Types: binary cycle, single-and double-flash, natural steam Capacity factor: 60–90%	condensing flash: 2,100–4,200 binary: 2,470–6,100	condensing flash: 5.7–8.4 binary: 6.2–10.7
Hydropower (grid-based)	Plant size: 1 MW–18,000+ MW Plant type: reservoir, run-of-river Capacity factor: 30–60%	Projects >300 MW: <2,000 Projects <300 MW: 2,000–4,000	5–10
Hydropower (off-grid/rural)	Plant capacity: 0.1–1,000 kW Plant type: run-of-river, hydrokinetic, diurnal storage	1,175–3,500	5–40
Ocean Power (tidal range)	Plant size: <1 to >250 MW Capacity factor: 23–29%	5,290–5,870	21–28
Solar PV (rooftop)	Peak capacity: 3–5 kW (residential); 100 kW (commercial); 500 kW (industrial) Conversion efficiency: 12–20%	2,480–3,270	22–44 (Europe)
Solar PV (ground-mounted utility-scale)	Peak capacity: 2.5–100 MW Conversion efficiency: 15–27%	1,830–2,350	20–37 (Europe)
Concentrating Solar Thermal Power (CSP)	Types: trough, tower, dish Plant size: 50–500 MW (trough), 50–300 MW (tower); Capacity factor: 20–25% (trough); 40–50% (trough with six hours storage); 40–80% (solar tower with 6–15 hours storage)	Trough without storage: 4,500; Trough with six hours storage: 7,100–9,000; Solar tower with 6–18 hours storage: 6,300–10,500	18.8–29
Wind Power (onshore)	Turbine size: 1.5–3.5 MW Rotor diameter: 60–110+ meters Capacity factor: 20–40%	1,410–2,475	5.2–16.5
Wind Power (offshore)	Turbine size: 1.5–7.5 MW Rotor diameter: 70–125 meters Capacity factor: 35–45%	3,760–5,870	11.4–22.4
Wind Power (small-scale)	Turbine size: up to 100 kW	3,000–6,000 (USA); 1,580 (China)	15–20 (USA)

In table 2 can also be seen that the lowest energy cost excluding hydropower is on-shore wind power which is competitive on the liberalized market. In the last 20 years production cost per kWh has been reduced by more than 80% and this trend is expected to continue.

Wind energy in the World

The wind energy power industry has been growing at an exponential rate for years. In figure 1 the last 17 years are shown.

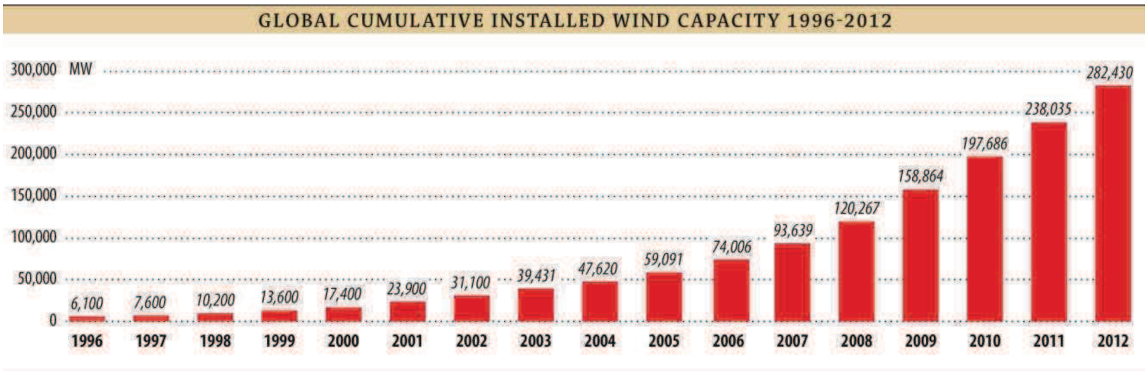


Figure 1: "Global cumulative installed wind capacity 1996-2012" [3]

From a global point of view, wind power capacity increased by 20% in 2011 and a 19% in 2012 until approximately 282 GW by year-end, seeing the greatest capacity additions of any renewable technology. As in 2011 more new capacity was added in developing countries and emerging markets than in OECD countries. [3]

China accounted for almost 34% of the global market capacity increase (adding much less capacity than it did in 2011), followed by the United States and India; Germany remained the largest market in Europe. [3]

In the last years the main growth has been located in Asia, as can be seen in figure 2, Europe, despite continuously being the main supplier of wind turbines and wind technology and the region with more capacity installed will be soon surpassed by Asia in installed capacity thanks to the impressively high investment of China in this technology.

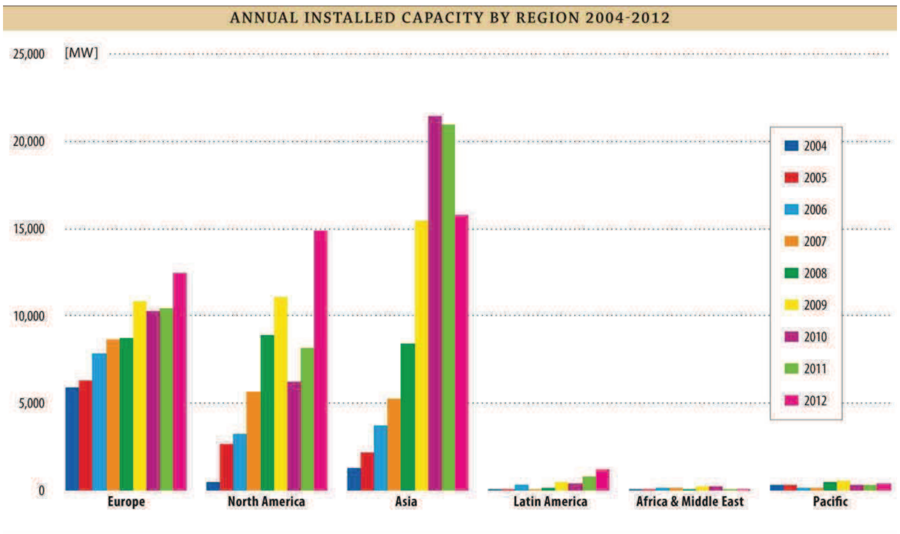


Figure 2: "Annual Installed Capacity by Region 2004-2012" [3]

In fact, nowadays China alone holds more than ¼ of the total World installed capacity followed close by USA.

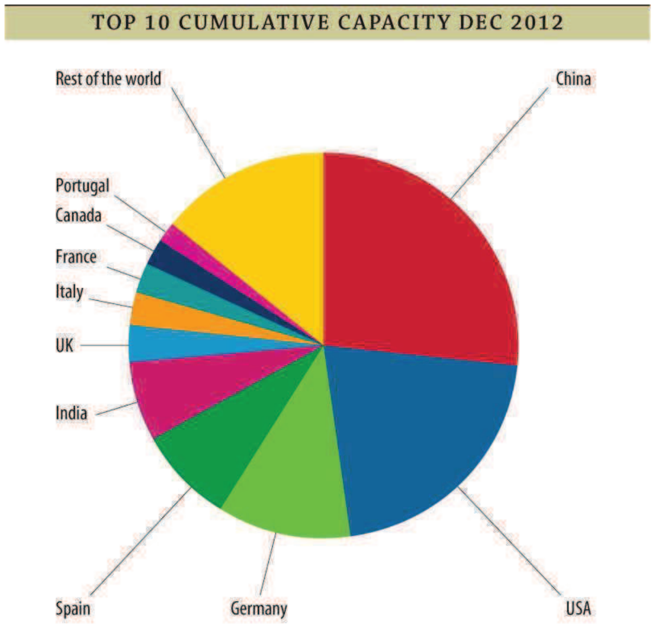


Figure 3: "Top 10 Cumulative Capacity December 2012" [3]

In spite of that, if all the power Capacity installed in the European Union is considered together as a whole, the Figure changes significantly:

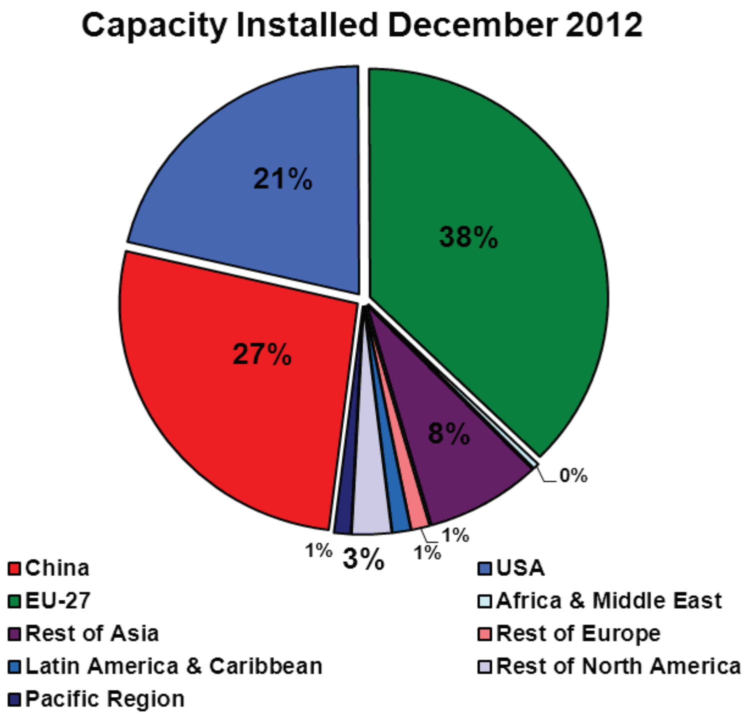


Figure 4: "Cumulative Capacity Installed in December 2012" [1]

As can be seen in figure 4, European Union is by far the world leader in this technology with more than 1/3 of world capacity.

At the same time as the market expansion, the search of more profits per installation has led to an increase of turbine size which is shown in figure 5:

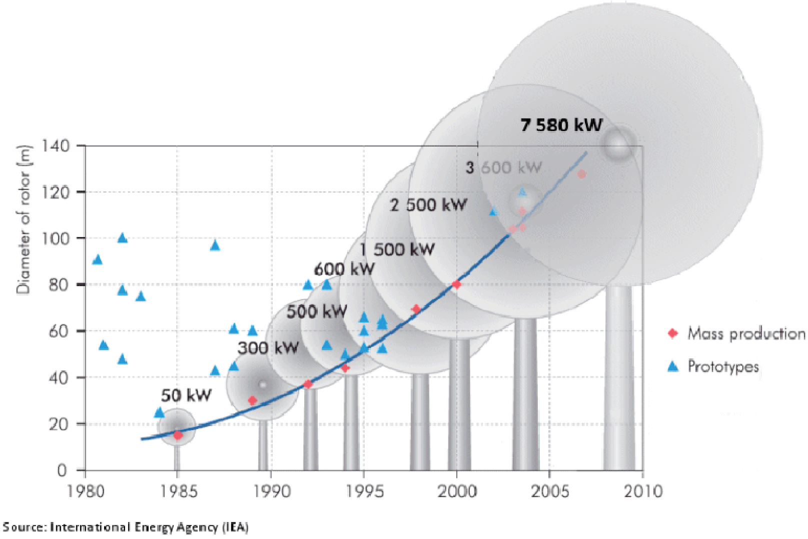


Figure 5: "Wind turbine Increase 1980-2011" [4]

Europe

In order to achieve the environmental objectives goals, the European Union has developed a huge variety of I+D projects in order to develop new technologies in each of those three fields: saving energy consumption and energy efficiency, reducing greenhouse gas emissions and improving renewable energies. [5]

This binding objective for renewable energy will have a large impact on Europe's future energy supply and at the same time will offer peace of mind to investors in renewable energy. On the geopolitical side it will mean a more energetically independent Europe in front of third countries and a real European energy policy and infrastructure to achieve these goals.

In 2011 wind energy installed in Europe reached 105 GW, which is by far more than the total consumption of Sweden, Ireland, Slovenia and Slovakia together. Equivalent to 72 Mt mined, transported and burned coal or 42,2 millions of m3 of gas. Also, this kind of energy powered 7% of total EU electricity demand, which can look more impressive looked country by country as in example Denmark with a 26% of its electricity generated by wind power in 2011 followed by Spain and Portugal with a 16%, Ireland with a 12% and Germany with a 11%. [5]

European wind energy sector contributed with 32€ billions to the EU economy and got a 27,4 % of the global wind energy market in 2010. It was also a net exporter of 5,7 billions worth of products and services. Just between 2007 and 2010 the wind energy sector increased its contribution to GDP by 33%. In addition, nearly 12,6 billions worth were invested in 2011 in EU wind farms. [5]

It is usually said that wind energy as any other renewable energy source is just competitive thanks to governmental subsidies, but Connie Hedegaard, EU Commissioner for climate action, said in December 2012 "Every time we spend 1$ subsidizing renewable (energy sources), we spend 6$ on subsidizing fossil fuels" [5]

By 2020, due to that European policy, the European wind energy association estimates that 230GW will have been installed, including nearly 40 GW of offshore wind power capacity.

2.3. Offshore Wind Energy

As well as in the oil & gas industry once explored on-shore locations comes the ocean. The occupation of the best on-shore locations in many of the developed countries and the requirement to avoid social opposition to the each time bigger wind turbines because of their environmental and aesthetical impact and the development of technology leaded the wind industry to the colonization the oceans.

Although its market share remains relatively small, the offshore wind sector continues expanding, with the use of larger turbines and conquering deeper water, farther from the shore. The trend towards increasing the size of individual wind projects and larger wind turbines continued.

This trend shapes with the fact that the majority of the world's population lives in coastal regions which suits perfectly with the offshore wind resource which can contribute to vast amounts of clean renewable energy to those regions.

Nowadays there are approximately 4 GW of offshore installations worldwide, most of them in the North Sea, Europe. The average nameplate capacity of these offshore wind turbines has grown from 2,98 MW in 2007 to 3,94 MW in 2011. [2]

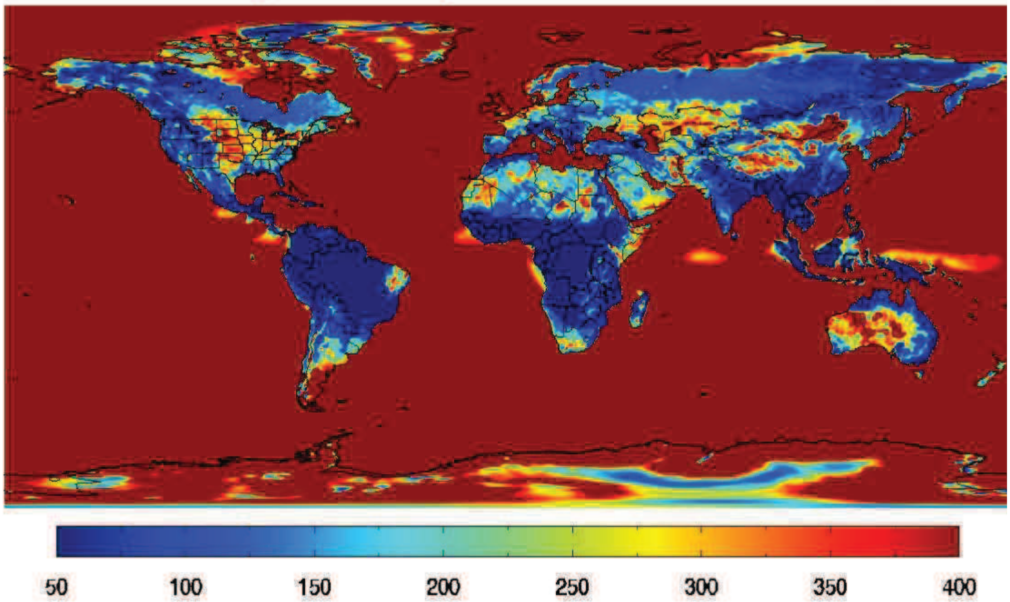


Figure 6: "Wind power density in Watt/ m^2" [6]

As can it be seen in figure 6, offshore winds can produce more energy as they are not encumbered to with topographical features such as buildings or hillsides and afford a more consistent wind profile. Despite that, recovering energy from offshore wind can be more expensive than on-shore, the resource provides as much as 50% more energy increasing the profitability. [7]

For this reason many countries are developing technology to harvest it, especially those with shallows waters which allow affordable costs, in table 3 all offshore projects until 2012 are shown.

Table 3: "Offshore projects" [8]

Region	Country	Number of Operational Projects	Total Capacity (MW)	Total Number of Turbines Installed
Asia	China	4	211.4	75
	Japan	3	25.32	14
Europe	Belgium	2	195	61
	Denmark	16	874.65	406
	Finland	3	32.3	11
	Germany	6	205.8	53
	Ireland	1	25.2	7
	Italy	1	0.1	1
	Netherlands	4	246.8	128
	Norway	1	2.3	1
	Portugal	1	2.0	1
	Sweden	5	163.65	75
	United Kingdom	20	2,117.6	640
	Total	**68**	**4,102**	**1,472**

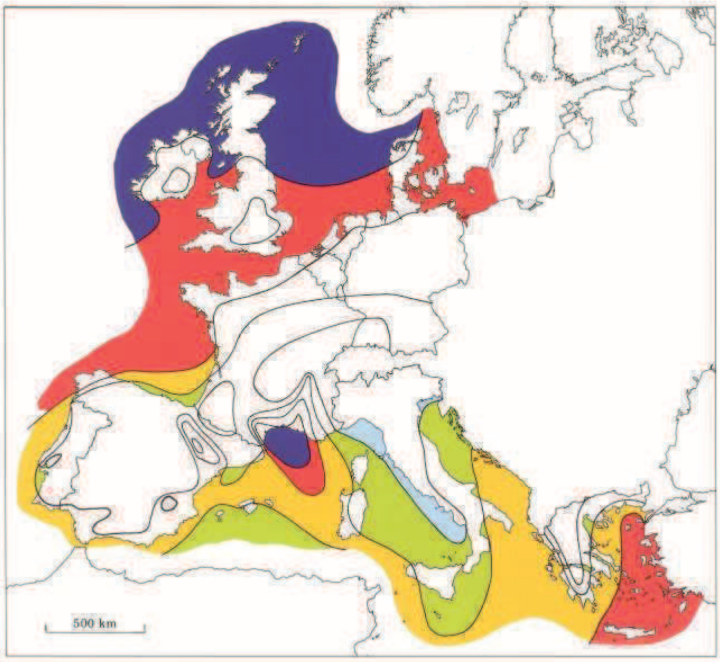
Some forecast expect European countries to install an additional 16 GW of capacity before the end of 2016. In Asia, China is positioning itself to make raped progress, being the world's largest land-based wind power market with 62 GW of operational land-based wind power. At the end of 2011, this country has announced plans to install 5 GW of offshore wind by 2015 and 30 GW by 2020. For the global wind market the forecast is of between 55 to 75 GW of cumulative capacity by 2020. [3]

2.3.1 Europe

Only in Europe offshore wind energy capacity reached 4995 MW in 2012 using 35000 direct + indirect employments and 55 offshore wind farms. This year Europe was by far the world's leader in offshore wind energy with more than 90% of the world's installed capacity with an average size of 4MW. [7]

Offshore represents around 10% of EU annual wind energy installations and its average water depth of the offshore wind farms reached 23 meters, a 31% per cent deeper than in 2010. It is expected that the wind energy sector will employ 462000 people in 2020 from these; almost a 40% will be in the offshore sector. [7]

In figure 7 a more detailed look on Europe shows us that the best resource's places to install wind power plants are the North Sea and the Lyon´s Gulf on the French Mediterranean coast.



	Wind resources over open sea (more than 10 km offshore) for five standard heights									
	10 m		25 m		50 m		100 m		200 m	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Figure 7: "European Wind Resources Over Open Sea" [9]

The offshore market was pioneered in Denmark in the late 1990s and early 2000s as a result of the research projects started from 1979 energy crisis, environmental friendly policies and favorable shallow waters. Since then, other countries have join this market until nowadays with U.K. together with Germany as the leaders with a lot of testing and developing wind farm zones in UK waters and an Offshore wind energy national focus in Germany. Collectively, as shown in Figure 8, Europe increased in nearly 3 GW of offshore capacity additions between 2007 and 2011, with a rate of annual installations that has ranged from 225 MG in 2007 to 1,26 GW in 2010. [8]

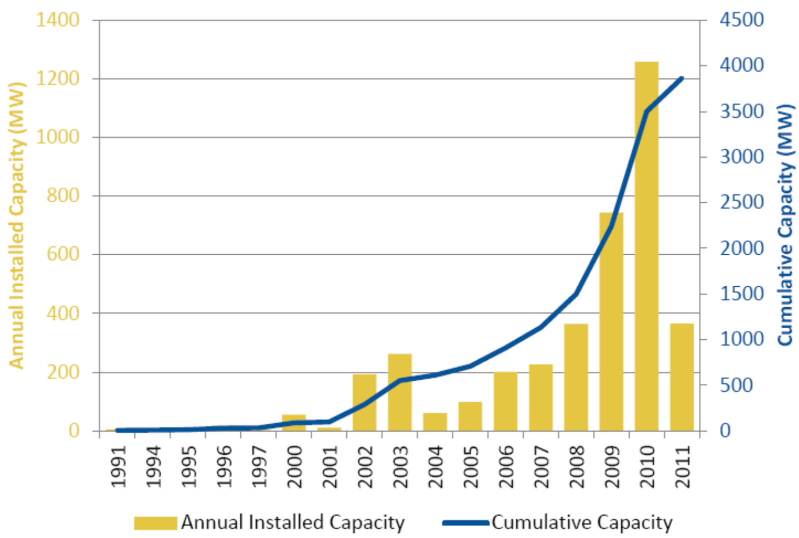


Figure 8: "Annual Installed and cumulative wind capacity in Europe" [8]

Due its shallow waters and high winds, offshore wind energy has focused on the North Sea. In figure 9, the wind farm zones which are already in use or planned can be seen:

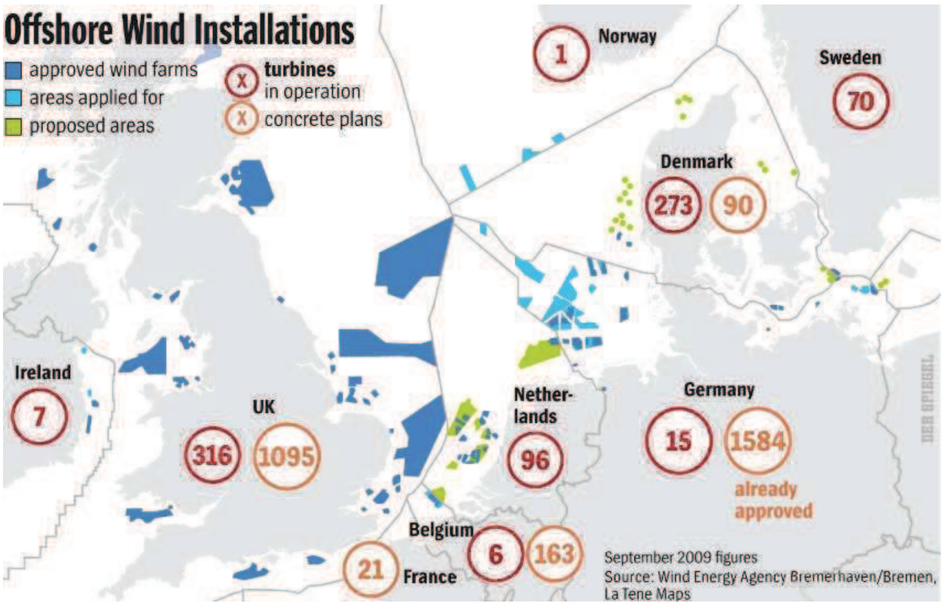


Figure 9: "Offshore Wind Installations in North Sea" [10]

It is in UK, off the coast of Suffolk where the biggest World wind farm is, with 504 MW generated by 140 turbines and the London Array in the Thames Estuary where 175 turbines will produce 630 MW at the end of this year, 2013 [11]

In 2011 in Europe there were 3 experimental floating turbines searching to take offshore wind energy to deeper waters on Atlantic and Mediterranean Sea basins. Now there are two full scale grid-connected floating turbines, and two down-scaled prototypes. [7]

2.3.2. U.S.A

The U.S. Government plans to achieve a 20% of wind energy by 2030. [56] That target includes necessarily offshore wind energy because it is estimated that 61% of the U.S. wind resource are in deep water. One of the best points for this technology in USA is that as shown in Figure 10, the majority of the population lives on the coast, getting close the energy production to the consumers. The technical problem comes from the coastal bathymetry because all the west coast, Hawaii, great lakes and many parts of the East coast have water depths beyond 60 meters, making the conventional foundations not applicable or unaffordable [8]

The National Renewable Energy Laboratory which started to investigate how to improving renewable energy more than 35 years ago and which is already participating in various floating projects, such as in the case of Sway and others, said in its report of July 2008 "*Floating wind technology plays a major role in achieving the national target*":

-Over 800 GW of energy potential could be harvested just on the West Coast using floating offshore wind technologies and 275 GW on East Coast.[8]

-150 GW of energy potential exists deeper than 40 meters in Mid-Atlantic coastal waters and 500GW in the Great Lakes. [56]

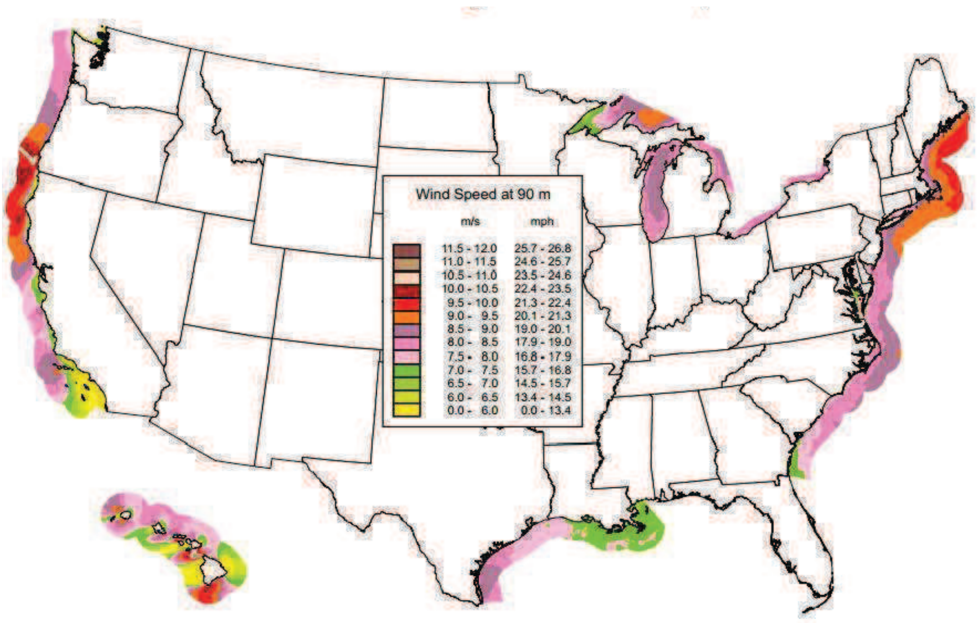


Figure 10: "United States Annual Average Offshore Wind Speed at 90 m" [12]

For these reasons, EEUU administrations have established offshore development wind farms areas in Rhode Island, Massachusetts and Virginia, all of them on the Atlantic coast. In fact there are 33 announced offshore wind projects in different stages of development along the Atlantic Coast, up to date, just 9 of them, see figure 11, have reached an advanced stage of development [8]. In one Maine's project, Statoil North America wants to build four three-megawatt turbines on floating structures in the Gulf of Maine near Boothbay Harbor. [14] The Department of Energy (DoE) is funding seven offshore wind demonstration projects amounting to 12-30 GW of grid-connected electricity, with a total potential generation cap of 36-82 MW. These projects are being pursued on both Atlantic and Pacific coasts, the Gulf of Mexico and the Great Lakes; each of which are receiving $4 million over the next year to complete initial engineering, design, and permitting. There is a required 20 percent cost-share for the first year, but typically the project participants are kicking in more (in some cases much more). The field will be narrowed down to three projects in February 2014, which will continue to the next phase of completed design and permits, installed offshore, and achieving operations in 2015-2017. Up to $47 million in DoE funding are at stake over the following four years, pending congressional appropriations; total funding levels could reach $180 million. [13]

2.3.3. Asia

The emerging Asian offshore market has also gained market share in recent years, with China adding 107,9 MW just in 2011 reaching an installed capacity greater than 200 MW. [8]

CHINA

On November 8, 2007 China National Offshore Oil Corporation constructed the first offshore wind turbine in the Bohai Bay of Bohai Gulf. It was a 1,5 MW turbine adapted for offshore us and the first Chinese offshore wind farm at Shanghai Donghai bridge consists in 34 wind turbines with a single installed capacity of 3 MW and has been in operation since June 2010. The total admitted cost was of 3 billion RMB. [2]

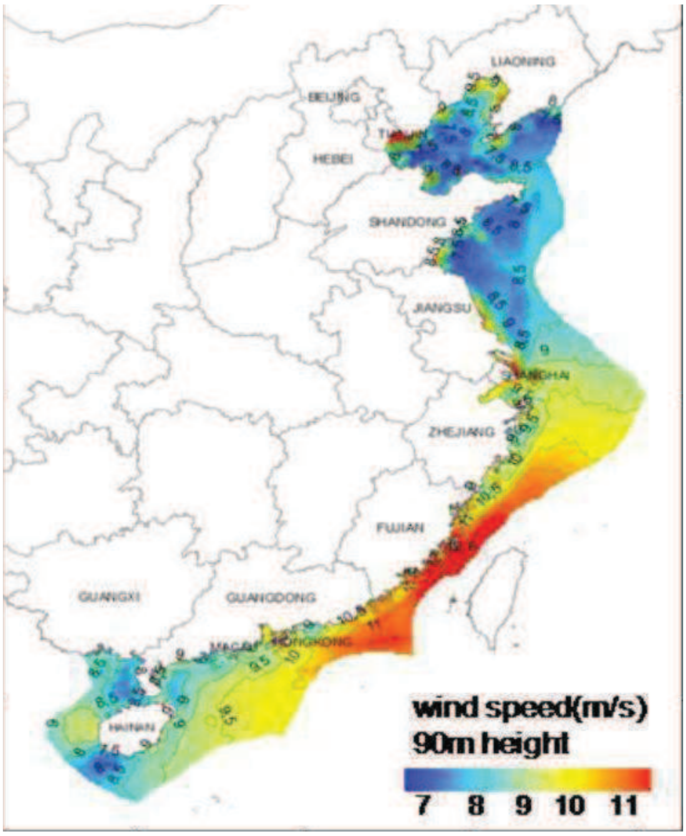


Figure 11: "Offshore wind energy potential in China" [15]

The country's offshore wind potential at 550 GW and 200 GW of them in water depths between 5 and 25 meters. [63]

The developing areas in a first phase are being Jiangsu and Shanghai provinces. Figure 13 shows that there are other provinces with bigger wind resources [63]

It is estimated that the total offshore wind power will reach 10 GW in 2015 and 30 GW in 2020. [15]

JAPAN

Japan has around 1,2 TW of offshore wind energy potential with 608 GW which can be used in an optimistic scenario or 141 GW in an economically one but more than 80% of this energy is in deep water areas, see figure 14. For this reason the research on floating wind turbine platform has been developed for a long time. [8]

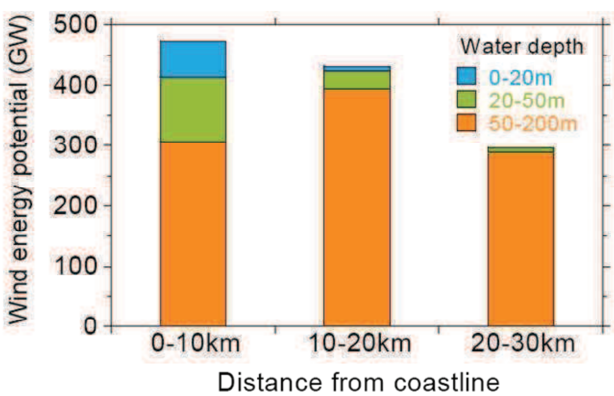


Figure 12: "Offshore Wind Potential in Japan " [17]

Japan, in a radical energy policy change from nuclear to renewable energy, prepares to build the world's largest offshore wind faros starting in July 2013. By 2020 the plan is to build a total of 143 wind turbines on platforms 16 kilometres off the coast of Fukushima.

Figure 13: "Offshore wind velocities in Japan" [16]

Despite of all their knowledge no commercial project was done. Nowadays due to Fukushima nuclear accident in March 2011 the situation has changed radically and the Japanese government has announced the construction of a floating wind farm pilot project in Fukushima coast. The objective is to take advantage of the already power grid existing there due to Fukushima nuclear plant and some thermal ones and restoring the economy of the region.

For the first phase which started in 2011 and will finish this year the idea is to test a floating substation and a compact semi-sub 2 MW wind turbine floating platform.
In June 2012 a 1:2 spar design was deployed off Kabashime Island and for 2013 a full scale spar is planned on the same place. [17]

On the second phase which will be held from 2014 to 2015 it is expected to try an advanced spar and a V-shape semi-sub.

In Japanese coast the main opposition to offshore wind industry specially the floating one is the impact on fish industry. With this project the Japanese government expects to get social acceptance besides the technical knowledge. [17]

CHAPTER 3: OFFSHORE PLATFORMS

3.1. Introduction

A high percentage of off-shore knowledge comes from the oil & gas industry which started to design and experiment with off-shore structures in the 20's of last century and thanks to that experience nowadays depths of more than a thousand meters [28] have been reached.

The first offshore platform was installed in 1947 off the coast of Lousiana in just 6 m depth waters, nowadays Perdido platform, a Spar platform type in Gulf of Mexico, is floating 2.438 meters over the sea bed. [28]
The major difference between oil and wind tower platforms is that the first one must be designed focusing on wave's actions and cargo load but the second one must also focus on the wind force which for oil platforms, due their stiffness, is not considered as important.

Even though we can consider that the physical principles are the same as for floating wind towers, the difference of weight, primary actions and functions provokes the necessity to expand the off-shore knowledge in smaller and lighter structures with non-oil purposes in order to get enough confidence to build and guarantee our structures.

The main targets to be improved are the high costs of offshore wind turbines and required installations vessels and the usually short construction weather windows, especially on the North Sea.

3.2. Floating platforms types

Despite the fact that sea-bed foundations off-shore installation are reaching now even 60 meters depth, its cost is extremely high. This problem joined with the risks related with the foundation stability and the ecological impacts makes them extremely expensive and limited to relative shallow waters. For this reason it is considered that floating wind turbines start to be adequate from 50-60 meters depth. For shallower waters technical problems in stability requirements and natural wave frequencies makes them economically unaffordable with the actual knowledge.

The main reason for floating offshore development is that bathymetries around nearly all world key markets with the exception of main parts of North Sea, are usually more than 100 meters deep. For example:
-NREL says that 61% of the US offshore wind resources are in water depths of more than 100 meters [16]
-Japan has nearly only deep waters in its coast and in Europe, Norway and Mediterranean countries the use of off-shore bottom based foundations is restricted due their lack of shallow waters. [16]

As can be seen floating off-shore market has a huge potential and some of the major "traditional" off-shore wind turbine manufacturers as Vestas, Siemens and Areva in

Europe, and Mitsubishi and Fuji Heavy Industries/Hitachi in Japan are already involved in those projects and Acciona, Alstom, Gamesa and Samsung will do it soon. [16]
Main(e) International Consulting LLC assures that currently more than 25 different FOWTs projects are being developed around the world and that the average time of research and developing efforts have been at least of 6 years each one.

Since 2009 with the installation of the Hywind floating wind turbine by Statoil Hydro in the Norwegian coast until 2016, it is expected to be the trial phase, with many projects arriving to the real scale trials.
After 2017 it is planned to have already full commercial designs and projects.

In Europe, the initiative was hold by Norwegian companies due their nation's deep water characteristics and oil&gas offshore background. Then other companies such as BlueH from the Netherlands, Nass et Wind of France or GICON of Germany started to work also on it. [16]

Some examples are the request from ETI (UK) which announced plans to invest up to 28 million of € in an offshore wind floating system demonstration project, in 2011 demanding proposals for TLP platform, or the projects covered by mass media of the Japanese proposal of build an off-shore wind farm off the coast of Fukushima. It is expected that by 2015 8 deep water testing sites will be available, one of them in the Catalonian coast, Spain. [16], [5]

Floating platforms for wind turbines concepts

Their designation and characteristics depend on which of the 6 degrees of freedom: surge, sway, heave, roll, pitch and yaw are restrained (*R)* or compliant (*C)*, see table 4. Even if a motion is defined as restrained, some little displacements can appear due to material elasticity, but due to its small range (a few centimeters) are considered insignificant compared to the displacements of meters in the other modes of motions.

Table 4: "Typical floaters and boundary conditions" [17]

Type	Surge	Sway	Heave	Roll	Pitch	Yaw
Deep Draft Floaters (DDF) [1]	C	C	C	C	C	C
Semi submersibles	C	C	C	C	C	C
Barges	C	C	C	C	C	C
Tension Leg Platforms (TLP)	C	C	R	R	R	C
Heave Restrained TLP (HRTLP) [2]	C	C	R	C	C	C
Heave Restrained DDF (HRDDF) [3]	C	C	R	C	C	C
Ship shaped	C	C	C	C	C	C
Truss Structures	C	C	C	C	C	C

In the next pages actual built prototypes state of the art is described, each of them has a different solution to get enough floatability and operative conditions.

[1] Classic, Truss & Cell Spar, deep draft semi, buoys
[2] Special type TLP which has not been built, but proposed and developed to a certain level
[3] Special type of DDF

3.2.1 Tension Leg Platform (TLP)

A TLP is a vertically moored, buoyant structural system wherein the excess buoyancy of the platform maintains tension in the station keeping system.

It consists of structural components of hull, tendon system and foundation system. It can also include a column top frame and topside deck. The hull consists of buoyant pontoons and columns. The top of the columns may be connected to the Tower directly or to a column top frame or a topside deck forming the global strength of the hull. The tendon system consists of a vertical mooring system called tethers which forms the link between the hull and the foundation for the purpose of mooring the floating support structure. The foundation system is used to anchor the tendons to the seafloor.

This characteristic makes the structure very rigid in the vertical direction and very flexible in the horizontal plane. Thanks to the excess of structure's floatability those tethers are extremely tensioned getting a stable position
These structures usually cannot be stable without by their tethers which make them extremely dependent of the mooring system making, doubts about the sea bottom capacity to resist these loads causes expensive safety factors and anchors.

The Blue H full scale prototype

Figure 14: "Blue H prototype in its emplacement" [19]

Dutch company Blue H Technologies has devised a "Submerged Deepwater Platform" (SDP). Essentially a modified form of a Tension Leg Platform, SDP is made of a buoyant hollow body that is 'semi-submerged' in water by chains or tethers, which are in turn connected to a counterweight on the sea bed – thus creating the necessary uplifting force to keep the chains constantly tensioned.
The 1st phase prototype was tested in the summer of 2008; the company installed a $^3/_4$ scale prototype SDP with a small wind turbine. The prototype was built in the Brindisi shipyard, with the support of regional resources in research, engineering and industrial production. [19]
It was installed in 113-metre deep waters at a distance of 11.5 nautical miles (21.3 km) off the coast of Otranto canal, near Tricase, in Southern Italy, near the site of the future offshore Tricase wind farm a 92 MW and 26 turbines project. After 6 months at sea, the unit was decommissioned early in 2009. Figure 16 shows Blue H installed. [16]

Currently, this project is in its 2nd phase in which Blue H has to develop a 2MW floating wind turbine which was expected to be installed in its Tricase windfarm in 2012, despite of that no reports until now are find, only two photographs from the construction site from the Blue H project website could be find, these pictures are shown in figure 17 a) and b).

Figure 15: “a) and b) 2 MW Blue H prototype during construction” [19]

In the UK, Blue H also led a consortium of companies involved in Project Deepwater, a two-year project that ran from 2009-2010 and looked at the feasibility and costs of generating electricity using offshore wind turbines mounted on a floating, tension legged platform in water depths of 70 to 300 meters.[72]
In addition, the company is currently undertaking extensive research work with partners Timolor Leroux & Lotz in what it calls Project DIWET (Deepwater Innovative Wind Energy Technology). The project, located off the coast of Brittany, France, consists of a floating platform concept that is anchored using rigid taut lines.

3.2.2. Spar

A Spar-type floating support structure is a deep draft, vertical floating structure of cylindrical shape, supporting the tower and a topside structure and moored to the seafloor. Usually his topology has been used in oil industry due its low wave diffraction.

It typically consists of an upper hull, mind-section and lower hull. The upper hull serves to provide buoyancy to support to the topside and provides spaces for variable ballast. The mind-section connects the upper hull with the lower hull. The mid-section can be a cylindrical column or a truss space frame with heave plates. The heave plates are a series of horizontal decks between each bay of the truss space frame and are designed to limit motions by providing added mass and hydrodynamic damping. The lower hull normally consists of a fixed ballast tank and, in the case of a truss Spar, a flotation tank. The fixed ballast tank provides temporary buoyancy during a horizontal wet tow and provides the needed ballast in upending by flooding the tank. After upending, the ballast water may be replaced by fixed ballast, to lower the Spar’s centre of gravity. The ballast in the fixed ballast tank results in a vertical centre of gravity well below the centre of buoyancy, which provides the Spar with sound stability, as well as desired motion characteristics. The flotation tank is located adjacent to the fixed ballast tank to provide additional buoyancy for wet tow and ballast in upending. It can be moored by catenaries or taut lines.

Hywind

The World's first full-scale floating wind turbine prototype was a spar platform done by Norwegian energy company Statoil. [20],

Figure 16: "The Hywind turbine being towed out to sea" [20]

It consists in a 2.3 MW Siemens turbine with a hub height of 65 meters and a rotor diameter of 82.4 meters was fixed to a floating slender cylinder which is also used by the oil and gas industry. This proof-of-concept turbine was assembled in Norway in the summer of 2009 and towed 12 km away from its south-western coast in 200 meters deep waters. [16] Figure 18 shows the Hywind prototype towed out to sea.

It is a 117 meters long steel cylinder, with a total weight of 5300 tons and 100 meters draft. In figure 19 it can be seen the depth marks. The trial period was until 2011 but nowadays it still continues active due the good results. The cost of this project is estimated around 50 million €. [20]

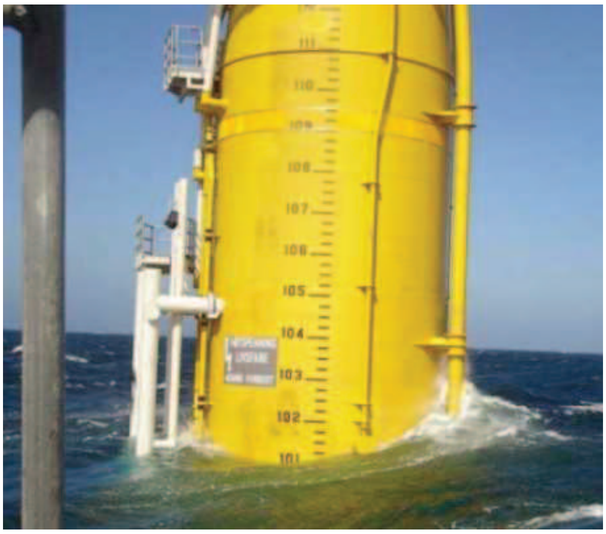


Figure 17: "Hywind prototype installed" [20]

It is also an example of European industry collaboration: the turbine was developed and manufactured in Denmark by Siemens, the floater and the power cable was built in France by Technip and Nexans respectively. [7]

Now Statoil is searching for a wind farm to develop the next step, a 5 to 6 next generation Hywind wind tower, probably in Maine, U.S. coast. [74]

Sway

Figure 18:"2nd Sway prototype being tested" [21]

Also in Norway another Spar project is being developed by Sway Company. Its project prototype construction started in 2007 with a 1/6 model size development. Its testing started in off coast near Bergen in June 2011, [26] unfortunately in November 2011 due to severe water conditions for such a scale model, it sank. [21] The reason explained by the company was that marine water entered in the tube of the cable connection making tilt all the structure. [6] Then waves up to 6,3 meters height and storms surge increased the water level on the turbine, ending with the prototype. [16]

Half year later, in May 2012 another same size prototype was refitted. Figure 20 shows this second prototype. It is expected to be tested during 2 years. [21]

Japanese Spar

In Japan, another spar type wind tower was installed about 1 km away from Kabashima Islands coast, on June 2012, the 100 kW Wind turbine was installed in a 90-100 meters deep range, see figure 21 a) with a hub height of 23 meters and a rotor diameter of 22 meters. It is expected that in this year, 2013, the 100 kW would be removed to make way for a 2MW turbine. [16],

The zone has an average wind speed of 7,5 m/s and an average wave height of 1 meter.[26] Turbine was manufactured by Japan Steel Works and Hitachi [26]. In figure 21 b) its transport system is seen.

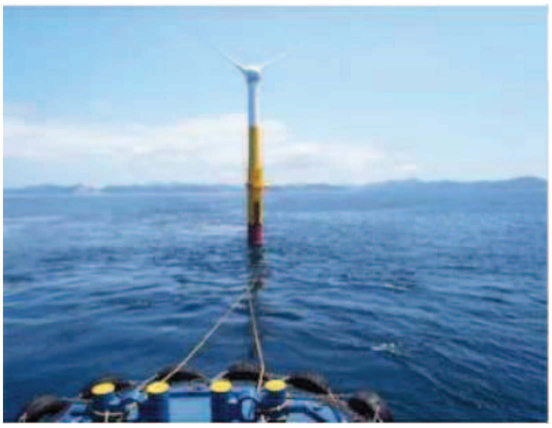


Figure 19: a) and b) "Japanese Spar" [16]

3.2.3. Semi-submersible

It consists of a topside structure connected to the underwater hull by columns or caissons. The floating support structure depends upon the buoyancy of columns or caissons for flotation and stability. Lower hulls or footings are normally provided at the bottom of the columns for additional buoyancy. The topside structure can be of an enclosed hull type or an open space frame truss construction. The topside structure is interconnected with the stability columns of the hull to form the overall strength of the platform.

These platforms get stabilized thanks to spreading the floating force through a hulls structure (columns and pontoons) with sufficient buoyancy to cause the structure to float, but with sufficient weight to keep the structure upright.

Semi-submersible platforms get partially submerged maintaining over surface the operating installations. They can be moved from place to place; can be ballasted up or down by altering the amount of flooding in buoyancy tanks and due their sensibility to low period waves they increment their draft in order to reduce the induced inclination; they are generally anchored by combinations of chain, wire rope or polyester rope, or both, during drilling or production operations, or both, though they can also be kept in place by the use of dynamic positioning.

The WindFloat prototyp

Principle Power, based in Seattle, US in collaboration with *Energías de Portugal* (EDP), developed the WindFloat wind turbine, focused on waters deeper than 40 meters. [23]

The prototype sits six kilometres off the coast of the windy town of Povoa do Varzim, close to Porto in northern Portugal since 2011. [73]

It is 54 metres tall and weights 1.200 tonnes, with a turbine from Denmark's Vestas and backup from Repsol and other local partners. [73]

Figure 20: "WindFloat prototype on dry dock" [22]

Its 2MW capacity is not so far below the average of offshore wind turbines in Europe, which was 4 MW at end-2012, according to the European Wind Energy association. [23]

This wind turbine is connected to the grid through cables that run on the ocean floor and are linked to an onshore sub-station. If the distances are much greater than 6 kilometres, the plan is to build mid-ocean substations. [22]

To control the draft and stability it uses its cylinders which inside are seawater tanks playing the internal water level as ballast. This kind of solution to get stability has the disadvantage of requiring expensive mechanism and telecontrol elements which increase the construction and maintenance cost. In figure 22 the floating platform is seen with its damping plates and complex structure. [73]

The main advantages are that its static and dynamic stability provides sufficiently low pitch performance to use conventional commercial offshore wind turbines; its low draft design allows an on-shore controlled assembly environment avoiding expensive marine task and use of specialised vessels. [16]

The main problem is the cost, around 20 million euros for the prototype makes it uncompetitive against traditional energy sources.

The VolturnUS prototype

On 31th May 2013, the VolturnUS project, backed the DeepCWind Consortium with the University of Maine's Advanced Structures and Composites Center and other 30 partners from government, academia, and industry, launched a 1:8 prototype on the Main(e) coast [25]. It is a 21 meters high semi-submersible platform with concrete hulls to get floatability and lightweight composite materials [24], see figure 23. It supports a 20 kW turbine. It was the latest FOWT prototype launched until the data when this thesis was submitted [74]

Figure 21: "VolturnUS on its launching day" [25]

3.2.4. Barge

A barge is a floating structure which maintains its stability thanks to its wide floating platform. Its draft is extremely low. Due to that, the stability is highly dependent of the water plane restoring moment; this makes it very sensitive to the natural wave frequencies. Its position is maintained by mooring lines or chains anchored to the sea bottom.

Japanese barge

At the end of 2011 the Kyushu University, Japan, launched the Wind Lens project first scale model.[26] The barge had a diameter of 18 meters and supported two 3kW turbines. It was installed 600 meters away from coast. In figure 24 the barge is seen floating in 5 meters depth waters. [16] The next step will be testing a 60 meters diameter one with a TLP mooring system, 2 km off the coast. The project was financed by Japan's Ministry of the Environment. [26]

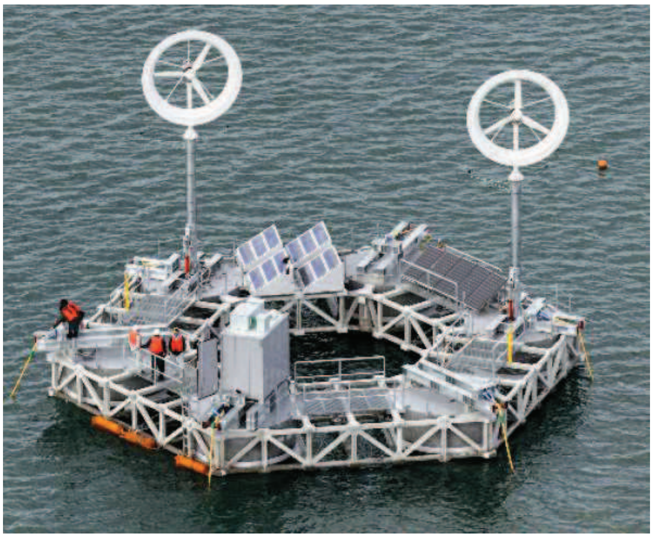


Figure 22: "Japanese barge being tested" [16]

Poseidon

In Europe, another kind of Barge has been developed. This project, called Poseidon is in a test phase [27]looking to collect data for the first commercial design, it is a complete floating wind power plant which transforms wave energy into electricity and serves as a floating platform for offshore wind turbines, in figure 25 Poseidon prototype in operative conditions is shown.[26] A 37 meters wide, 25 meters long, 6 meters high (without Wind Towers) which weighs 320 tons off-shore demonstration plant was launched in the summer of 2008 until 2010 in Vindeby off-shore wind turbine park, off the coast of Lolland in Denmark's waters. [16]

Figure 23: "Poseidon full-scale demostrator" [27]

3.2.5. Station keeping system

Station keeping system fix the floating platform to the sea bottom and is vital for keep structure displacements between controlled limits, especially when it is installed with other ones in windfarms.

Mooring systems can be defined as passive or active.

Passive positioning
It is the most common systems because of their relative low cost and maintenance requirements, these characteristics are consistent with floating wind turbines requirements and for this reason will be the ones used in this case study. [72]

Steel catenaries mooring
It is the most common mooring system in offshore industry. Structures are connected to sea bottom through steel catenaries which are lifted from the sea bed when are tensioned and lay over seabed when loosens figure 24. With this displacement they are able to generate forces big enough to reduce motions of the floating structure. [57]

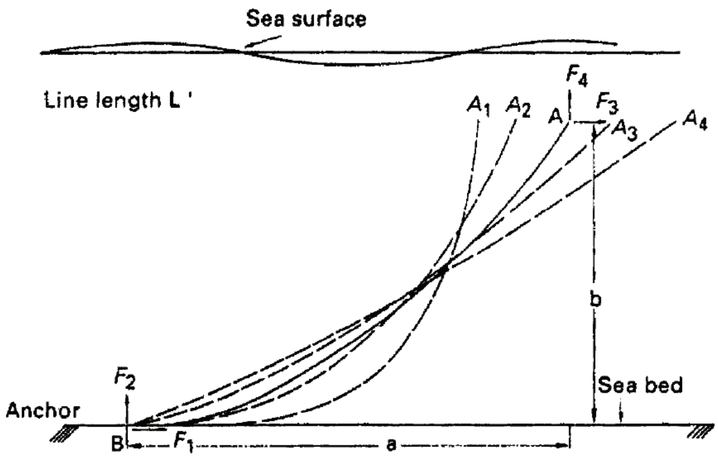


Figure 24: "Requirements for offshore concretes" [34]

Usually mooring lines are spliced in 3 zones [72]:
-Upper one connects mooring line with structure and it has to support erosion due waves impact and corrosion due wet&dry cycles. For this reason chains are used in this zone see figure 25 a) and b)

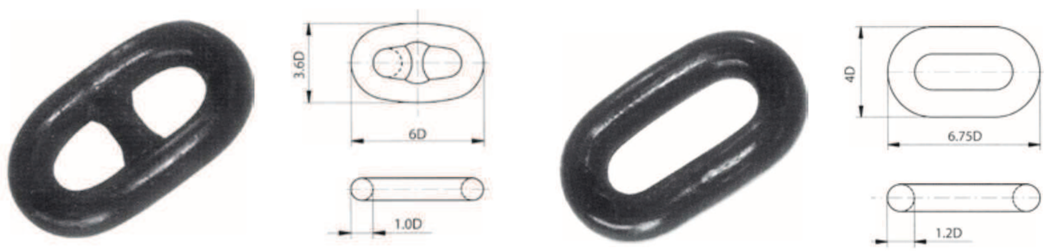


Figure 25: a) Common Link [46] **b) Studless chain** [46]

In order to reduce catenaries weight for mooring purposes studless chain is used also improves the fatigue life.

-Middle one supports tensions cycles but thanks to its position corrosion problems are not as important as on upper zone and neither the erosion ones because it has no contact with other bodies.

The element used on this zone is the steel cable figure 26, sheltered by a polyurethane coating, using zinc filler wires to act as cathodes or using galvanized wires. Also fibres cables can be used

Figure 26: „Mooring steel cable“ [46]

-Lower one connect mooring line with anchor and it has to manage a high erosion due friction with sea bottom.

Catenary mooring can be used individualy or in groups:

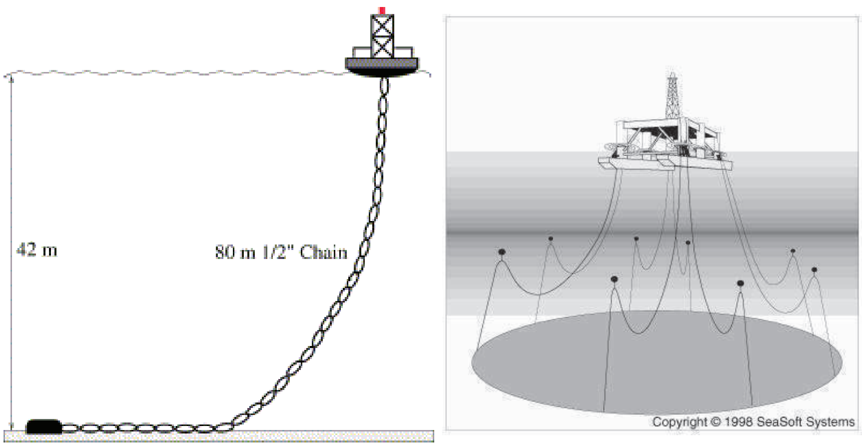


Figure 27: a)"Catenary mooring" [52], **b)Multi-catenary mooring"** [52]

-Catenary mooring: Mooring lines from floating structure to seabed develop a geometry see figure 27 a), that allows to have only horizontal forces on the anchor point. Also, the friction between seabed and mooring helps to stability purposes.[57]

-Multi-catenary mooring: Mooring have buoys and weights in some specifics points along their length, see figure 27 b), to reduce or increase mooring weight wherever it is needed. [57]

Synthetic taut mooring

This system, figure 28, is used in deep water locations thanks to their lighter weight. As they are constantly in tension there is no friction with sea bottom decreasing the foot print.
Problems are their low testing on real site information and bigger structural complexity forcing to use high safety factors, increasing section and therefore weight. [57]

Figure 28: "Synthetic taut mooring" [57]

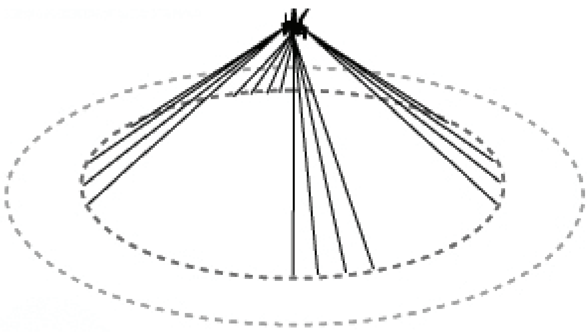


Figure 29: "Taut spread mooring" [52]

-Taut spread mooring: Mooring lines make an angle with the seabed bottom see figure 29, being able to resist vertical and horizontal tensions. Restoring forces come from the mooring cables elasticity.

Dynamic positioning
-Active mooring: It is controlled by a servo-contro ller. By using software the tension on lines is adjusted to get a correct position.
-Propulsion: Structure position is adjusted using s oftware controlled thrusters that relocate the structure.
However, these technologies are expensive and requi re many maintenance labours which make them inadequate for floating wind turbin es.

Anchors types
Depending of soil capacity and efforts from mooring lines different sea bed fixation elements can be used.

There are three basic groups:

-Embebed figure 30 a) anchors penetrate deeply in s oil having a good response to horizontal tensions.
-Suction anchors, figure 30 b) are installed extrac ting the water inside of them therefore thanks to hydrostatic pressure and friction between their walls with soil they get good response against vertical tensions.

Figure 30: a) Embebed Anchor [52] **b) Suction anchor** [52]

-Self-suction anchors figure 44, get fixation to sea bottom through their own massive weight.

3.3. Concrete use in marine structures

Despite the fact that steel is the most used material in marine structures; concrete has also been used in the marine environment for a very long time from bridges, docks and lighthouses to barges and ships in war time when the steel was scarce. In the last decades oil and gas industry has contributed hugely to concrete marine research and technology development constructing huge structures from hundreds of tonnes to thousands and higher than two hundred meters or in deeps greater than one hundred meters [34]

3.3.1 Bottom fixed

Concrete offshore structures started to be built for O&G industry during the 70s of the last century in the North Sea. [29]. The first concrete platform design was developed in1973 by the French-Canadian group C G DORIS, called Ekofisk Tank was placed in the Norwegian North Sea waters at 71 meters of water depth. Its design consists in a large volume caisson based on the sea floor merging into a monolithic structure which is offering the base for the deck. This multi-layer walled column is surrounded by an outer breaker wall perforated to break up waves in order to reduce the forces over the column. Figure 27 a) shows Ekofisk Tank being constructed.
Since then other designs have been developed as the Coondeep (concrete deep water structure). These kind of platforms rest on the sea floor thanks to a large base which is used to storage oil. From the base a variable number of columns rise even more than 100 meters being the support of the platform deck. Two platforms of this type have the world record of being the tallest and largest structures ever moved, Troll A with a total height of 472 meters and Gullfaks C with 836.000 tons respectively [34]

Figure 31 b) shows Troll A platform being towed out to its installation point. The extremly high columns can be seen. They are submerged after transporting phase. In figure 31 c) Gullfacks platform during construction.

Figure 31: a)"Ekofisk Tank" [28]**; b)"Troll A"; c) "Gullfaks C"** [28]

This technology has experimented in Norway the biggest use and development with several platforms and typologies becoming an important national industry and from where the reference construction and design guides comes. Figure 32 shows a complete catalog of the platforms constructed by Det Norske Veritas.

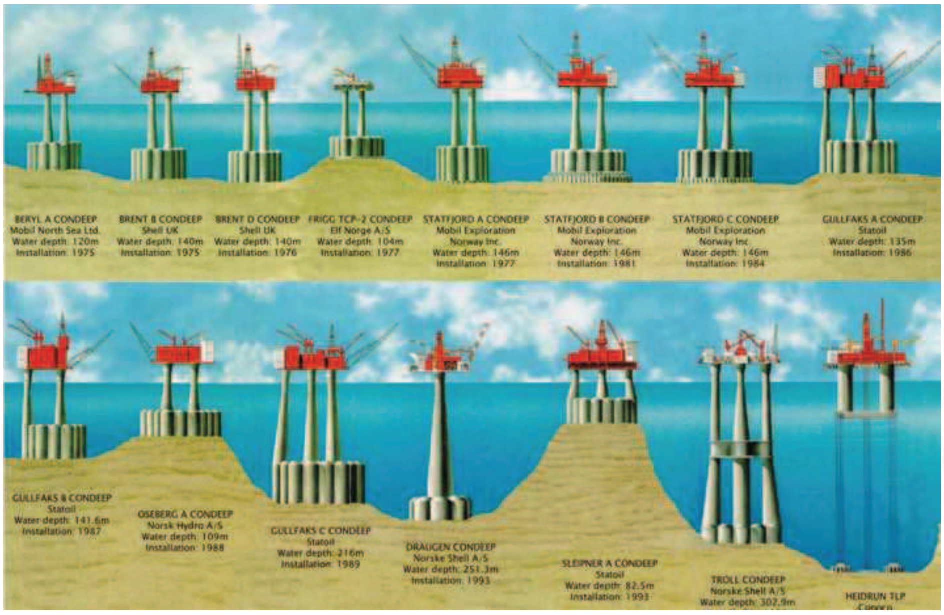


Figure 32: "Concrete Offshore Platform built by DNV" [29]

3.3.2 Floating

In 1848 Lambot used reinforced concrete to build the boat shown in figure 33 a). During I World War, 14 concrete ships were built due to the steel shortage; the largest one was the U.S.S Selma with 130 meters long. That technology was also tested in Norway with the Namsenfjor, the first sailing boat in 1917 [34] [30], see figure 33 b)

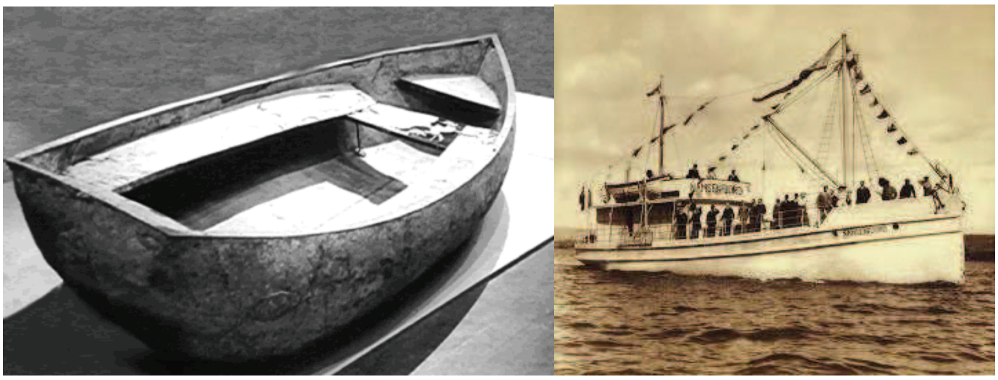


Figure 33: a)" Lambot boat"; b)"Namsenfjor vessel" [30]

This kind of boats was used as a response to the steel scarcity due the World Wars. During the II WW some of them reached 140.250 Tons of cargo capacity. But it wasn't until the 60's decade that the concrete boats appear as a real alternative thanks to the 19 boats constructed by Alfred Yee for Lusteveco in Philippines see Figure 34 b). They were made with pre tensioned reinforcement, see Figure 34 a) and they had a great acceptance and competitiveness basically due their low maintenance cost. [30]

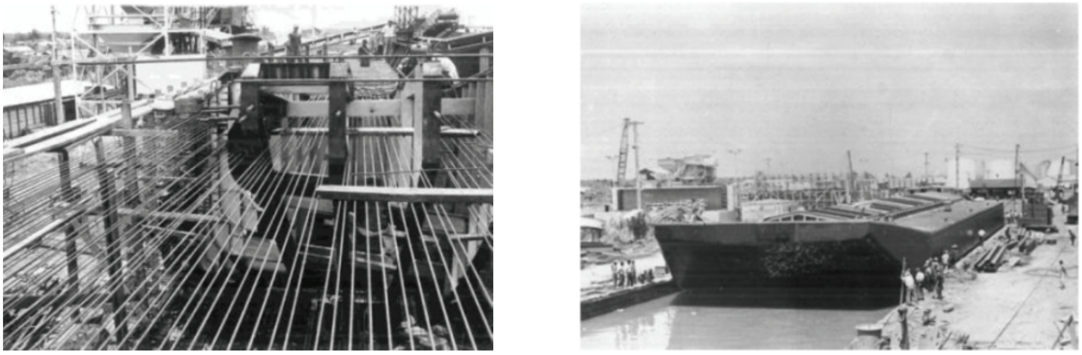


Figure 34: a) "Prestressed steel armor in Yee's Barge "; b) "Alfred Yee's Barge" [30]

The largest pre-stressed concrete barge actually in operation is the N'Kossa. A barge built in Marseille, France for Elf Congo in 1995, see Figure 35 a) and b). With dimensions of 220x46x16 meters was towed 8.334 kilometers to the west coast of Congo where it is permanently anchored in 170 water depth since 1996. Its function is to be the Nkossa field's production and control vessel containing all the equipment needed to treat the oil and gas, see figure 31 c). The total displacement fully loaded is 107.000 tons and a concrete volume of 27.000 m^3. Its advantage is being rust-free and has the possibility to be re-utilized at some future date. [31]

Figure 35:a) & b) "N'Kossa being assembled" [31] c)" N'kossa with the superstructure" [30]

Concrete Semi-Submersibles

Figure 36: "Troll B semi-submersible platform" [28]

Troll B platform shown in figure 36, is suited in 335 meters depth waters in North Sea since 1995 and operated by StatoilHydro is the world's first concrete catenary anchored floater. The platform has a semi-submersible hull with 46.000 m^3 of volume and supports a topside weight of 32.500 tons and has a displacement of 190.000 tons. It was designed for a 70 year life. [34]

Concrete Tension Leg Platform (TLP)

Figure 37: " Heidrum TLP" [30]

The Heidrun TLP is the world's first TLP with a concrete hull and the largest permanently floating concrete structure ever, see figure 37 with a concrete volume of 67.000 m^3. It was installed in June 1995 at the Heidrun field of the North Sea at 345 m water depth. The platform consists of a square pontoon with box cross section. The length of the pontoons is 110 m and the height 13 m. The circular columns, 4 one in each corner, gives the construction a total height of 109 m. It has a displacement of 285.000 tons. The specifications required concrete with density less than 2000 kg/m^3 for slip formed parts and 1950 kg/m^3 for conventionally cast parts of the structure. It was designed for a 50 years life. [32].

Other Floating Concrete Structures

The enlargement and modernization of Port Condamine, see figure 38 b) in the Principality of Monaco required an innovative solution due the prevailing geographical conditions. An essential part of these works consists of an enormous pre-stressed and reinforced concrete floating breakwater which is 352 m long by 28 m wide and 19 m high which forms the main section of the new sea walls. The breakwater is connected to an abutment caisson pier by means of a 2,60 m diameter ball and socket joint and is secured at the other end by eight large chains attached to sunken steel piles set at depths of between 50 and 80 m. The breakwater was built in Spain in a purpose-built dry dock of 420x80x20 m and the front wall was excavated and dredged to allow the launching of the breakwater on the flooding of the dry dock and the floating of the dike. Then it was towed by sea to Monaco. [33] see figure 31 a)

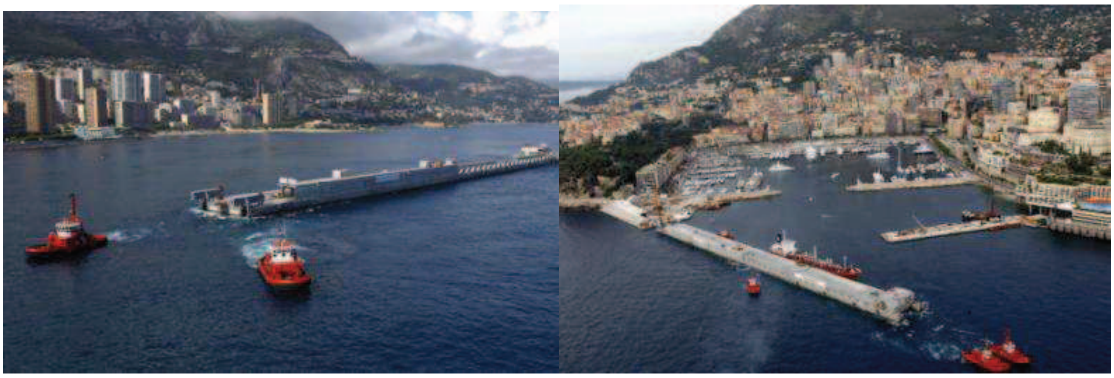


Figure 38: a) & b) "Floating concrete breakwater being installed in Port Condamine, Monaco" [33]

3.3.3 Concrete properties for marine environments

Several hundreds of concrete barges and boats since the beginning of the XX century and more than 50 concrete offshore platforms that are or have been operating in water deeper than 15 meters around the world (50% of them in water deeper than 100 meters)[34] give an important amount of data available from maintenance and repair reports. Based on such data, the durability of offshore concrete structures has been studied by a working group appointed by FIP. [35]
It is necessary to say that most of the platforms analysed in those reports were built more than two decades ago, which means concrete mixtures and techniques out-dated. Since then almost everything related to concrete has been improved, being possible to produce concrete mixtures with compressive resistance with more than 100MPa and with permeability below than 10^{-13}m/s. [36] Even so, with those out-dated techniques, [35] It can be assumed that in some of the studied concrete platforms the lifetime may be greater than 60 years [35] [35] [37]

The main advantages and disadvantages are:

Advantages

- Lower maintenance cost:
  -From floating concrete docks in the 1970's show maintenance requirements more than a 90% minor than for similar all steel docks. [34]
  -From Sare and Yee report, repair and maintenance costs for the 19 pre-stressed concrete barges constructed in the Philippines during 60's for Lusteveco an average value of 1/3 of the annual maintenance cost from compared to steel barges is find. [30]
  -In 1973 one of the Lusteveco's barges hit a mine, the cost of this 10 days repairing job was only of 4.381 US$. [34]
  -From North Sea concrete structures no significant sign of material deterioration, corrosion of reinforcement or other material-related deficiencies have been observed. [45]
- Lower fabrication costs:

-The fabrication costs of Yee's barges were a saving of 16% compared to that of steel. [34],

- Downtime of the structure:
  -In Yee's barges, between 1974 and 1975, the total downtime per floating barge and year for maintenance work was only six days for the concrete structures. Similar steel barges had an average of 24 days. [34],
- Major resistance to accidents:
  -In North Sea platforms the only damages in concrete are coming from falling objects or ramming ships. Also, from two hydrocarbon fires inside one of the platforms were studied and the only damages find were a surface scaling smaller than 20 mm deep over a height of 5-10 meters. [30]
  -Two concrete barges survived the Bikini Atoll nuclear bomb tests in good shape when their cargo of fuel oil was set alight moored only 100 yards from the test centre. [34]
  -During II World War a 1000 tonne German concrete barge hit a mine, which exploded under the stern, and the damage was repaired while afloat with underwater concreting. [34]
  -Lusteveco's barges serviced the Vietnam War along they were rocketed or damaged by plastic bombs; these damages were mostly confined to a limited small area on the hull's surface. [30]
  This shows the extensive heat capacity and low thermal conductivity that allows him to support fire without major consequences, in fact, in those two accidents no repair was necessary. In offshore oil or gas platforms or storage structures this has an unquestionable importance.
- Longer life of the structure:
  -There is no significant additional cost related to extension of design life. This is because the reinforced and pre-stressed concrete is much less sensitive to fatigue than steel. Concrete platforms in North Sea designed for 20 years operation have now passed the end of their design life without problems. In 1999 a large Norwegian research program investigated the durability of concreted structures included six offshore concrete structures as Gullfaks C or Troll B. Calculation based on the chloride profile showed that all platforms were in excellent condition and that there would be no risk for corrosion within their expected lifetime. Two of them wouldn't theoretically reach risky chloride concentrations at the reinforcement bars until more than 200 years of service. [34]
- ARCO barge, a pre-stressed one, after twenty years of continuous service various test were carried and an indefinite lifespan was given due its excellent performance of concrete in a marine environment as well as its good fatigue resistance. [45]
- Better motion characteristics:
  -Due to the generally larger mass and draught concrete structures have larger stiffness, the result is less flexibility and less deformation applied onto outfitting steel. This makes them suited for very harsh environmental conditions wind tower floating platforms because it provides a stable foundation.
  However, from the Schiehallion FPSO the mooring size and cost was reported to be 10% more expensive than for a steel hull.[30]

As summary the main advantages are:

- High stiffness: Due to larger mass and drafts have a more stable behaviour which is highly recommendable to facilitate wind operation conditions.
- Good resistance to environmental loading: Usually FOWTS are installed in seas with strong winds and high waves; concrete has a good resistance and low sensibility to these aggressive factors.
- Robust with respect to accidental loading such as ship impact, dropped objects or sabotage.
- Excellent fatigue resistance: Due to inconstant and cyclic variations in wind and wave forces fatigue is one of the most long terms hazard factors. The excellent response to fatigue of concrete gives structural security and low maintenance and control costs.
- Good durability and inexpensive maintenance: If the construction was correctly done, the durability of those structures can reach more than 60 years, giving the possibility of reuse for bigger wind turbines or to other locations movements.
- No high specialised workforce requirements for the construction work, giving a high flexibility and construction sites options, helping to a local execution letting to local communities work and involucrate in the project.

To get a real profitability of these aspects some parameters and tips have to be taken into account:

- Simple designs help to a faster and more cost effective construction because it allows using and reusing materials and construction installations also to manufacture it at large scale easily, and being more competitive in structures with soft shapes and large dimensions [44].
- A deep study of the equipment needs to be done before the structure construction because a post-constructed modification can affect the maintenance costs and structural long terms resistance to marine environment.
- Due to the huge volumes of material needed, the local availability of labour and material around the construction site has to be check.
- Due to the graving dock cost, a high number of units should be built to get a good profitability. The graving dock should be planned as a construction site for multiple windmills, for this reason collaboration between companies have to be realised to use if possible a unique platform design or, if not enough dock flexibility to be able to build different designs.

Disadvantages

- Stresses in concrete may present a wide range of variation depending on the design and use of the structure, so very accurate designs should be required.
- High cost of the dry-dock construction. Despite of that, if construction at large scale is considered, this cost is reduced until to be a marginal cost for each structure, depending on the number of structures built in.
- It is necessary to use high density concrete to guarantee the minimum possible permeability in order to avoid the sea water penetration inside the concrete.

As summary the main disadvantages are:

- Sensitivity to stresses: concrete resistance to tensions is nearly zero. To solve it, active and passive steel armour should be added.

- Due to a higher mass, depending on the geometry, deeper waters are needed.
- To avoid corrosion's hazards on the steel armours, the quality of concrete and the construction procedure should be carefully supervised during the construction phase.

Concrete armours

In naval construction and offshore industry the pre-stressed and the reinforced concrete are used.
The reinforced concrete has inside a steel structure; see figure 39 a) and b) to be able to support compression (concrete) and tension (steel) efforts. Reinforced concrete has less maintenance requirements than steel if it is correctly executed. However, if it is charged with tension, in the long time will appear breaks which could let the sea water go inside the concrete reaching and rusting the steel armor. It is important to consider that steel strength per unit volume is much higher than concrete, implying massive concrete structures if compared with the steel ones.
The reinforced concrete is optimal for cylindrical constructions submitted to compression. A good application find is for submarines, nowadays there are few concrete submarines being used.
Pre –stressed concrete or post-stressed concrete have also an especial steel armor in tendons submitted to traction which compresses the concrete, allowing it to have a higher tolerance to traction loads. The major point respect the reinforced concrete is that a post-tessed structure supports better the tensions caused by forces or moments. Higher installation costs are partially compensated by the reduced amount of materials used. Because of these induced compressions over concrete, it is necessary an accurate distribution of these tendons in order to avoid an excess of compression on concrete which could reach its limit.
The pre tensioned or post tensioned concrete is suitable for offshore concrete structures because thanks to these induced compressions; micro fissures due tensions efforts on concrete are avoided or minimized.

Figure 39: a)" Installation of the armor in Nkossa Barge"; b) "Nkossa Barge' armour" [31]

Concrete response to marine environment

Different domains can be specified when talking about marine concrete corrosion: Submerged and in tidal range or in splash zone [38], [39], [40], see figures 40 and 41 a) b)

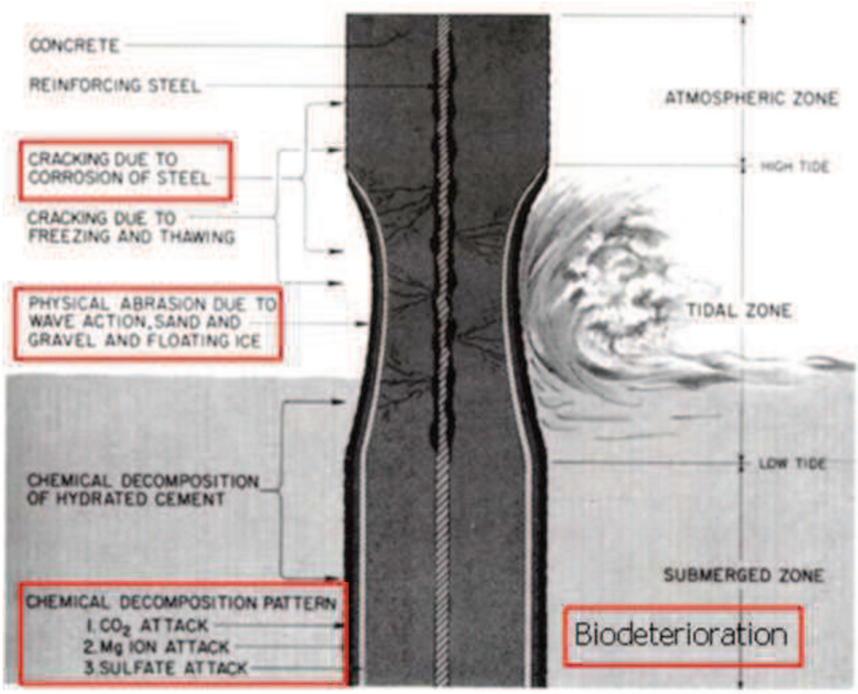


Figure 40: " Typical degradation mechanisms in coastal concrete piling" [39]

- Submerged zone: All time underwater, in this condition concrete is always saturated by sea water, on the contrary one could think that it is the less aggressive situation because although the chlorides penetration is quick, the corrosion is slow due to the lack of oxygen access to the armors thanks to the saturation of concrete pores by water. It has been contrasted that higher values of chlorides concentrations than admissible in Recommendations (0,4% in cement weight) have not made armor corrosion.
  In this zone water penetration appears through capillarity suction and it is accelerated thanks to the hydraulic pressure. This water has Chlorides and sulfites dissolved in it.

- Tidal Range zone: This zone goes from the low tide to high tide levels where the concrete is permanently wet. As it is always wet the porous are constantly saturated and the oxygen cannot reach the armor. The erosion here appears as fissures by wave impacts during the low tides or by floating elements impacts.

- Splash zone: It is over the high tide level, this zone receive splash and surf from marine water and has drying and wetting cycles which are highly aggressive for the concrete durability. During the wet period the chloride ion by diffusion penetrate trough pours into the concrete matrix and during the drying phase the water evaporates but the chlorides remain. After several cycles the concentration of chlorides is very high and due to the free access of the oxygen, the corrosion can become besides chlorides also from carbonation.

- Atmospheric zone: Concrete here has no contact with marine water, however, the marine breeze and fog transport salts several kilometers inland. In this zone, concrete's most usual problem come from chlorides corrosion. Corrosion produces fissures, cracks and detachment of the coating. Also, the armor affected loses steel area, decreasing the load that is capable of withstanding.

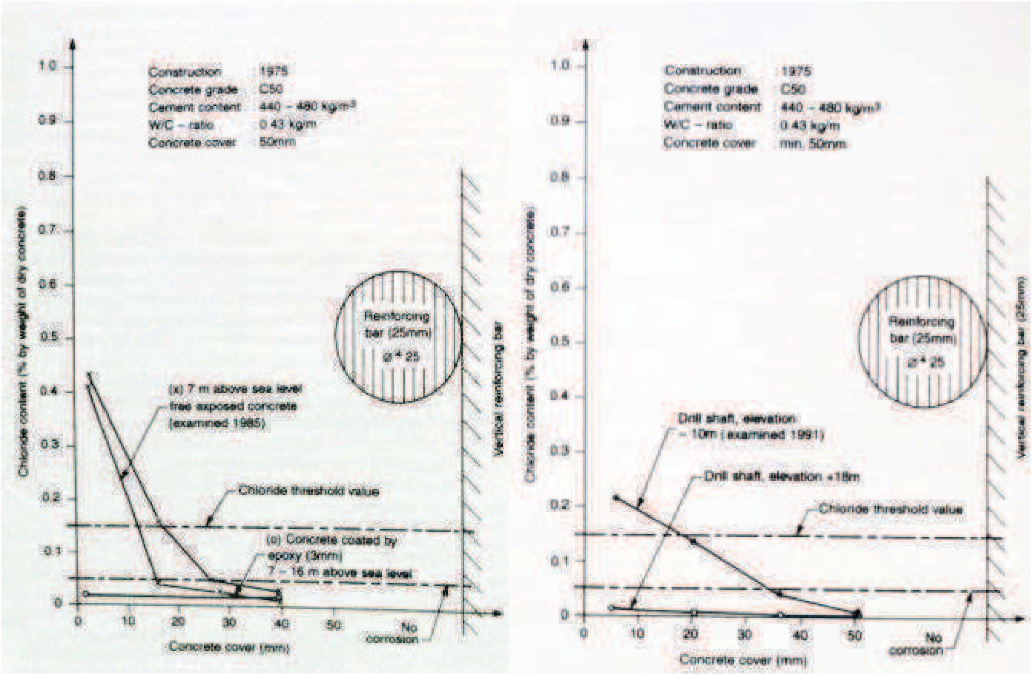


Figure 41: a) & b) "Chloride penetration on offshore platform concrete cores" [34]

In that case, the concrete for the most unfavorable situation should be chosen.
As a conclusion, it can be said that the most important factors to get impermeability are the ratio (in mass) water/concrete. By adding a significant amount of blast furnace slag a very impermeable concrete can be obtained by using less severe dosage.

Also, it is necessary to think about the erosion suffered because of the waves: Square corners are susceptible to further deterioration due water erosion and ropes due construction and movements stages, see figure 42 a) and b). In order to avoid that problem it is recommended to build structures with simple shapes and round and smooth surfaces. It should be avoided especially in the tidal range. In case of necessity large chamfers can be used instead of corners. [41]
Due to erosion, see Figure 42 c) and d), concrete needs additional requisites in aggregates quality and cement quantity. These recommendations and more can be consulted in many international marine constructions recommendations from U.S. Army Coastal Engineering Research Center as example.

Figure 42: a) & b) " Breaks"; c) & d) "Erosion in sea structures" [41]

Structural Concrete requirements

Structural design for concrete members is typically based in assuring that the maximum compressive stresses do not exceed the concrete compressive strength, while tensile stresses are resisted by steel reinforcement bars or pre-stressed tendons.[38] The sections and its reinforcement are designed to present ductile failure when subjected to normal stresses (axial plus bending forces). [38] After that, it is possible to verify the capacity of the section subjected to the shear forces and torque.

The durability design implies to control the maximum crack width in order to prevent future corrosion problems and other concrete deteriorating processes related to the penetration of water and salts inside the concrete. Depending on the environmental exposure, consistent covers have to be defined to ensure an adequate durability. [38] [43]
In case of offshore structures, it is usually required to avoid cracks, which means to not have tensile stresses or, at least, to not exceed the tensile concrete strength [42] [34]
Fatigue verification in concrete structures is uncommon because most structures are subjected to short ranges of stress variation or to a reduced number of cycles, but in the case of offshore floating elements this phenomenon has to be taken into account.
An affordable approach to the verification of fatigue is to select a low stress level in service conditions [44] [34]
In order to prevent the reinforcement corrosion, the prior measure is to get low concrete permeability, using silica aggregate. The second one is to avoid the steel corrosion implementing cathodic protection or even using epoxy coated reinforcement bars [45] (see Figure 43) on the splash zone, which is the most affected zone by this phenomenon [45], [36] It is also possible to use stainless steel reinforcement bars, but they have to be limited to specific zones because its high price in comparison with conventional reinforcement. Epoxy coating is also available for post-tensioned tendons.

Figure 43: a)"Epoxy coated boned post-tensioned tendon"; b)"Epoxy coated steel reinforcement bar"[45]

Also, concrete mixtures to use on those environments are different than mixtures used for other conventional purposes in order to assure impermeability and corrosion resistance.

Some of these differences are concrete cover about 100mm, addition of silica fume or slag, etc [34]. On **¡Error! No se encuentra el origen de la referencia.** there is an example of high performance marine concrete mixtures. As cited before, an important effort on execution control must be done to guarantee the designed properties in the final structure.

Table 5: “Requirements for offshore concretes” [34]

Requirements	Exposure Zones	Codes				
		ACI 357	CSA S474	FIP	DNV	BS6235
Maximum water/cement ratio	Submerged	0,45	0,45	0,45	0,45	0,4
	Splash	0,4	0,4	0,45	0,45	0,4
	Atmospheric	0,4	0,4	0,45	0,45	0,4
Minimum cement content, kg/m^3	Submerged	356	360	320-360[24]	300	320-360[2]
	Splash	356	400	400	400	400
	Atmospheric	356	400	320-360[2]	300	400
Maximum cement content, kg/m^3	Submerged	415	300	500	-	-
	Splash	415	300	500	-	-
	Atmospheric	415	300	500	-	-
Minimum 28-day cylinder compressive strength, MPa	Submerged	35	30	32	-	32
	Splash	35[5]	40	32[4]	-	32[4]
	Atmospheric	35	40	32	-	32

Due to the limited, null in practice, tensile strength of concrete, besides passive steel reinforcement it is necessary to achieve a whole compressive state to prevent tensile stresses due to bending moments and the appearance of associated cracks. This state is achieved by using post-tensioned steel tendons, which can be bonded or unbounded. Unbounded tendons can also be installed outside the concrete mixture. [43]

From the fatigue point of view, it is necessary to point out that in the offshore concrete platforms analysed after 20 years in service, no signs of deterioration caused by concrete fatigue effects have been detected. [35] Nevertheless, concrete fatigue is an important phenomenon to be considered during design to prevent possible failures.

The fatigue behaviour of concrete is very different from the steel one because fatigue also affects concrete subjected to compression stresses and not only in tension stresses as in the case of steel. [45] Unfortunately, the fatigue behaviour of concrete is less well known than in steel. Post-tensioning can help offshore structures to prevent the effects of concrete fatigue [36] However, in the case of offshore floating platforms, with a broad variation of stresses, this phenomenon must be considered carefully.

[4] 320 kg/m3 for a maximum aggregate size of 40 mm; 360 kg/m3 for a maximum aggregate size of 20 mm. Cylinder strength is assumed to be 80% of specified cube strength.

[5] If subject to abrasion, 40 MPa

3.4 Typology analysis and selection

Floating platforms can be classified by system they get the static stability [37]:

- Buoyancy: They get the stability with a distributed displaced volume along the water plane area, see figure 44. In order to achieve this, platforms with a unique (barge), three or four floating (semi-submersibles) bodies have been suggested.

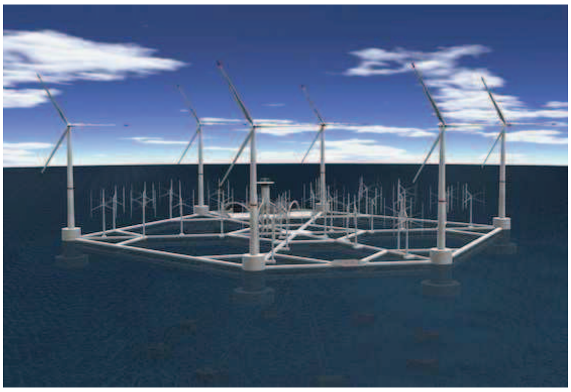


Figure 44: "Hexicon Barge" [47]

Figure 45: "Hywind Statoil" [20]

- Ballast: They get the stability thanks to a huge ballast weight which lows the overall platform center of mass under the buoyancy point, auto stabilising any tilting through a positive restoring moment and a high inertia against pitch and roll tilting. A long shape with a small diameter in the water plane area helps to minimize the radiation and diffraction effects. One example is the Hywind prototype from Statoil Hydro, see figure 45, already tested.

- TLP: They get the stability using an excess of floatability to get a tensioned mooring lines. An already tested prototype is Blue H prototype see figure 46:

Figure 46: "Blue H" [19]

Each of these solutions have their own advantages and disadvantages, see table 6 and for that reason there are hybrid designs which try to get the better combination of these characteristics.

The absence of a unique answer explains the wide amount of different designs in different phases of development.

Table 6: "Floating wind platform typologies" [70]

Typology	Advantages	Disadvantages
TLP	Stable and able for shallows waters	High tension forces High dependence from mooring tendons
SPAR	Simple shape Auto stabilized	Bigger draft and material needed.
Semi-submersible	Stable and able for shallows waters	Tension forces Complex shape
Barge	Simple shape Able for shallow waters	Highly sensitive to waves

After description of the different floating platform types it can be said that TLP type is not suitable for this case study because its high tension forces generated by mooring tendons would imply a high amount of postessation. Semi-submersible ones requires complex geometries unable be built economically with concrete, the inclusion of steel components would increase the maintenance labours reducing one of the major advantages of concrete on marine environments which is the low maintenance requirements.
Barges are highly sensitive to waves requiring extremely big dimensions to get stability making them economically unaffordable.
Spar design due to its simple shape and absence of external stabilizing component make it suitable for concrete designs however requires big drafts excluding their use on shallow waters.

Therefore a mixed solution is selected. Platform type of study will be a low draft ballasted which is autostabilized and with a simplex geometry as a spar type but with a big floater diameter compensating the reduced draft.

CHAPTER 4: BASIC CONCEPTS FOR FLOATING PLATFORMS

4.1. Introduction

In this chapter the theoretical tools used to develop the study of a floating platform are held. In the first paragraph concepts related with static stability like buoyancy, metacentric height, eigenperiod and hydrostatic stiffness are explained.
In the second paragraph concepts used for a dynamic analysis like diffraction, added mass and response amplitude operator are explained.

4.2. Environmental conditions

In order to know and computing the different environmental elements that may affect the structure a basic description of is done in the next paragraphs

4.2.1. Wave theory

Oceans waves in a real sea state are generally random. To solve that problem and make the mathematical resolution easier, some physical assumptions are made:
-Marine water is considered as an ideal fluid which means that it is inviscid and incompressible
-It has no rotational motion
-Wave flow is bi-dimensional
-Sea bottom is considered as horizontal

<u>A wave can be parameterized with the following parameters</u>

Period (T): Time needed between two crests from consecutive waves to cross a stationary point.

Height (H): Distance in y axis between the crest and the following through. [72]

Water depth (d): Vertical distance between the mean SwL and the sea bottom.

From them other parameters can be computed:

Wavelength (L): Distance between two consecutive wave crests.

Wave celerity (c): Represents propagation velocity of the wave crest.

Frequency (f): Reciprocal of the period.

Wave elevation (η): Instantaneous elevation of the wave from the SwL

Horizontal water particle velocity (u): Instantaneous velocity in y axis

Vertical water particle velocity (v): Instantaneous velocity in x axis

Horizontal water particle acceleration $(\dot{u})$*:* Instantaneous acceleration along x of a particle.

Vertical water particle acceleration $(\dot{v})$*:* Instantaneous acceleration along y of a particle.

Table 32 shows types of oceanic waves with typical periods "*T*" and wave lengths "L"

Table 7: "Types of oceanic waves" [1]

Name	Typical Periods	Wave lengths	Forcing mechanism
Ripples	<0.2 sec	10^{-2} m	wind on sea surface
Sea	0.2 - 9 sec	130 m	wind on sea surface
Swell	9 - 30 sec	100s of meters	wind on sea surface
Tsunamis	15 minutes - 1 hour	few 100s of km	seismic
Tides	several hours	several 100s - few 1000s km	gravitational (mainly sun and moon)

There are several wave theories useful for offshore structures design

Linear Wave Theory

It is the simplest theory also called Airy theory. In the Airy's theory non-linear terms are discarded and the two free surface conditions are written at the still water level.

These assumptions are acceptable if deep waters are deeper than half of the wave length, $d > \frac{L}{\lambda}$, and wave amplitude is low in comparison with wave length, H<<<L

Wave describes a sine curve, figure 47 and (1) form being able to describe its free surface as:

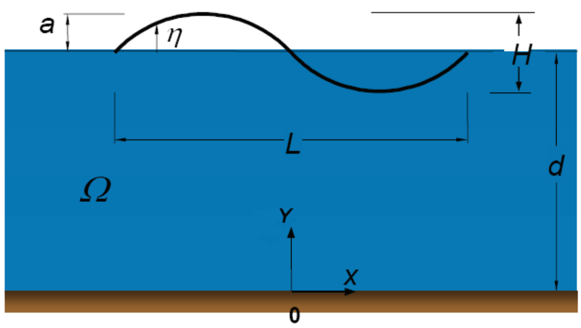


Figure 47: "Parameters of linear wave theory" [51]

$$\eta = a\sin(kx - \omega t) \tag{1}$$

"a" is the amplitude of the wave which is th.e distance along "*y*" between the wave crest and the mean water level, "ω" the frequency of oscillation (3) of the wave and "k "the wave number (2). With them wave celerity can be obtained (4):

$$k = \frac{2\pi}{L} \quad (2) \qquad \omega = \frac{2\pi}{T} \quad (3) \qquad c = \frac{L}{T} = \frac{\omega}{k} \quad (4)$$

This theory assumes particles are stationary describing a periodic motion over closed elliptic orbits, figure 48 whose amplitude decreases exponentially with water depth being at the bottom a purely oscillatory meeting boundary condition on sea bottom.

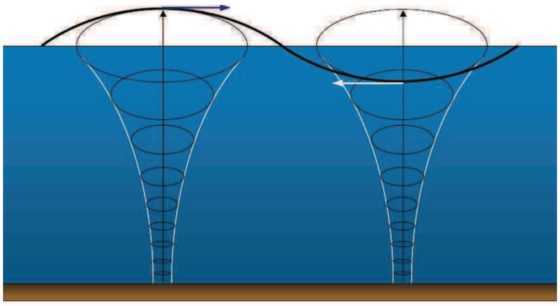


Figure 48: "Particles movement" [51]

This theory is valid for deep waters and small waves height.

Second and fifth order stokes wave theory

Stokes theories are non-lineal, they develop velocity potential and the free surface is developed in power series. Generally second and fifth order contribution in deep waters in quite small because waves can be described using linear theory.
Their usefulness is when increases in wave steepness for storms or shallow waters wave computing are needed.

The number of terms retained in the power series, figure 49, determines the order of the Stokes' theory.

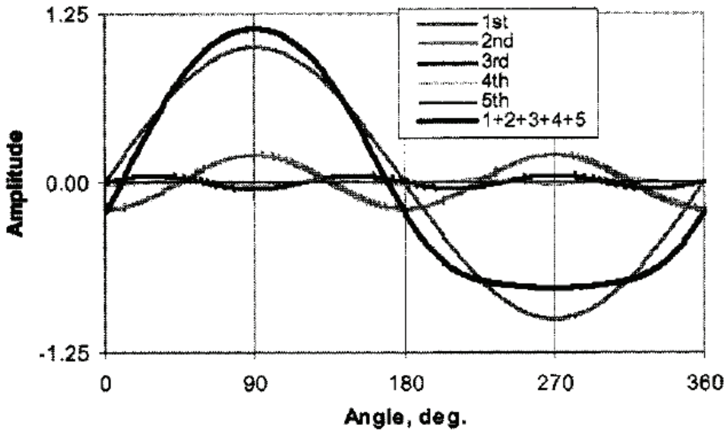


Figure 49: „Stokes' waves power series" [72]

Second order one provides two components for the wave kinematics, the first one at the wave frequency and the second one at twice the wave frequency.

Fifth order is used for deep water high waves; each of the five components of the series is one order of magnitude smaller than the previous one in succession.

Stream Function Theory

This is another non-linear theory with two types of stream function theory.
The regular stream function theory is based on (5) a prescribed wave period, wave height and water depth. It includes currents veloci ty adding it to wave celerity terminus.

$$\Psi(x,y) = (c-U)y + \sum_{n=1}^{N} X(n)\sinh(nky)\ \cos(nkx) \quad (5)$$

In order to choose the appropriate order of the str eam function theory in a particular application there is, figure 50, a *H, d* and *T* dependent abacus:

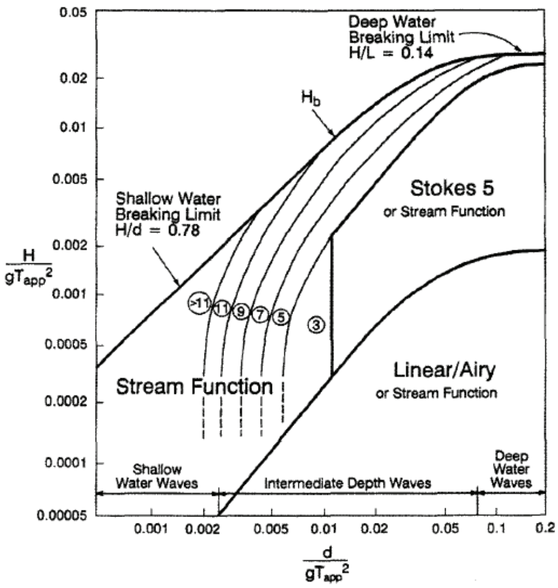


Figure 50: „Abacus showing suitable theories depending of (H,d and T) [51]

The irregular stream function theory is useful when the wave profile is known. Instead of use the wave period, it gets data from profile and creates cycles from it. If the wave is irregular a steep wave cycle within the random wave representing an extreme wave is chosen for the subsequent design analysis of a stru cture.

This theory allows to computing even breaking waves getting acceptable results.

Finally the following figure is a scheme for the wave theory selection where two dimensionless parameters representing water depth and wave steepness are related:

From [72] this table shows the appropriate theory to use in specific cases.

Table 8: "Theory and cases"

Theory	Case
Linear	Low seastates (1 yr strom) Fatigue analysis Swell Large inertia dominated fixed and floating structures Linear radiation damping Long term statistics
Stokes' second order	Slow drift oscillation of soft moored structures TLP tendon analysis
Stokes' fifth order or	Storm waves

stream function	Drag dominated structures Wave tank data (irregular stream function) Air gap Moorings and risers Non-linear damping near natural period

Braking waves

Breaking waves occur when in shallow waters wave crest gets too much steepness and collapse dispersing energy. This effect will be neglected because despite platform is considered in shallow waters, the wave height is significantly less than the breaking limit.

Wave group

Ocean random waves of different periods create wave groups, figure 51. These wave groups have their own height, period and length.

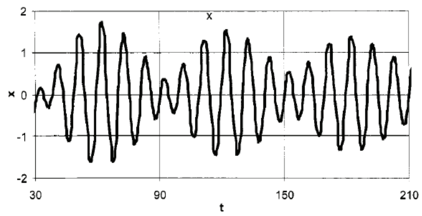


Figure 51: „Wave grop" [72]

Wave groups can induce structural problems over floating structures as resonance or metal fatigue.

Wave spectrum

Here wave spectrum method is explained which is one of the methods to describe Sea state.

Wave force is closely related to the wave elevation ζ because the higher the wave is, the bigger the amount of water mass is and therefore, the force exerted over the structure.

Due to the wide range of wave's frequencies that can affect the structure, a wave's spectral density description is used in order to get enough accurate description of the wave energy distribution in the frequency domain, figure 53

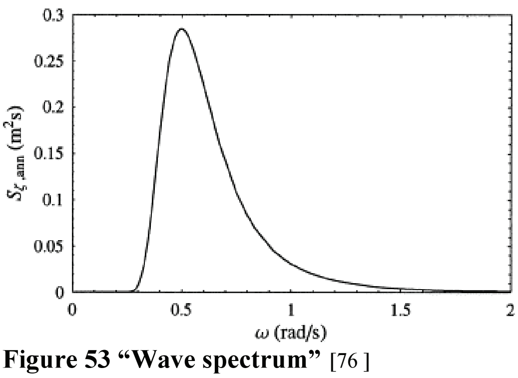


Figure 53 "Wave spectrum" [76]

In order to get an overview of the spectral method in wave forces calculation, a little explanation is given as follows:

$S_{\eta\eta}(\omega)$ is the *Spectrum of the surface elevation* (6.1), an stochastic description of waves. It represents the distribution of η 's variance in the frequency domain:

$$\sigma_\eta^2 = \int_0^\infty S_{\eta\eta}(\omega)d\omega \tag{6.1}$$

As frequency is related to wave's velocity, with $S_{\eta\eta}(\omega)$ a wave elevation and velocity relation is stablished (6.2) describing the mechanical energy of the wave E (7.1), which is a combination of kinetic K (7.2) and potential energy V (7.3)

$$\sigma_\eta^2 = \frac{E}{\rho g} \tag{6.1}$$

$$E = K + V \tag{7.1}$$

$$K = \frac{1}{L}\int_0^L\int_0^{d+\eta}\frac{1}{2}\rho u^2 dxdz \tag{7.2}$$

$$V = \frac{1}{L}\int_0^L\int_0^{\eta}\frac{1}{2}\rho gzdxdz \tag{7.3}$$

If linear wave's theory is used, both terms (7.4) and (7.5) are simplified as follows

$$K = \frac{1}{16}\rho gH^2 \tag{7.4}$$

$$V = \frac{1}{16}\rho gH^2 \tag{7.5}$$

Which means that the kinetic energy is equal to potential energy (7.6) getting

$$E = \frac{1}{8}\rho gH^2 \tag{7.6}$$

Table 9: "Wave height though Spectral Method and Linear Theory"

Wave Height	Spectral Method	Linear Theory
$H_{mean} = H_{1/2}$	$2{,}5\sigma_\eta$	$2{,}5\sqrt{\frac{E}{\rho g}}$
$H_{significant} = H_{1/3}$	$4\sigma_\eta$	$4\sqrt{\frac{E}{\rho g}}$

Also, significant wave heights, table 46, can be obtained from both systems

Knowing the incident wave potential, there are several numerical procedures that can be used to describe the potential function generated in the vicinity of the structure.

4.2.2. Wind

Wind condition is typically represented by a mean wind speed and a standard wind speed deviation. The turbulence intensity, which measures the variation of wind speed relative to the mean wind speed, is defined as the ratio of the wind standard deviation to the mean wind speed V_{hub} with a 10-minute averaging duration. It is employed to define the design load conditions.

The turbulence of wind within 10 minutes is generally considered stationary and can be modelled by a power spectral density function and a coherence function. The purpose of turbulence model is to include the effects of varying wind speed, shears and directions and to allow rotational sampling through varying shears.

The three vector components of turbulent wind velocity are:
-Longitudinal: Along the direction of the mean wind speed.
-Lateral: Horizontal and normal to the longitudinal direction
-Upward: Normal to both the longitudinal and lateral directions and pointing upward.

Wind profile: The mean wind speed profile (vertical wind shear) is to be defined by the power law expressed on (8)

$$V(z) = V_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha} \tag{8}$$

With:
-V(z) as wind profile of the 10-minute mean wind speed as a function of height, z, above the Still Water Level (SWL), in m/s
-V_{hub} as the 10-minute mean wind speed at turbine hub height, in m/s
-α as power law exponent.
-z as the height above the SWL in m
-z_{hub} as the height above the SWL in m

For storm wind conditions, such as a hurricane wind with a return period bigger than 10 years, the mean wind speed profile may be represented by the following logarithmic wind shear (9) using the 1 hour mean wind speed at 10 m

$$V(z,t) = V(z,t_0)\left[1 - 0{,}41 I_u(z)\ln\left(t/t_0\right)\right] \quad for\ t < t_o \tag{9}$$

With:
-V(z,t) as the mean wind speed at height z and corresponding to an averaging time - period t, in m/s
-z as height above the SWL in m
-t as averaging time period shorter than t_0=3600 seconds

$V(z,t_0)$ as 1-hour mean wind speed at height z in m/s calculated with (10)

$$V(z,t_0) = V_0\left[1 + C\ln\left(\frac{z}{10\Phi}\right)\right] \tag{10}$$

Being:
t_0 = reference averaging time period 3600 seconds
and C expressed as (11)

$$C = 0{,}0573\sqrt{1 + \frac{0{,}15V_0}{\Phi}} \tag{11}$$

V_0= 1-hour mean wind speed at 10 m above the SWL in m/s
$I_u(z)$= turbulence intensity, which represents the standard deviation to the mean wind speed at height z. This term is dimensionless and is calculated thought (12) formula:

$$I_u(z) = 0{,}06\left[1 + 0{,}043\frac{V_0}{\Phi}\right]\left(\frac{z}{10\Phi}\right)^{-0{,}22} \tag{12}$$

With Φ as a dimensionless unit conversion factor which is 1 when using meters and meters per second units.

Wind data were obtained from 10 meters over the Sea water level observatory, it is necessary to convert these wind profiles to the application point of the wind turbine studied in this study. The application point will be at 90,55 meters over the Sea water level because that is where the rotor axis is. A 0,9 conversion factor is used to obtain the 10-minute wind speed from the 1-hour average wind speed.

Data conversion is realized with (13) formula:

$$V(z) = V(z_{ref})\frac{\ln\left(z/z_0\right)}{\ln\left(z_{ref}/z_0\right)} \tag{13}$$

With:
V (z) = wind speed at elevation z
V (z_{ref}) = wind speed at elevation z_{ref}
z_{ref} =elevation for which speed is given
z_o =roughness length. For offshore locations this value is 0,002 meters.

4.2.3 Currents

Data from currents have to include information on current speed, direction and variation with depth.
There are three types of currents origin:
The wind generated currents which are assumed to be aligned with the wind direction.
Tide, density, circulation, and river-outflow generated sub-surface current.
Near shore, breaking wave induced surface currents running parallel to the coast.

This last type of current won't be studied here because the location is far away from coast.
Here, currents are considered to consist of sub surface currents, mainly driven by tide and wind generated near surface currents.
The near surface current is described by a linear distribution of velocity, reducing from the surface velocity to zero at a depth of 20 meters below SWL see (14)

$$U_w(z) = U_w(0)(1+\frac{z}{20}) \tag{14}$$

The wind generated sea surface current velocity may be assumed to be aligned with the wind direction, and may be estimated from (15)

$$U_w(0) = 0{,}01V_{1-hour}(z=10m) \tag{15}$$

Where $V_{1-hour}(z=10$ meters) is defined as the 1-hour mean value of wind speed at 10 meters above SWL.

And the subsurface current is given by (16), a power law description over the water depth d

$$U_{SS}(z) = U_{SS}(0)\left[\frac{(z+d)}{d}\right]^{1/7} \tag{16}$$

Following [54] it may be acceptable to assume that the sub-surface currents are aligned with the wave direction.

Both currents are given as a function of the height z above the sea surface and d is the water depth.

4.2.4 Location of study

The location of the floating wind turbine is in the East Anglia sector from the Round 3 offshore windmills program of United Kingdom. Wind data comes from a location in the Dutch North Sea, see figure 53.

Figure 53: "Installation area and K13 data buoy"

Despite the lack of available data from those locations due to the cost necessary to recollect them, data from

Koninklijk Nederlands Meteorologisch Instituut, the Royal Dutch Meteorological Institut are available through an UpWind Project [55] On it, data from the K13 buoy is processed. Also data has been obtained from [71]

4.2.5. Loads

Loads can be summarized [58], [72] as:

- Environmental Loads
  -Wind
  -Wave
  -Currents
  -Tides, storm surges and water levels
  -Marine growth
  -Sea ice and ice accumulation

- Permanent Loads

Those loads do not change during the mode of operation under consideration.
  -Weight of Upper Mass which includes: Blades, Hub and Nacelle housing structures and their inner equipment in case.
  -Weight of permanent ballast
  -External hydrostatic pressure
  -Pretension in mooring lines

- Variable Loads

Those loads are associated with the normal operation of any wind turbine.
  -Actuation loads generated by wind turbine during operation.
  -Deformation loads due to post-stress.

On environmental loads, directionality needs to be used. Loads are to be applied producing the most unfavourable global or local effects on the structure or the station keeping system. [72]

Load cases [58] are studied by:

- *Design Load Cases* (DLCs) which are defined as the combination of turbine operational conditions, site-specific environmental conditions and other design conditions.
  "All load cases with a reasonable probability of occurrence and covering the most significant conditions that the floating wind platform may experience" [44]
  There are a minimum of 25 DLCs adapted to a floating wind platform [34]

Survival Load Cases (SLCs) which are defined to verify the survivability of the station keeping system and the adequacy of air gap when the floating wind platform is under environmental conditions more severe than the extreme design environmental conditions.

These load cases depends also from the type of sea state to study. There are three main types of sea state:

Normal Sea State (NSS)

This sea state is represented by a significant wave height "$H_{S,NSS}$" a peak spectral period, and a wave direction. It is to be determined based on the site-specific and long-term joint probability distribution of sea state parameters. The NSS is used to define a number of Design Load Cases (DLCs) requiring either strength analysis or fatigue analysis.
For strength analyses, the Normal Sea State can be characterized by the expected value of significant wave height conditioned upon a given value of V_{hub}. A range of peak period, T_p associated with each significant wave height is to be determined for load calculation. Finally, the resultant highest loads are to be used in the design of the Floating Support Structure

Extreme Sea State (ESS)

The purpose of the extreme Sea state is to represent a 1-year return or 50-year return wave condition.
The significant wave height of this model is denoted as $H_{s,1\text{-}yr}$ or $H_{s,50\text{-}yr}$ for the extreme significant wave height with a return period of 1 year or 50 years, respectively. Their values are determined from on-site measurements or from another place adapted to this site data. The peak spectral periods appropriate to site-specific $H_{s,1\text{-}yr}$ and $H_{s,50\text{-}yr}$ respectively are to be determined for load calculations. ESS will not be studied here.
In this study ESS will not be used. SurSS will be used with a return period of 50 years.

Survival Sea State (SurSS)

The survival sea state condition is similar to the Extreme Sea State but with a return period longer than 50 years

4.3. Static Analysis concepts

For the static analysis a series of different macros have been written in Visual Basic and ran in Microsoft Excel. For these macros, structure geometry and materials densities were provided, obtaining volumes, masses, center of masses, drafts or ballast mass necessary for stability, stiffness and eigeneperiod. All the output data were automatically compiled and plotted in graphics for an easier comprehension of results. Volumes, centers of masses and inertias have been contrasted using AutoCAD.

4.3.1 Buoyancy

It is necessary to know if the platform is able to float and, if it does, where the floating level is or in other words, which is the platform draft.
Arquimedes' principle is used for buoyancy. It says that any object immersed totally or partially in a fluid is buoyed up by a force equal to the weight of the fluid displaced by the object, see figure 54.

Archimedes Law and buoyancy takes the form
$F_\nabla = \rho g \nabla$ where F_∇ is the buoyant force, ρ is the water density with a value of 1.025 kg/m3, g is the gravity acceleration with a value of 9,81 m/s2
And ∇ is the volume of the submerged part of the object.
From this, only a static equilibrium can be studied as a distributed mass force analogous to the gravity force on the mass of the platform.
Ballast plays an effective adjustment role over the buoyancy and stability. First I check the necessary displaced volume to let the platform float.

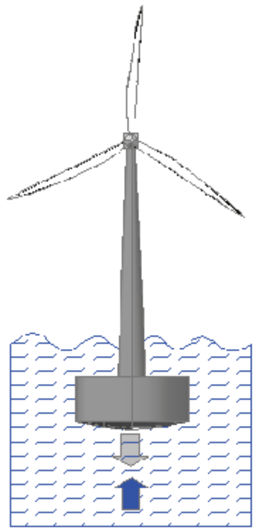


Figure 54: "Buoyancy "

Necessary volume to be displaced will be the result of divide the mass of the structure and mooring lines by the water density (17), obtaining the minimum water displacement need.

$$V_{\min} = \frac{(M_{Struc} + M_{Mooring})}{\rho_W} \tag{17}$$

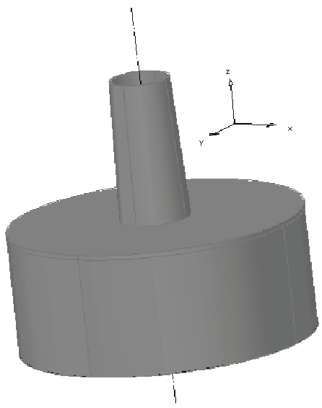


Figure 55: "Z Simetry axis"

After obtaining the minimum volume is necessary to check if the structure is able to displace at least a volume equal to V_{min}

If the previous step is successful, the ballast mass necessary is checked to get the desired draft, as platform is symmetric in the z axis figure 55, it easy to get that volume (18) considering that the platform is stable in the z axis which needs to be checked in the next step.

$$V_{Draft} = \int_{z=0}^{z=Draft} V dz \tag{18}$$

And then by adding ballast the desired draft is adjusted (19).

$$M_B = V_{Draft}\rho_W - M_{Plat.Conc.} - M_T - M_{Up.M} - M_{Mooring} \tag{19}$$

4.3.2 Metacentric height

After checking the vertical equilibrium that it will float with the desired draft through the study of buoyancy, it is necessary to check its static stability against a force or disturbing moment known as rotational equilibrium. This equilibrium will be reached when the sum of the moments about the center of mass equals zero. The structure will suffer translation and/or rotation about its center of gravity due these loads.

The metacentric height is the distance between the center of buoyancy, which means the center of masses of the displaced water, and the total structure center of masses which includes the concrete platform and tower, the ballast and the upper mass, figure 56. This parameter gives an estimation of the initial static stability of a floating body. If the metacentric height is big, there will be a good initial stability against overturning.

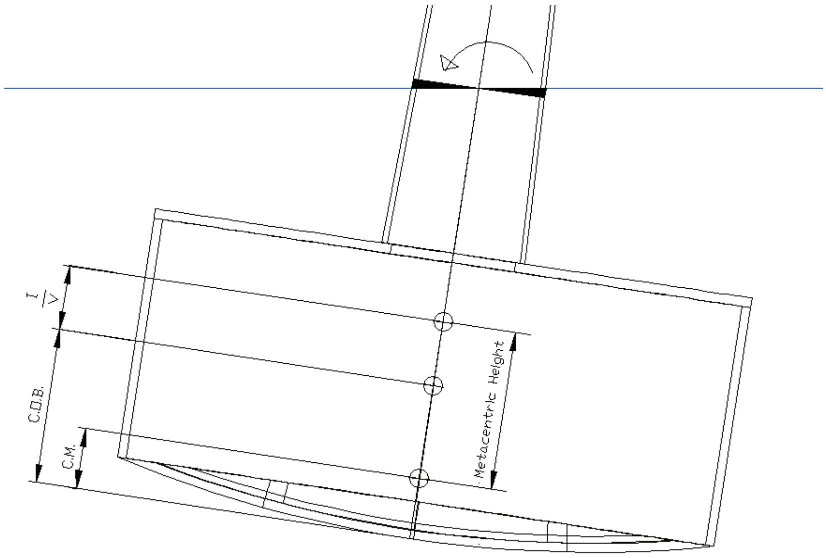


Figure 56: "Relevant parameters for Metacentric Height"

$C.M._{Struc}$, and $C.O.B.$ (21) are referenced to the bottom of the structure. The resulting metacentric height (20) is the distance between the C.M. and C.O.B (19) plus the I_{xx} (22) divided this last terminus by the displaced volume which is equal to the submerged volume (23)

$$h_{metacentric} = C.O.B. - C.M._{Struc.} + \frac{I_{xx}}{V_{Sub}} \tag{20}$$

With:

$$C.O.B. = \left(\frac{C.M._{D.Ext} V_{D.Ext} + C.M._{C.Ext} V_{C.Ext} + C.M._{L.Ext} V_{L.Ext} + C.M._{F.Ext} V_{F.Ext}}{V_{D.Ext} + V_{C.Ext} + V_{L.Ext} + V_{F.Ext}} \right) \tag{21}$$

$$I_{xx} = I_{yy} = \frac{1}{4} \pi r_1^2 \tag{22}$$

$$V_{Sub} = V_{D.Ext} + V_{C.Ext} + V_{L.Ext} + V_{F.Ext} \tag{23}$$

To get a stable structure, the metacentric height must be >0 which means that any movement will be stabilised by the structure mass.

4.3.3 Hydrostatic stiffness

In the Hydrostatic problem, platform stability is studied. Due to that, this platform is a Spar type; its mayor parameters to reach it are the platform Inertia, including the ballast mass; and its buoyancy.

The stability requirements to correct operative conditions of the wind turbine are focused on the platform heave, roll and pitch which, as previously explained, are the vertical displacement and the tilting in the X and Y axis respectively.

To get these parameters, ANSYS Aqwa software has been used. This software allows detailed studies of the Hydrodynamic effects over floating structures.

In order to get an overview of the problem's calculation, the Hydrostatic restoring matrix is showed in table 44. It is also important to see that in this platform, the body-fixed *yz-plane* of the submerged portion of the support platform is also a plane of symmetry, so the (3, 5) and (5, 3) components of the matrix are zero, getting a matrix which shows us that only roll, pitch and heave motions are restored by hydrostatic, letting the other modes of motion restored by the mooring system.

Table 10: "Restoring motions"

	X	Y	Z	RX	RY	RZ
X	-	-	-	-	-	-
Y	-	-	-	-	-	-
Z	-	-	Heave C_{33}	-	-	-
RX	-	-	-	Roll C_{44}	-	-
RY	-	-	-	-	Pitch C_{55}	-
RZ	-	-	-	-	-	-

It can be seen in table 10 that only three restoring elements act. Calculation of each of them is shown in figure 57.

$$C_{ij}^{Hydrostatics} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_0 & 0 & 0 & 0 \\ 0 & 0 & & \rho g \iint_{A_0} y^2 dA + \rho g V_0 z_{COB} & 0 & 0 \\ 0 & 0 & & 0 & \rho g \iint_{A_0} x^2 dA + \rho g V_0 z_{COB} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Figure 57: "Hydrostatic matrix" [65]

The term $\rho g V_o \delta_{13}$ represents the Archimedes' principle of the buoyancy force. This principle says that any submerged body suffers a force in the opposite direction equal to the amount of liquid displaced.

The symbol ρ is the water density, here considered as the medium water density in the North Sea 1025 kg/m^3, g which is the gravitational acceleration, constant 9,81 m/s^2. V_0 is the displaced volume of fluid when the support platform is in its stable position.

The term A_o is the water plane area occupied by the platform in its in displaced position.

The term z_{COB} represents the platform vertical location of the *COB*. It affects the hydrostatic load because of the vector position of the *COB* changes due to platform displacements.

Also, it is important because the cross product of the buoyancy force with the *COB*'s vector position produces a hydrostatic moment about the platform reference point; this moment is known as "*Restoring Moment*".

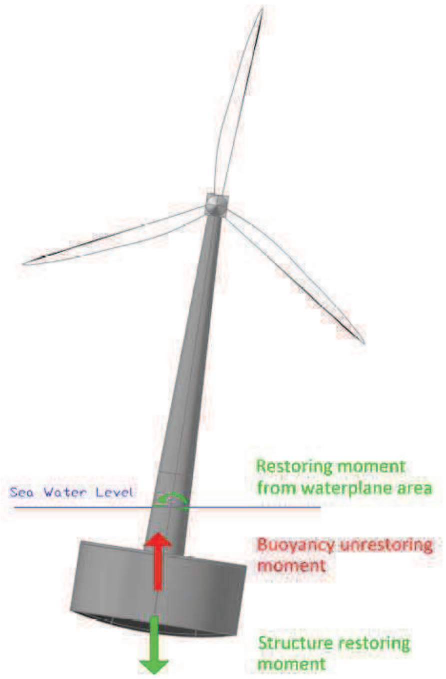


Figure 58: "Relevant moments in hydrostatic stiffness"

This platform as a low draft ballasted type, reaches auto stability in pitch and roll thanks to the use of its shape and ballast weight, different restoring and disturbing moments can be find figure 58, in the analysis.
All these moments are referred to the *SwL* and are:

Restoring moments

There are two restoring moments one from the structure mass (24) and one from the water plane area.

Structure mass ($Moment_{Rest.Struc}$):
It is the most important restoring moment; it is got by the huge structure and ballast weight and also from the upper mass.

$$Moment_{Rest.Struc.} = M_{Struc.} g\left(Draft_{Plat} - C.M._{Struc.}\right) \quad (24)$$

Being "$Draft_{Plat}$" the platform draft

Water plane area:
It depends of the platform geometry in the interface between water and air. It is produced due to the different submerged volumes between both sides of the platform. Its effect is much bigger in other floating structures as boats; the most sensible offshore wind platform types are the semi-submersibles and barges. Here as the diameter of the structure in the SwL is small, its restoring moment can be neglected.

Unrestoring moment

Buoyancy unrestoring moment ($Moment_{Unrest.Buoyancy}$): It is done by the displaced fluid pressure trying to recover its position (25)

$$Moment_{Unrest.Buoyancy} = V_{Draft} \rho_W g\left(Draft_{Plat.} - C.B._{Struc.}\right) \quad (25)$$

With all these moments, the C_{55} term (26) can be obtained. This term is the hydrostatic stiffness of platform in its pitch angle.

$$C_{55} = Moment_{Rest.Struc.} + Moment_{Unrest.Buoyancy} \quad (26)$$

C_{55} should be bigger than 0 if stability is desired. And the bigger this parameter is, the more stable the platform is. That means that it is less sensible to the induced movements which is usually good but if the values are extremely high it can be harmful because the platform loses flexibility to the natural movement of the sea and the waves' diffraction. By symmetry, C_{44} term which represents the hydrostatic stiffness of platform for tilting in roll has the same value.

4.3.4 Maximum Static Pitch

In order to assure minimum operational conditions, it is necessary to check the platform tilt that wind can create. For that, "F_{Thrust}" has to be referenced to the "$C.M._{Struc}$" in order to obtain the maximum wind moment that the platform is able to manage for a specified inclination, see figure 59.

As the upper mass, and therefore the rotor has its center of mass at 115,65 meters over the "$C.M._{Struc.}$" equation (27) gives the moment. Deformation is neglected because of material employed, postesed concrete and high height which makes the possible deformation non relevant.[62]

$$Moment_{Thrust} = F_{Thrust}\ d \tag{27}$$

Tilting of the platform due this moment (28) is obtained by dividing "$Moment_{Thrust}$" by C_{44}:

$$\alpha_{Pitch} = \frac{Moment_{Thrust}}{C_{55}} \tag{28}$$

For operative reasons the maximum defined angle is 0,0785 radians which is equal to 4,5º [67]

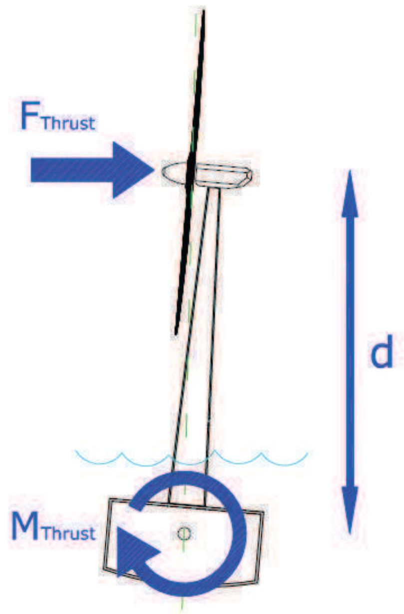


Figure 59: "M_{Thrust}"

4.3.5 Eigenperiod

The importance of this value comes from the waves influence. If the structure has a similar Eigen period than waves it will oscillate which would cause operative, and structural problems. [62]
To solve that problem, the structure should be above the most frequent waves periods, table 7, which are usually between 0,2 to 9 seconds for *Sea* state and from 9 to 30 seconds for *Swell* state, see table 7.

For that reason, platform designs with Eigen periods under 30 seconds should be avoided.

Eigenperiod formula depends of hydrostatic stiffness and structure inertia (29)

$$T_{Eigen,xx} = \frac{2\pi}{\sqrt{\frac{k_{xx}}{m_{xx}}}} \tag{29}$$

Being k_{xx} the stiffness of the structure and m_{xx} the virtual mass in the degree of freedom studied.
The only important components for this level of design are heave, pitch and roll. Due to structure symmetry pitch and roll have the same excitation period.
Therefore for heave Eigenperiod formula (30) results in:

$$T_{Eigen,33} = \frac{2\pi}{\sqrt{\frac{C_{33}}{m_{33}}}} \tag{30}$$

With $C_{33} = A_0\rho 1m$ and $m_{33} = (M_{Struc.} + M_{Ad.Mass})$

And for pitch and roll Eigenperiods formula (31) is:

$$T_{Eigen,33} = \frac{2\pi}{\sqrt{\frac{C_{55}}{I_{Struc}}}} \tag{31}$$

With $C_{55} = \rho g \iint_{A_0} x^2 dA + \rho g V_0 z_{COB}$ and $m_{55} = I_{Struc.}$

As can be seen, Eigenperiod depends of the platform stiffness and inertia. For big stiffness values T_{Eigen} is smaller being possible to fall under the wave periods. On the other hand, low stiffness implies large inclinations, so a compromise solution between them should be assumed.

4.4. Dynamic Analysis concepts

Relevant aspect related with wave-structure interaction are here shown.

4.4.1. Morison Equation

This equation is useful on small structures for compute wave forces when $\frac{D}{\lambda} < 0{,}2$ being D the platform diameter on SwL and λ the wave length.[62]
Despite this asumption may not be enough accurate for the cylinder, it has been selected due its simplicity and availability in software

Morison (31) includes inertia, C_m, and C_d drag coefficients obtained through emphirical experiments. For this study experimental obtention of these data was not able therefore drag coefficients were used from [67].

$$dF(x,z,t) = C_m \frac{\rho \pi D^2}{4} \dot{u} + C_d \frac{\rho D}{2} u|u| \tag{31}$$

Where the first term represents water on wave inertia and the second one the drag force on platform.

C_m: Inertia coefficient due hydrodynamic mass
C_d : Drag coefficient

Other parameters are:

u : relative water velocity (m/s)
$\dot{u}$: water acceleration over structure (m/s^2)
D : Diameter of submerged body in z position. (m)
ρ : Water density (1024 kg/m^3)

4.4.2. Radiation Damping

Floating wind turbines displacements are not totally synchronized with the waves. That mismatch creates waves radiation originated by the structure. [64] This phenomenon is called Radiation damping.

4.4.3. Response amplitude Operators (RAOs)

They describe the sensitivity of a structure to wave excitation. They are transfer functions of the system with a harmonic free-surface elevation as input.
Using them floating structure behaviour and its sensitivity to excitation by some determined wave frequencies which could create huge displacements or accelerations in a determined motion's axis is obtained. For each degree of freedom there is a different frequency or frequencies of resonance. [64]
There are different methods to determine those frequencies such as small-scale experimentation or simulations through specialized software.
The determination of those values consists in exciting the structure with a unique frequency waves series and seeing the scope of the displacement obtained. By repeating this process with a wide range of frequencies an approximate analysis of the structure motions behaviour can be obtained. It may occur that contributions as from viscosity are not accurately taken into consideration or even neglected, depending on the process used.

Response amplitude operators allow improving the platform response and structural resistance to those frequencies.[64]

4.4.4. Added Mass

Structure gets floatability as was seen in 4.4.1 by buoyancy. This implies that a considerable volume of fluid, in this case water, has been displaced from its original position. The implicit consequences of this are that for each accelerations or decelerations in any of the degrees of freedom, a certain amount of water has to be displaced to allow the floating body allocates in the new position. That means that not only structure is moving, but also a determined amount of water mass.

For calculations, the simplification consists in considering a certain amount of fluid moving at the same time with the structure motions (32):

$$F = \left(M_{Struc.} + M_{Ad.M}\right)\ddot{u} \tag{32}$$

Being ü the acceleration of the structure in the direction of study.
This mass combination, applied for the 6 existent degrees of freedom, defines the so-known as mass matrix of the dynamic system, also known as virtual mass.
This added mass due to its influence over the structure motions will be taken into consideration for calculations affected by inertia as in the study of Eigenperiods

Fluid affected by platform varies depending on structure accelerations, and due to that structure accelerations depend on the wave frequency, added mass requires frequency domain study.

Wave excitation in heave direction depends strongly on the structure area at sea water level. Reducing at water sea level excitation period increases being more difficult to reach by waves periods.

External structures can be added to reduce heave damping; Windfloat prototype has damping plates in the low part of its floatability hulls to reduce it.

Wave excitation in pitch/roll can be solved increasing restoring moment.

CHAPTER 5: PLATFORM DEFINITION

5.1. Introduction

A description of platform properties is done for each body that shapes the structure.

5.2. Assumptions

<u>*Platform Draft*</u>
This is one of the most critical parameters of the structure because it affects strongly on the market's perspectives of use.

With the objective of creating a cheaper alternative for waters deeper than 50 meters possibilities for floating platforms with drafts in a range of 40-65 meters are investigated. To facilitate the design election, 6 draft options: 40, 45, 50, 55, 60, 65 meters of draft are studied. Also between the platform's bottom and the seabed it is necessary a distance large enough to avoid impacts due to the vertical platform's displacements (Heave) and the change on the sea water level caused by tides or meteorological phenomena.

<u>*Dome height*</u>
Dome's functions are:
-Resist hydrostatic pressure acting on the underside of the platform. For this purpose the best design would be a hemispherical surface that would optimize the natural concrete's resistance to compression.

-Reducing the damping-effect: Hydrodynamicly a flat surface provides more resistance to water than a curved one. Therefore in order to increase damping, see chapter 5, a flat surface should be chosen.

-Contain ballast on its inner face: The purpose of the ballast is to lower the platform's center of masses, therefore has to be achieved to store ballast as low as possible. While it may seem that a large curvature favours this effect, the reality is that it is counterproductive as a large curvature implies a greater height of the dome and therefore less mass concentrated at the lowest part. For this reason a flat surface is adequate.

For all those reasons I choose to use a slight curvature, which will be related with the radio in a ratio defined in (33):

$$h_D = \frac{R_C}{8} \tag{33}$$

<u>*Cylinder Heigh*</u>
This height plays a major role assuring enough buoyancy and stability on platform. Dome, Lid and Submerged tower heights are fixed due to operational requirements.

Hence, the cylinder height is the only height variable. A big cylinder height increases platform draft, reducing the potential markets for its installation but improving floatability and stability.

Platform concrete thickness

To perform the preliminary design it is necessary to specify a particular concrete thickness of platform's elements. Given that loads acting over the platform are important, the thickness is fixed at 0,8 meters for the dome, cylinder and lid. Later, in the structural design phase this thickness will be optimized to the efforts that each section has to support.

Height of submerged tower

To avoid the structure's excitation due to waves it is necessary to have the least possible water plane area to reach a relation between the diameter of the cylinder and the wave length small enough to not modify the wave, minimizing the radiation effect. Generally this effect is reached for $\frac{D}{\lambda} < 0{,}2$ being D the diameter of the section in the wave splash zone and λ the wave length

To choose the depth where the concrete tower starts, next factors have to be considered:

-Wave range: Installation of the platform is foreseen in the East Anglia Zone within the Round 3 United Kingdom's development program Windmills, see 4.2.4.
East Anglia characteristics for this aspect are from [55]:

H_s(T=1 years) = 7,1 m $\quad$ H_{max} (T=50 years) = 17,48 m

Draft for operations

The most restrictive maintenance and auxiliary services boats in offshore windmills, which are used for workers transhipments to wind towers are small water plane and twin hull boats which have the next characteristics [48]:

Table 11: Operation Parameter

Maximum wave height	2,5 m
Maximum disembarkation wave height	1,5 m
Mínimum platform draft	2,7 m

Maximum platform's pitch

Platform's tilting plays a crucial role in the efficiency and operation of rotor. For this thesis is assumed 4,5° as the maximum static inclination able to assure rotor's operability. The design must ensure that this inclination is not exceeded even for winds of 10-14 m/s which are the ones that more thrust exert on the rotor and therefore cause more time on the platform see figure 60.
For stronger winds, in order to ensure their structural integrity, blades are placed on a pitch angle end, to minimize the surface wind resistance. Therefore, a higher wind speed which exceeds the threshold does not involve a greater inclination.

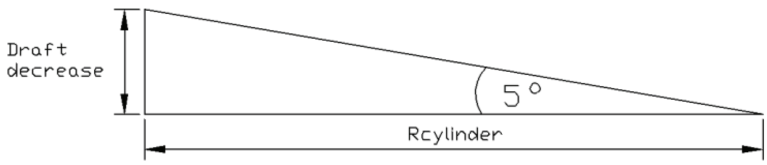


Figure 60: "Draft decrease sketch"

Given that the radius of the platform is still unknown but can vary between 15 and 40 meters, the elevation at the edge of the platform could be between 1,2 and 3,1 meters see figure 61. As a conservative election I choose to use 3,1 meters.

The submerged tower height will be:

For normal sea state operation boats can be able to arrive to the tower, the safety deep is obtained using (34.1), the values are shown in (34.2)

$$Elevation_{Total(NSS)} = Disembarcation_{Max.Height} + \frac{H_s \, for \; boats}{2} + Elevation_{Pitch=10°} \qquad (34)$$

The result is that elevation needed is 8,15 meters

It is also important to check which is the depth needed for the Extreme Sea State, in order to know if the amplitude of the H_{max} for a 50 years return period is bigger than the submerged tower height.

For extreme sea state only the maximum wave height for 50 years return period is considered, the safety deep for this case is obtained using (35.1) and values are shown in (35.2):

$$Elevation_{Total(ESS)} = \frac{H_{\max}(T_{50})}{2} \qquad (35)$$

For this case 8,74 meters are needed.
"Hand book of offshore engineering" [72] considers 10 meters under water as possible impact zone. However, due the big radius below I add a 60% more depth to let that volume away from the more intense wave energy induced efforts. The final design value is shown in (36)

$$H_{F.Sub} = Elevation_{Total(ESS)} + 7 \; meters = 14 \; meters \qquad (36)$$

This height and the lid one are the only ones that don't change for the different configurations to be studied, all parameters which define the platform are shown in Table 14 within the platform draft to be studied.

Table 12: "Parameters which define the platform height"

Platform's drafts	40 m; 45 m; 50 m; 55 m; 60 m; 65 m
Dome Height	$H_D=R_{Cyl}/8$
Cylinder radius	From 15 to 40 meters
Cylinder Height	$H_{Cyl}= Draft-H_D-H_{Cyl}-H_L-H_{F.Sub}$

Lid height	0,8 meters
Height of submerged tower	14 meters

Concrete Tower Parameters

The thickness of the concrete tower, despite being divided in two parts, submerged and emerged, is constant.

On tower design a thickness of 0,4 meters is assumed for the entire tower, a radius of 6 meters on the tower's base and 2,04 meters on top and 100 meters height.

From these data and considering a liner progression between the two sections the needed parameters are obtained.[59]

Tower parameters are the common ones used to support a 5 MW wind turbine [66], for this study, the tower height has been changed in order to add the submerged frustum to this geometry. In table 13 tower height includes the submerged one.

Table 13: "Concrete Tower Parameters"

Tower concrete thickness	0,4 meters
Radius on submerged tower's bottom	6,08 meters
Radius on emerged tower's upper limit	2,04 meters
Tower height	102 meters
Total tower Mass	2.400.177 Kg

Concrete density

The standard density is 2.500 Kg/m^3. But in order to take into account all the auxiliary elements inside the structure as postesed armour, equipment, auxiliary structures as stairs, walls… a 5% more of density is used in order to add easily all these elements to the platform calculations, with means 125 Kg/m^3. The resultant density will be obtained using (37.1) and (37.2)

$$\rho_{Conc.} = \rho_{Standard\ concrete} + 5\% \quad (37)$$

The density is therefore 2.625 Kg/m^3

Water density

Despite the fact that salinity, temperature and sediments can change the sea water density, a standard value is assumed: 1025 Kg/m^3.

Ballast density

Due to the amount of ballast required which can reach several thousands of tons, a material with enough density and a really low price is needed. The proposal is to use black slag from blast furnaces which as a density about 2500 Kg/m^3. Nowadays despite the starting re-utilizing applications, it is still considered as an expensive disposal waste product. In the steel making process about 120-150 kg slag per ton of steel manufactured [49] [50] is produced so the resources of this material are large.

Main materials used for structure design are shown in table 16:

Table 14: "Densities of materials used"

Concrete Density	2.625 Kg/m^3
Water Density	1.025 Kg/m^3
Ballast Density	2.500 Kg/m^3

Thrust Force

It is the force generated by the wind over the rotor. From [65],[68] it is shown that the maximum value is 584 kN, which is from a 10 m/s -14 m/s wind speed.
The resultant moment over the platform will be equal to that thrust force by its distance to the sea water level, which is 88,5 meters.

Therefore M_{Thrust} is 51.690 kNm

With the M_{Thrust} known and C_{55} see [4.3.3] platform pitch angle can be calculated (38)

$$\alpha = \frac{M_{Thrust}}{C_{55}} \tag{38}$$

Because of operation reasons, the maximum static pitch cannot be larger than 4,5° or 0,07886 radians.

Upper mass

The upper mass includes the mass of the blades, hub and nacelle, see figure 61. These elements are not part of the structure but are the heaviest equipment and it is necessary to take them in consideration when the structure is designed. Their characteristics are the ones used in [6] it consist in a nacelle of 240.000 Kg, three blades each of them with 17.740 Kg and a hub of 56.780 Kg.

Considering from [52] that the nacelle and rotor have their center of mass 2,5 meters above the tower top the $C.M._{Struc.}$ is at 88,5 m over the SwL.
Due the relative low mass only the Steiner part is considered from their rotational inertias.
The I_x=I_y are 4.696.473.841 Kgm^2
Now with all fixed parameters defined, I can start calculating the different bodies volumes, mass, centers of masses and rotational inertias.

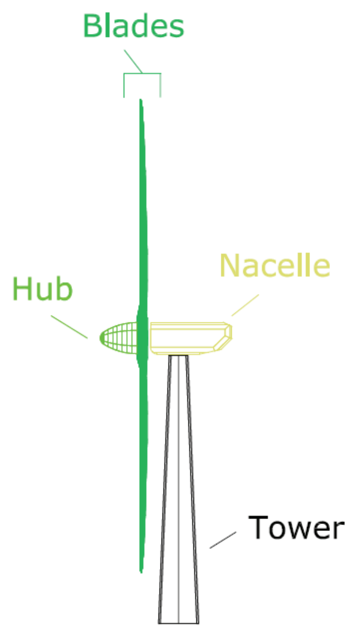


Figure 61: "Upper Mass"

5.3. Requirements

To design correctly the floating platform, the following aspects should be considered:

-Draft requirements
-Platform design description
-Motions restraints

Those conditions come from platform's function whose purpose is not only getting a correct floatability but also the necessary stability to assure the operative conditions for the wind turbine.

5.3.1 Draft requirements

The target of this platform design is to give a response to the technological emptiness between the jacket foundations useful until 50-60 water depth and the floating platforms type "SPAR" suitable for waters deeper than 100-120 meters where the spar solution is the most adequate.

Therefore one of the bounding factors in the structure design is its draft that won't be less than 35 meters because its operative depth would be around 50 meters and for those depths, as mentioned before, the jackets foundations are already being used.

In order to define the maximum draft it is necessary to take into consideration that the deeper the draft is, the more market opportunities it will have, therefore, the smallest draft that fulfils the platform operative and safety conditions should be chosen.

5.3.2 Platform design description

In this section the formulation and procedure used to choose the shape and elements of the platform are explained, as well as the computation of its geometric and physical properties.

The geometric design of the platform plays an essential role to achieve an adequate response to external efforts and an optimised dynamic behaviour.

First, due to the material chosen for its construction, as stated in the previous section, simple shape design is required in order to facilitate industrial constructive chain and post-stressed labours and also to take profit of the concrete resistance to compressive forces and its low maintenance requirements.

For this reason the platform is spliced in different geometric parts. Each of them fulfils a specific function.

As can be seen in figure 62, the structure is composed by two main bodies:
-Platform composed by 4 different bodies with a geometry that as it will be seen later it has been chosen to get the best behaviour to the hydrostatic pressure, the volume of water displaced, the center of gravity reduction by the ballast, the position of the center

of mass, the efforts and the damping effect, being all compatible with the correct prestressing of each and between parts to avoid the appearance of cracks that threaten the durability of the structure.

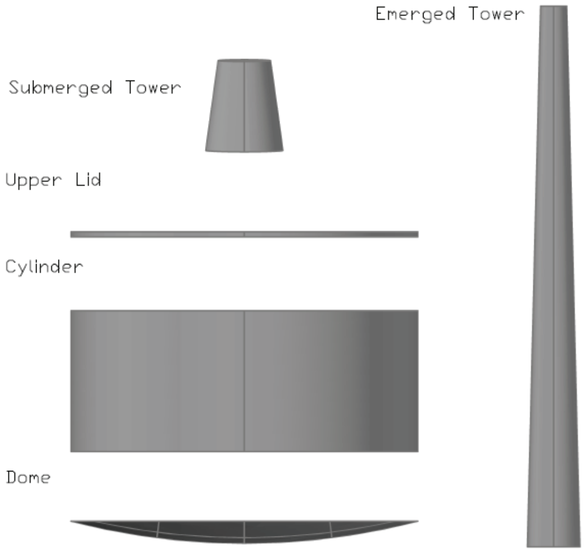


Figure 62: "FOWT's components of study"

The platform parts are, see figure 63:
-A dome
-A cylinder
-A lid
-A frustum cone of 24 meters of height, 14 of them are submerged.

Platform frustum is the lower part of a 100 meters height wind tower. Tower is studied on section [4.1.3]

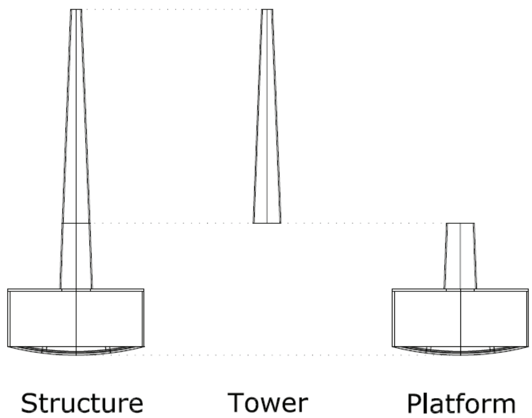


Figure 63: "Structure and its main sub bodies

Since the design is a "Low draft ballasted" the use of ballast for stability and buoyancy is needed. Because of this kind of platform is self-stabilizing. The ballast is considered as a rigid body for computations, see figure 64.

In the structural assessment stage which will be seen in chapter 5, the ballast will be treated as composed by different subsections, each of them between the internal structural concrete diaphragms or stiffeners.

Otherwise and due to the low volume occupied by those stiffeners it can be assumed in this chapter as a unique body.

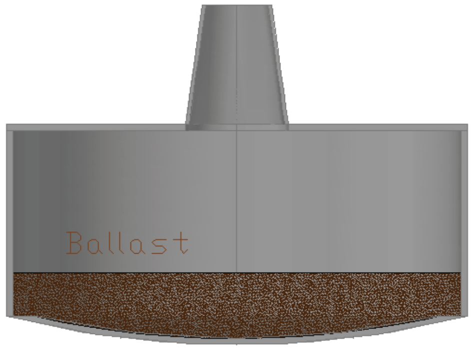


Figure 64: "Ballast simplified position inside structure"

This structure should be able to respond appropriately to all charges and deterioration that could act over it during its lifetime. The lifetime period is considered of 50 years due to the low maintenance concrete's requirements. Also, it should maintain a minimum safety conditions for maintenance and inspection labours.

5.3.3 Motion restraints

The sea water surface is irregular and moves, this movement is transmitted to the platform creating motions and efforts over the platform. Those together with the wind forces over the rotor are the main loads which induce the structure motions.

For this reason an accurate approach to the design is needed, minimizing those movements and efforts as well as simple and economical construction, installation and maintenance labours.

The function of the platform is to provide adequate support to the wind tower whose function is to generate electricity from wind. To do this, a number of restrictive conditions of the movement must be satisfied to ensure that pitch, roll and yaw's movements as well as surge, sway and heave are enough small to not affect the operation of the wind tower.

Surge and sway are sensitive to mooring lines while heave is mostly depending from the platform design, for example flat bottom surfaces increase damping and therefore vertical stability.

Regarding Roll, Pitch and Yaw, they are primarily controlled by a suitable design of the platform to avoid excessive platform's excitation due to the wave action. Those are also controlled by the dynamic control exerted on the rotor by varying the blades pitch, its rotation speed and even the use of air brakes.

5.4. Structure geometry

Concrete structure is composed as mentioned in 3.1 by a platform which gives floatability and stability and a tower which supports the wind turbine equipment to the desired height.

Platform and tower are built using concrete while the upper mass is the bigger equipment of a wind tower, composed by multiple elements as nacelle, blades, hub…each of them with different materials and properties.

5.4.1 Structure bodies

Structure is composed by two main bodies known as platform and tower.

Platform assures floatability and stability meanwhile tower supports wind turbine.

The concrete tower is a frustum cone, see figure 70. It has all the parameters fixed. The lower part of this frustum cone is part of the platform and has some of its length submerged.

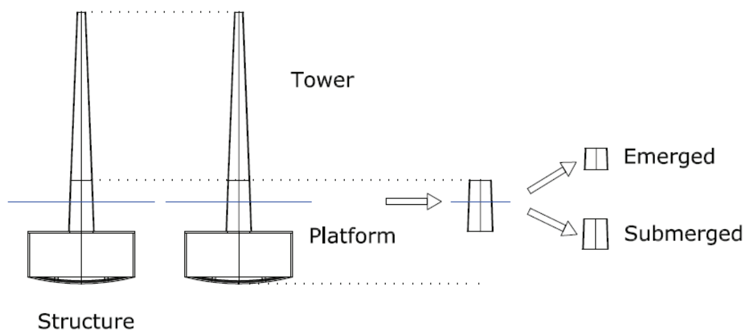


Figure 70: "Tower"

The tower starts 10 meters over SwL and is 78 meters tall. That means that the top height over the SwL is 88 meters. The lower part of the frustum cone is the upper body of platform. It is known as frustum cone.

5.4.2 Global Properties

With all the parameters obtained for each part of the body the global values are obtained.

The mass of the structure (39) includes all the concrete structures, ballast and upper mass:

$$M_{Struc.} = M_D + M_C + M_L + M_F + M_T + M_B + M_{Up.M} \tag{39}$$

The mass of the platform (40) it is only from the concrete elements of platform and ballast:

$$M_{Plat} = M_D + M_C + M_L + M_{F.} + M_B \tag{40}$$

The structure center of mass (41) is obtained as summation of all the centers of masses divided by the mass of the whole structure:

$$C.M_{Struc.} = \frac{\left(C.M._D + C.M._C + C.M._L + C.M._F + C.M._T + C.M._B + C.M._{Up}\right)}{M_{Struc.}} \tag{41}$$

The platform center of mass (42) includes the center of masses of concrete bodies of platform and ballast divided by the platform mass:

$$C.M_{Plat} = \frac{\left(C.M._D + C.M._C + C.M._L + C.M._F + C.M._B\right)}{M_{Plat}} \tag{42}$$

Inertia of the structure (43.1) and (43.2) is equal to all the inertias of each part plus each Steiner application to reference all of them to the $C.M._{Struc.}$

$$I_{Struc.Z} = I_{Plat.Z} + I_{T_Z} + I_{Up.M_Z} + I_{Ad.M_Z} \tag{43.1}$$

$$I_{Struc.Y} = I_{Struc.X} = I_{Plat.X} + I_{T_X} + I_{Up.M_X} + I_{Ad.M_X} \tag{43.2}$$

Platform inertia (44.1) and (44.2) is summary of all the concrete bodies conforming platform and the ballast. All these inertias must be referenced to $C.M._{Struc}$ using Steiner when necessary:

$$I_{Plat_Z} = I_{D_Z} + I_{C_Z} + I_{L_Z} + I_{F_Z} + I_{B_Z} \tag{44.1}$$

$$I_{Plat_Y} = I_{Plat_X} = I_{D_X} + I_{C_X} + I_{L_X} + I_{F_X} + I_{B_X} \tag{44.2}$$

The concept of added mass comes from the necessity of considering the natural resistance to be displaced of the fluid volume affected by a submerged body which acelerate or decelerate. It plays a fundamental role in floating bodies. The bigger the added mass of an structure is, the bigger amount of energy will be necessary to use to displace it trough the water, because the submerged body not only has to displace its own mass but also the added mass.

The added mass inertia for the structure (45.1) and (45.2) are the displaced volumes of water from all the submerged bodies which are in contact with the water that excludes ballast:

$$I_{Struct.Ad.M_Z} = I_{D.Ad.M_Z} + I_{C.Ad.M_Z} + I_{L.Ad.M_Z} + I_{F.Ad.M_Z} \tag{45.1}$$

$$I_{Struc.Ad.M_Y} = I_{Struc.Ad.M_X} = I_{D.Ad.M_X} + I_{C.Ad.M_X} + I_{L.Ad.M_X} + I_{F.Ad.M_X} \tag{45.2}$$

With all those parameters defined, the calculation of the behaviour properties can be done.

CHAPTER 6: STATIC ANALYSIS AND SELECTION

6.1. Introduction

After a definition of the boundary and limiting conditions, Platform buoyancy and the platform draft are the first characteristics to be analysed.
Then stability is studied through metacentric height for auto-stability and hydrostatic stiffness for stability against external forces as wind.
Finally the natural excitation period of the platform is obtained. This frequency should be avoided being always over it. This period is related with the platform inertia and stiffness.
Finally a comparison between the different platforms studied is done, choosing for the dynamic analysis the one with the best characteristics.

The static structure parameters explained in chapter 5 are in figure 71 shown:

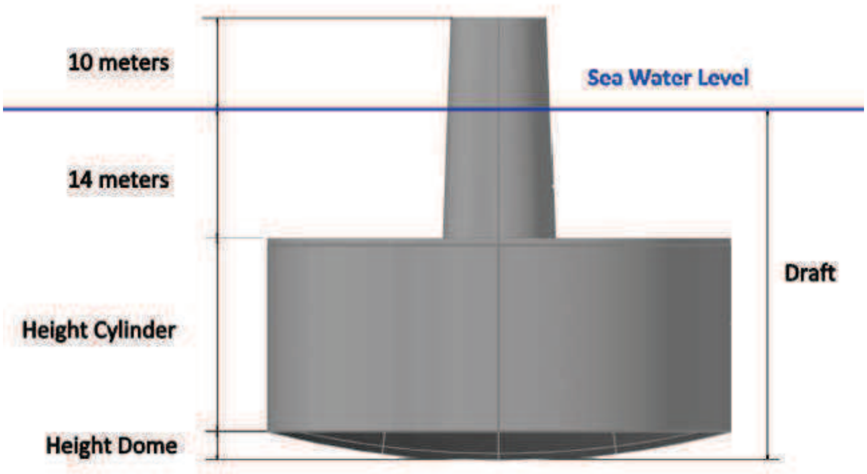


Figure 71: "Platform main dimensions"

6.2. Static Analysis

Parameters values computed with VBA macros for platforms with drafts of 35, 40, 45, 50, 55 and 60 meters and radius between 15 and 40 meters are in the next pages shown through plots.

6.2.1 Pitch Angle

As explained in paragraph 5.2, pitch angle has to be smaller than 0,07845 radians or 4,5º. This is one of the most significant parameters because it is related to the inertia, the mass and the metacentric height, therefore it will be used as the main value to determine the platform parameters.
In this case the maximum operational wind is 10-14 m/s, which makes a 584 kN force over the rotor area on the nacelle.
This condition is fulfilled for different a_C depending on the $Draft_{Plat}$:

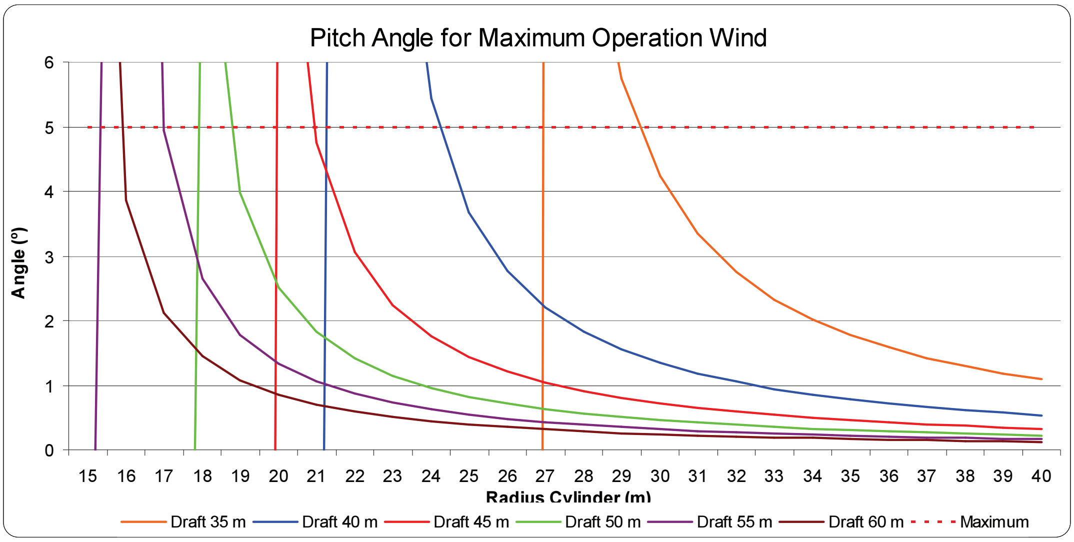


Figure 72: "Pich angle for maximum operation wind"

In figure 72 it can be seen how for the same F_{Thrust} pitch angle decreases for big diameters and drafts. Table 15 summarizes the minimum values needed to keep pitch angle under the maximum previously specified.

Table 15: "Minimum radius necessary for each draft to meet pitch angle conditions"

$Draft_{Plat}$	35 m	40 m	45 m	50 m	55 m	60 m
r_c (m)	30 m	25 m	22 m	19 m	18 m	16 m

6.2.2 Eigen period

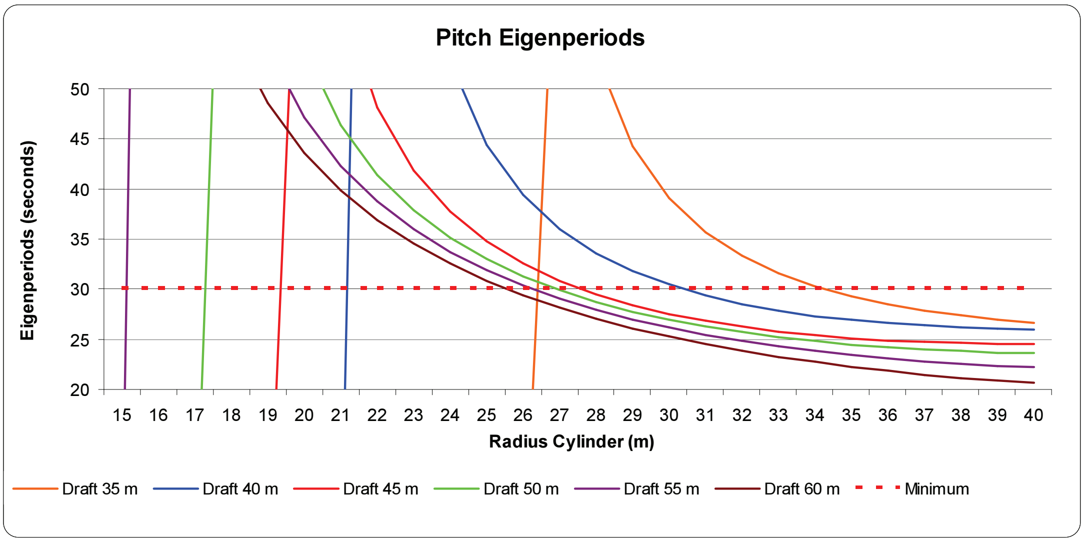


Figure 73: "Eigenperiods"

Figure 73 shows how for a same platform draft, big diameters maintain eigenperiod asymptotically in the same value. As this value is under the minimum needed to be far from the wave periods smaller diameters need to be chosen.

Table 16 shows the maximum diameters providing useful periods.

Table 16: "Maximum radius for each draft to meet Eigenperiod conditions"

$Draft_{Plat}$	35 m	40 m	45 m	50 m	55 m	60 m
r_c(m)	33 m	30 m	27 m	26 m	29 m	29 m

6.2.3 Hydrostatic stiffness

This parameter describes platform stability against disturbing moments, see [4.3.3].

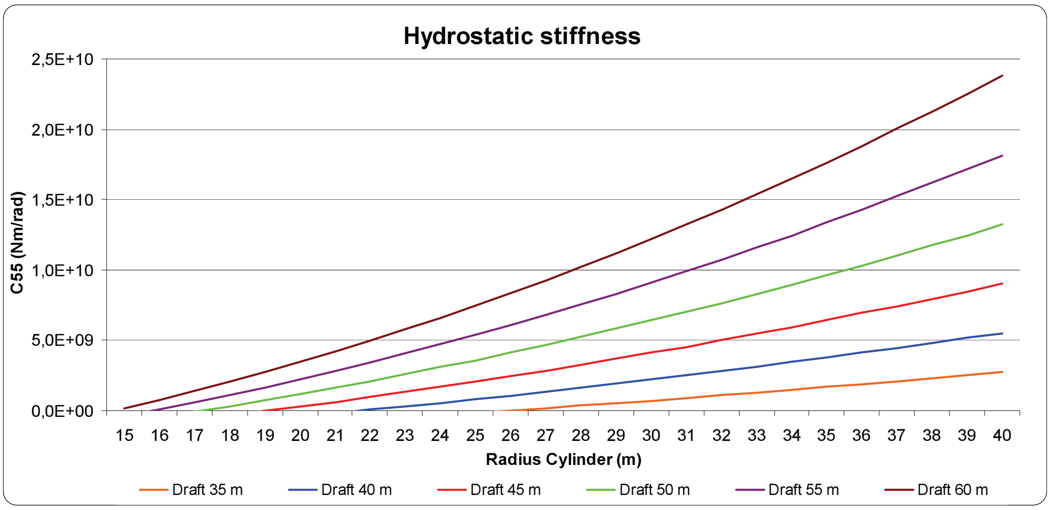


Figure 74: "Hydrostatic stiffness"

On figure 74 hydrostatic stiffness values for all drafts and radius are shown. It can be seen how an increase in platform dimension and therefore in weight, is favourable to get high hydrostatic stiffness values. The reason is that big diameters involves great amounts of ballast increasing the $Moment_{Rest.Struc.}$ also deeper drafts platforms have their ballast mass, which is the bigger of all the structure bodies, further from SwL increasing $Moment_{Rest.Struc.}$

After this analysis the maximum and minimum possible radius for each draft are shown in table 17.

Table 17 "Available platforms radius"

$Draft_{Plat}$	35	40	45	50	55	60
Rmax (m)	33	30	27	26	29	29
Rmin (m)	31	25	22	20	18	17

Now another parameters as ballast mass requirements or metacentric height can be discussed.

6.2.4 Ballast

Its function is to fulfil the mass needed to get the desired total mass and stiffness. Figure 75 shows how for big radius the ballast mass increases. That is because bigger radius implies bigger ballast volumes in order to compensate the bigger water volume displaced.

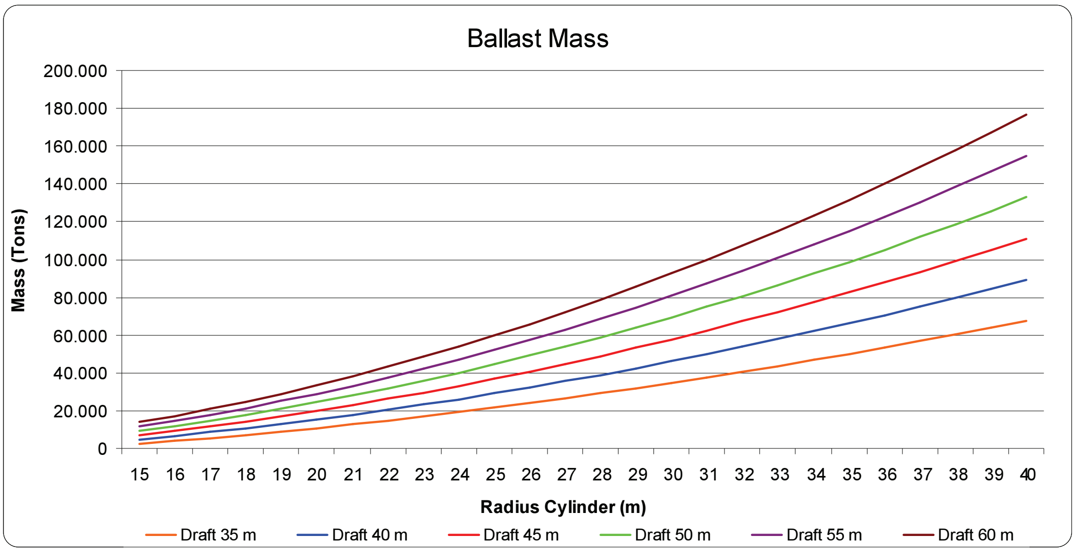


Figure 75: "Ballast Mass"

For shorts drafts bigger ballast mass is necessary to compensate the lower metacentric height available due the proximity between the center of mass and the center of buoyancy. This figure just describes the ballast mass variation depending of platform draft and radius but does not mean that all these combinations are stable. Stable draft&radius configurations can be seen in table 17.

6.2.5 Metacentric height

The metacentric height gives an idea about the static stability of the platform. It can be seen that after a quick grow, the increase of metacentric height turns nearly asymptotic, which explains the asymptotic effect seen for the pitch Eigenperiod and pitch angle graphs and also with the exponential increase of ballast mass.

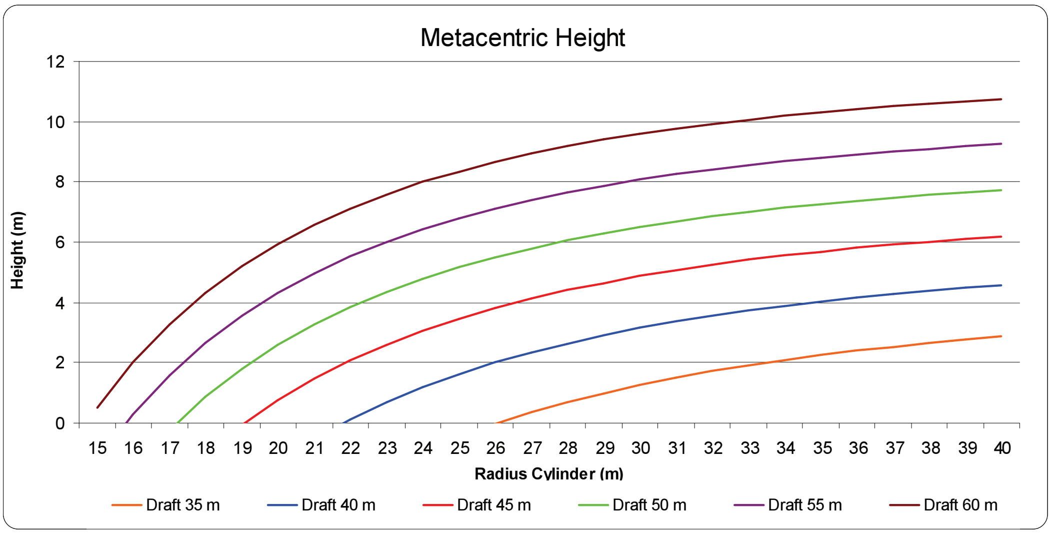


Figure 76: "Metacentric Height"

In figure 76 only positive metacentric heights are shown the explanation is that it has to be >0, see [4.3.2] implying that an angular variation in roll and pitch will be restored and therefore that the structure is autoestable.

6.2.6 Total Mass

In order to facilitate the transport labours and to reduce the amount of material needed, the lighter mass which meets the requirements should to be chosen. Figure 77 shows how total mass depends mostly from radius cylinder and draft.

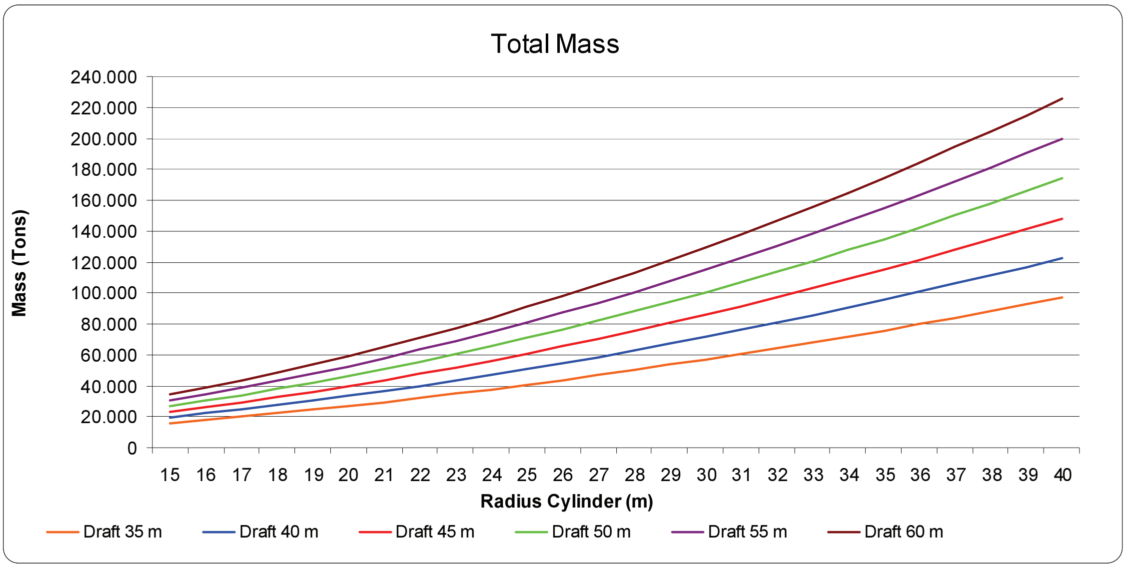


Figure 77: "Total Mass"

As conclusion, a bigger ballast mass and draft increases stiffness. Also, metacentric height does not improve significantly after a determined radius. Therefore smaller draft and cylinder radius as possible should be chosen from table 17

In table 18 these selected radius are shown with its correspondent total mass.

Table 18: "Alternatives for each draft to be studied"

$Draft_{Plat}$ (m)	35	40	45	50	55	60
r_C (m)	31	25	22	20	18	17
$M_{Struc.}$ (Tons)	60.489	50.670	47.655	46.241	43.083	43.299

As a first approximation, it can be considered that the structure is composed only by concrete and ballast. Obtaining masses for concrete and ballast, table 19, and giving prices for these elements a useful cost perspective can be obtained.

Table 19: "Structure masses"

$Draft_{Plat}$ (m)	35	40	45	50	55	60
r_C (m)	31	25	22	20	18	17
$M_{StrucConc}$ (Tons)	23.031	21.570	21.547	21.866	21.813	22.437

M_B (Tons)	37.459	29.100	26.108	24.375	21.270	20.861

Continuing with this first approximation, prices for concrete and ballast have been introduced for simple cost estimation. For concrete a cost of 150 €/m^3 equal to 54,54 €/ton. For ballast a cost of 35 €/ton has been chosen including transportation.
The main costs are obtained in table 20

Table 20: "Structure costs"

$Draft_{Plat}$ (m)	35	40	45	50	55	60
Concrete (€)	1.256.220	1.176.553	1.175.317	1.192.707	1.189.775	1 .223.843
Ballast (€)	1.311.056	1.018.508	913.776	853.111	744.450	730.148
Total (€)	2.567.276	2.195.061	2.089.093	2.045.818	1.934.226	1 .953.991

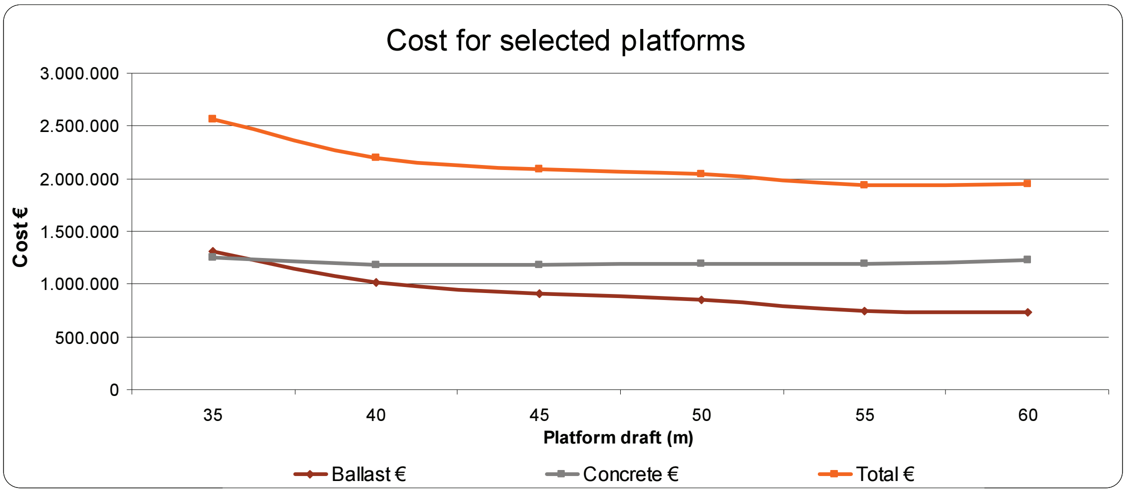


Figure 78: "Cost for selected platforms"

It can be seen in figure 78, that the most expensive one is the platform 35 meters of draft, for the other ones the cost can be considered as stable or with a minimum for the 55 meters draft platform.
The 35 meters of draft alternative is neglected due its high relative cost and between platforms with 40 and 60 meters of draft, the cost has a variation minor than a 11%. In order to test a platform valid of a wider range on locations the 40 meters platform draft is chosen. Because in this phase the vertical movement of the platform known as *heave* is not yet studied, a distance of 20 meters with the sea bed on lowest astronomical tide is let free in order to avoid problems with high height waves between the platform and the sea bottom will be let free in order to avoid impacts with the sea bottom.

6.3. Prototype characteristics

The depth considered for install it is 60 meters of depth because of safety distances previously mentioned. The main platform characteristics are summarized in table 28.

Table 21: "Characteristics summary"

Draft (m)	40
Cylinder radius (m)	25
Submerged volume (m3)	49.480,9
Structure mass (tons)	50.670
Concrete mass (tons)	21.570
Ballast mass (tons)	29.100
C.M. (m)	12,89
C.B.O (m)	14,31
$I_{Struc.z}\,(kgm^2)$	4,53E10
$I_{Struc_X} = I_{Struc.y}\,(kgm^2)$	5,03E10
Eigenperiod (s)	36
Hydrostatic stiffness (Kg.m2/s2)	8,05E8
Metacentric Height (m)	1,62

Figure 79 shows geometric characteristics of platform:

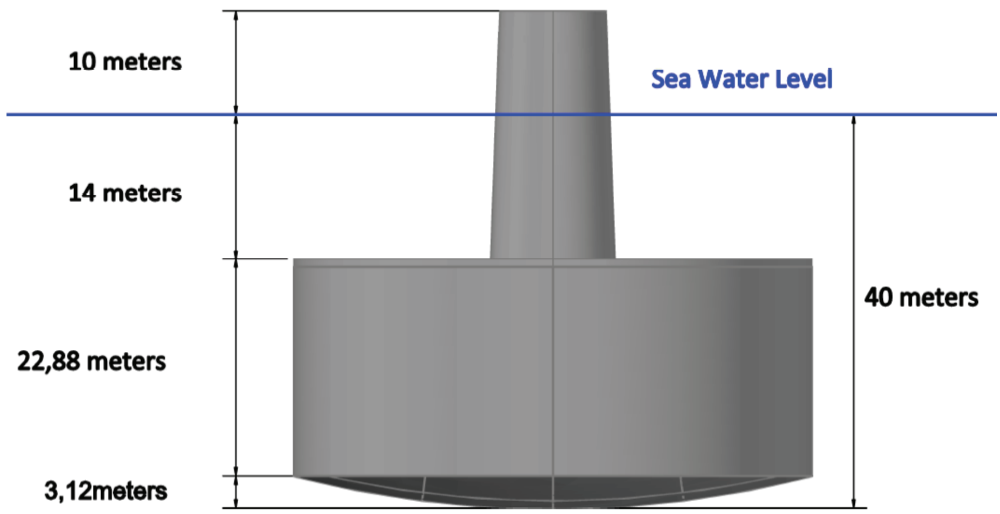


Figure 79: "Main platform characteristics"

Prototype moorings election and properties

Due to the platform type of study, the mooring system adopted will be the spread mooring, see figure 80, composed by three cable lines which split the platform in three sectors of 120° each one.

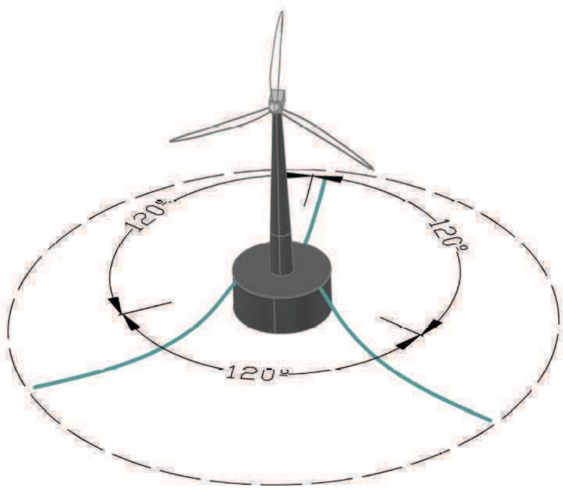


Figure 80: "Catenary mooring distribution"

Mooring lines behaviour change depending of the efforts dimension they are supporting.

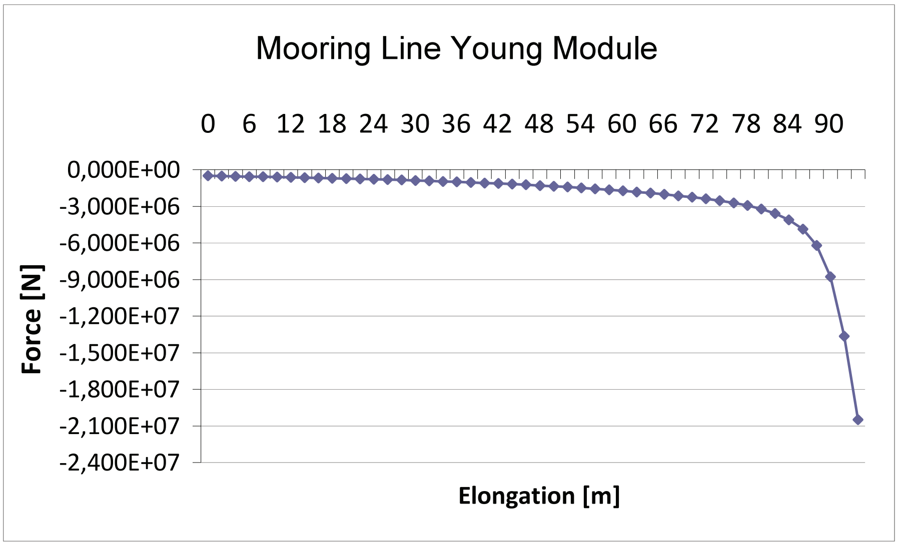


Figure 81: Mooring Line Force-displacement curve

In figure 81 can be seen how for low tension loads, Young 's mooring lines module can be considered lineal. When the mooring line get into the loaded section of the diagram behaviour changes to non-lineal increasing extremly quickly the tension.

For mooring lines computing in Ansys due simulation limitation, a non-linear analysis couldn't be realized. As alternative, a linear behaviour was considered, being all the study time on the linear branch of the graphic.
Ansys software allow the use of springs to simulate mooringl lines. However spring behaviour is far away from a catenary one. To solve this, a preload of 857 KN on each of the three springs was introduced in order to get the springs always in tension.

Cable stiffness (47) was obtained from linear zone on figure 81. The value is 32300 N/m:

$$E = \frac{\sigma}{\varepsilon} \tag{47}$$

Their length depends of the connexion point with the platform. This position has to be calculated in order to get the maximum stability as possible, that means limited translations and tilting, but avoiding excessive tension efforts, since could affect the platform structural integrity or exceed their own breaking resistance. Mooring lines ratio between water depth and lines affection has been obtained using [65] as reference.

Figure 82 shows water depth of the site study is 60 meters and the mooring lines afection radio is 120 meters.

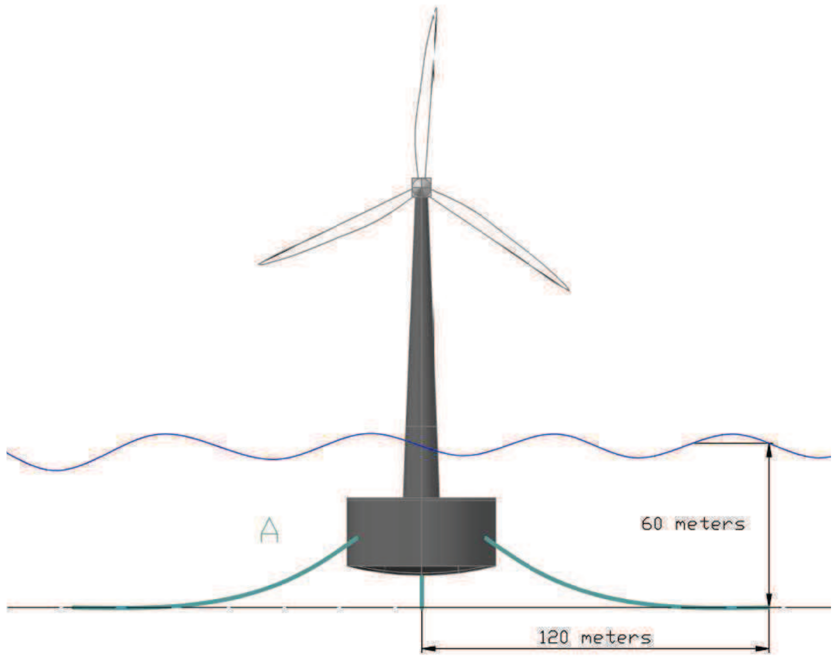


Figure 82: "Mooring cases to study"

CHAPTER 7: DYNAMIC ANALYSIS RESULTS

7.1. Introduction

First of all, it is necessary to define the degrees of freedom of platform, figure 83:

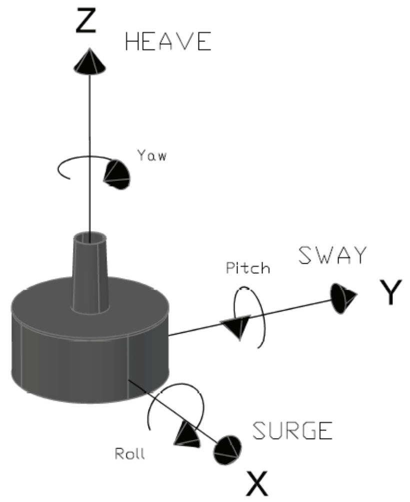


Figure 83: "Degrees of freedom"

Structure center of masses is the origin of the XYZ coordinate system.

These degrees of freedom are composed by three translation motions respect the origin:

-Surge: Displacement in the longitudinal x-direction, positive forwards
-Sway: Displacement in the lateral y-direction, positive to port side.
-Heave: Displacement in the vertical z-direction, positive upwards

And three rotations about XYZ axes:
-Roll about the x-axis,
-Pitch about the y-axis, *All of them positive right turning.*
-Yaw about the z-axis,

Also in the operational mode, the rotating turbine will influence the global motions (mainly roll and pitch). Typically, these influences are solved or minimized using control software on the rotor.
The roll and pitch wind damping effects may be vital in relation to reducing the inclinations and thereby motions and acceleration as well as global bending moments in the platform and tower. These software-based improvements have positive effects in mooring and structural fatigue.

To understand and modelling a floating wind turbine hydrodynamics behaviour it is necessary to use computer simulation programs which include a suitable combination of incident-wave kinematics and hydrodynamics loading models.

Software used has been ANSYS Aqwa, ANSYS Structural and FAST. For each phenomenon the software used is specified in its correspondent paragraph.
Determination of hydrodynamic loading and response is crucial, since this loading and response involves wave excitation, added mass, wave and viscous damping, currents, stiffness as well as the geometry of the floater in question.
For this study, ANSYS Aqwa module is used. In this software, maximum wave frequency depends on the number of nodes used in the Mesh, which modelize the structure. For this reason, the wave's frequency range will be from 0,05 rad/s (125 seconds) to 2,45 rad/s (2,56 seconds)
More results regarding the dynamic analysis can be found in Annex 1.

7.2 Hydrostatic

Hydrostatic Stiffness depends from center of gravity position, table 45:

Table 22: "Centre of gravity position"

X	Y	Z
0 m	0 m	-27,15 m

The restoring forces and moments are shown in table 46.

Table 23: "Restoring matrix"

	Z	RX	RY
Heave (Z)	971141,75 N/m	-	-
Roll (RX)	-	2,6241e9 N.m/rad	-
Pitch (RY)	-	-	2,6241e9 N.m/rad

7.3. Morison

In figure 84 a caption from computing of incident wave forces for survival case studied in chapter 6 is shown. Survival case is characterized by 41 m/s winds, H_s=9,87 m and T_p=12,44 s which implies huge water masses displacing to high velocities and creating high pressures over the platform. On this caption wave crest is just crossing the platform frustum creating high pressures over it.

Maximum red value is 32,04 kN/m^2 while minimum blue one is -7,47 kN/m^2

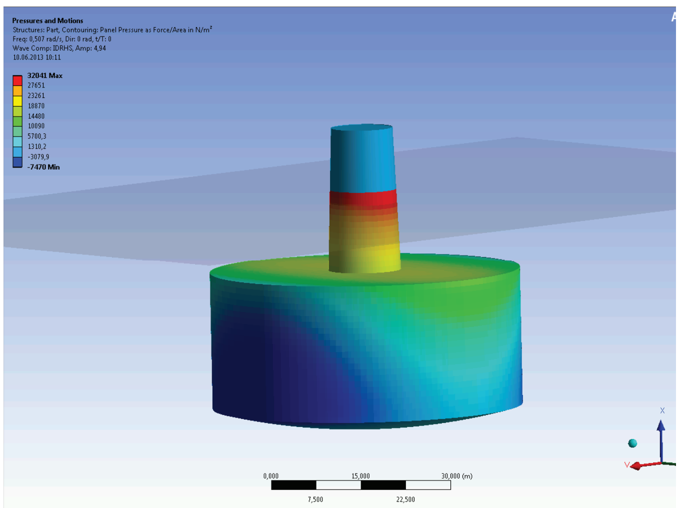


Figure 84: "Diffraction, pressure on platform"

Therefore maximum pressure due waves occurs on platform frustum due waves as expected from waves theory.

7.4. Added mass

As an example, in figure 85 is shown the added mass for heave. It can be seen how for low frequencies more water mass is displaced.

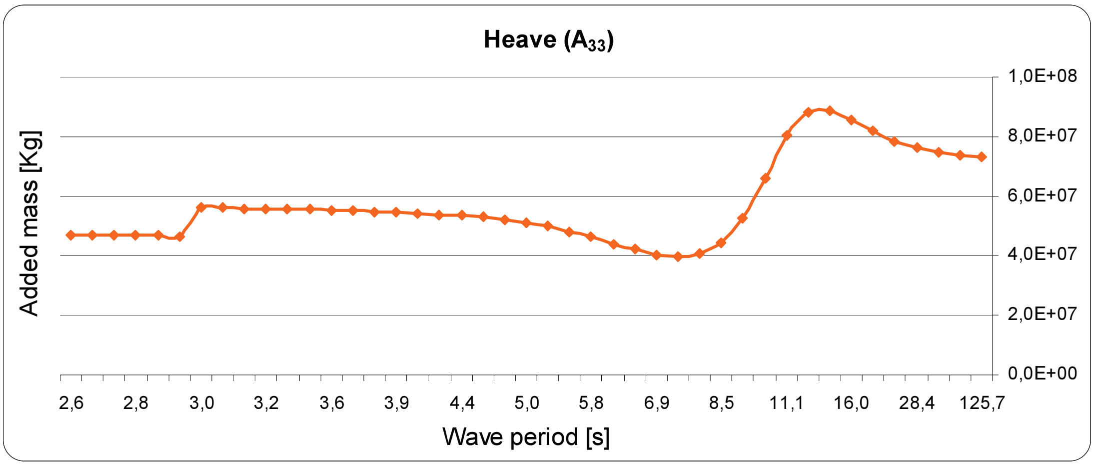


Figure 85: "Added Mass on Heave"

Added mass increases the system mass in all degrees of freedom by several tonnes. These added masses increases inertia and natural period of excitation.
Results for the other degrees of freedom can be seen in Annex 2.

7.5. Radiation Damping

For radiation damping, it can be seen in figure 86 how there is a great peak for 1,44 rad/s which is equal to a period of 82,5 seconds. For this frequency is the maximum misalignment between platform movement and waves.

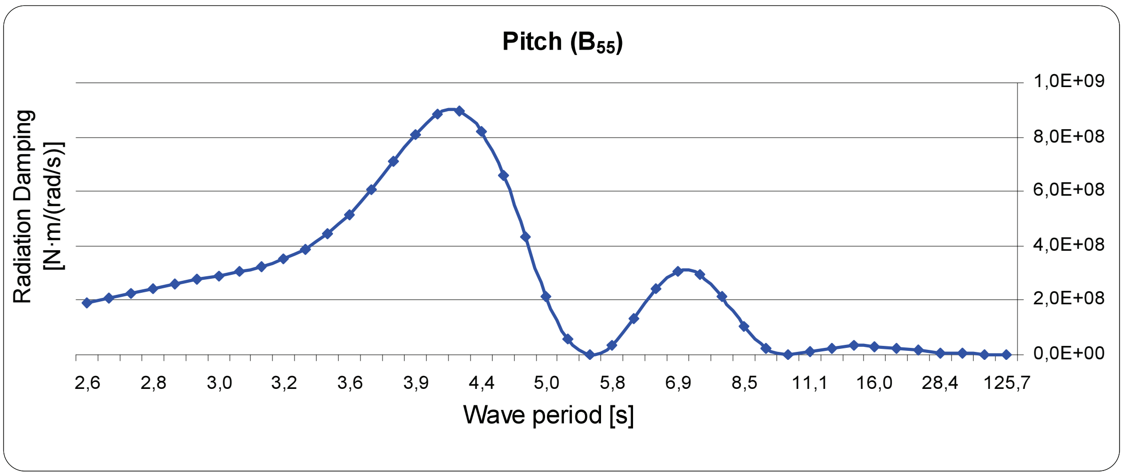


Figure 86: "Radiation Damping on Pitch"

7.6. Response Amplitude Operators

In this study response amplitude operators have been obtained using ANSYS Aqwa module.

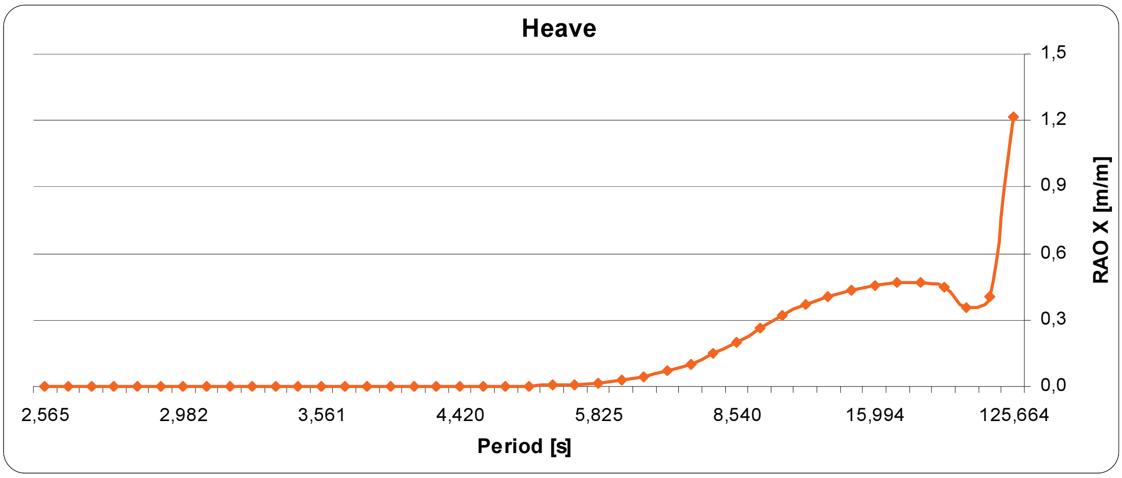


Figure 87: "Response Amplitude Operators on Heave, [X axis]"

On figure 87 it can be seen how there is no excitation for frequencies smaller than 5 seconds and that until periods greater than 120 seconds this excitation is insignificant.

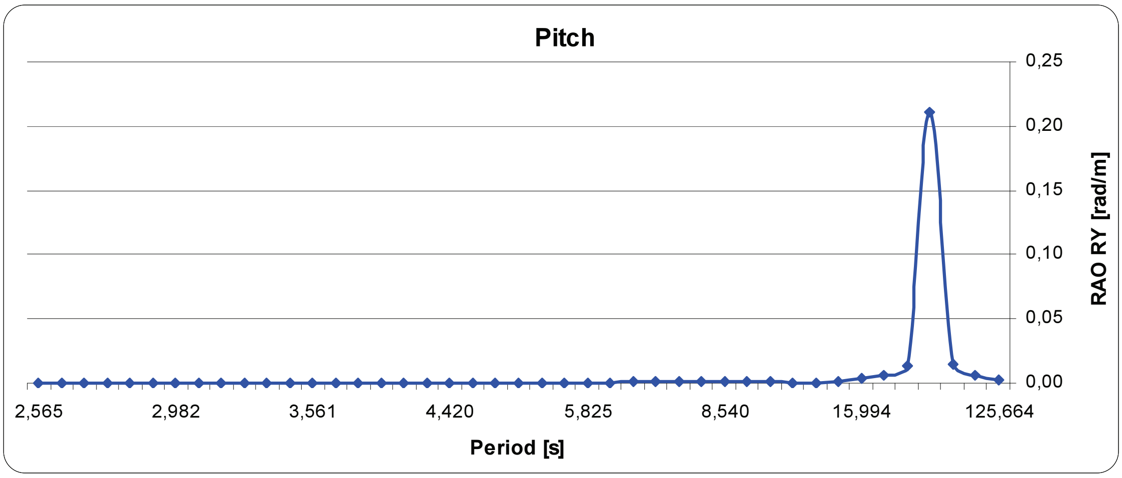


Figure 88: "Response Amplitude Operators on Pitch"

On figure 88, RAOs analysis for pitch shows clearly a peak of excitation in 70 seconds. Usually normal waves have not such high periods. However a exhaustive analysis should be done to find ways to reduce sensitivity to that peak.

8. LOADS

8.1. Introduction

Wind turbines on floating support platforms are designed to be installed in a deep offshore environment, greater than 60 meters. The loads on these systems are dominated by aerodynamic and hydrodynamic effects.
The origin of these effects can vary from sea ice to air turbulence.
For load cases simulation, FAST and ANSYS software are used.
FAST allows getting accurate values for many of the FOWT parameters and a precise description of wind forces.
ANSYS allows getting structural analysis of the FOWT introducing the efforts obtained with FAST.

As an academically study, not all the combinations can be studied and for that reason its installation site is just a theoretical one, only a design case study is considered, however, this case is one of the most unfavourable ones.

The parameters to obtain will be:

Table 24: "Parameters to obtain"[61]

Wind		Waves			Currents	
Velocity	Heading direction	Significant Height	Peak Period	Heading direction	Velocity	Heading direction
V_{Wind} (m/s)	Θ_{Wind} (Deg)	H_s (m)	T_p (Secs)	Θ_{Wave} (Deg)	$V_{Currents}$ (m/s)	$\Theta_{Currents}$ (Deg)

With all the previous data known, now it is possible to calculate the loads that the FOWT should support.

8.2 Definition of Design Load Cases (DLCs)

Extreme Coherent gust with Direction change (ECD) adapted to this study.
It uses the wind velocity that transmits the biggest load to rotor. That wind velocity is not the maximum operative but the 12-14 m/s wind speed. [see page 97]. But in this thesis these conditions are used to characterise the structure.

The conditions are:

Table 25: "Extreme Coherent gust with direction change (ECD)"

Turbine Condition	Wind Condition	Waves	Wind and Wave Directionality	Sea Currents NCM	Water Level MSL
Power Production	$V_{hub}=V_r\pm2m/s$	NSS $H_s=E[H_s\|V_{hub}]$	MIS, wind direction change	NCM	MSL

V_{hub}=10 minute mean wind speed at hub height
V_r= rated wind speed
H_s = Significant wave height
T_p = Peak period of wave spectrum
θ_{wind} =Wind direction
θ_{wave} = Wave direction
NSS = Normal Sea State
MIS = Misaligned wind and wave directions
NCM = Normal current Model
MSL = Mean sea level

The objective of the design load conditions is to assure that the operative level of 5º for the pitch tilt is not reached.

8.3 Definition of Survival Load Case (SLC)

Survival Load cases are used to check the structure and station keeping system integrity and the air gap.
In *"Floating Offshore Wind Turbine Installations"* published by the American Bureau of Shipping (2013), there are two SLCs, for the purpose of this study only the most unfavourable will be checked.
The return period is defined as the one which creates the hardest conditions that blade can support without be damaged. Due to the absence of durability parameters of blades, a return period of 50 years will be used.

The conditions are:

Table 26: "Survival Condition case"

Design Condition Parked RNA	Wind Condition	Waves	Wind and Wave Directionality	Sea Currents	Water Level
	SurWM	SurSS	MIS, MUL		
	$V_{hub} = k_1 \cdot V_{10\ min,\ 100\text{-}yr}$	$H_s=k_2 \cdot H_{s,100\text{-}yr}$	$\theta_{wind} = \theta_{wave} + 90º$	SurCM 50-yr	SurWLR 50-yr
Intact Blades Intact Hull	$V_{hub} = 0,95 \cdot 44,50$ $V_{hub} = 42,275$ m/s	$H_s=1,09 \cdot 9,90$ $H_s=10,79$	$\theta_{wind} = \theta_{wave} + 90º$	1,2 m/s	5,66 m

50-yr = Maximum return period (n years) of the storm wind conditions that turbine blades can sustain and remain intact for 50 years. $H_{s,50\text{-}yr}$ = Significant wave height with a return period of 50 years
$V_{10\ min,\ 50\text{-}years}$ = 10 minute mean wind speed at hub height with a return period of 50 years
SurWM = Survival wind model
SurSS = Survival sea state
SurCM = Survival current model
SurWLR = Survival water level range
MIS = Misaligned wind and wave directions
MUL = Multidirectional wind and wave directions

The objective of the survival load conditions is to assure that the platform is able to maintain its structural integrity and does not sink.

These conditions will be tested for different mooring lines distribution, [9.3]

8.4. Wind

Figure 89 shows the relation between wind speed and its probability, which can be assimilated to a Weibull distribution:

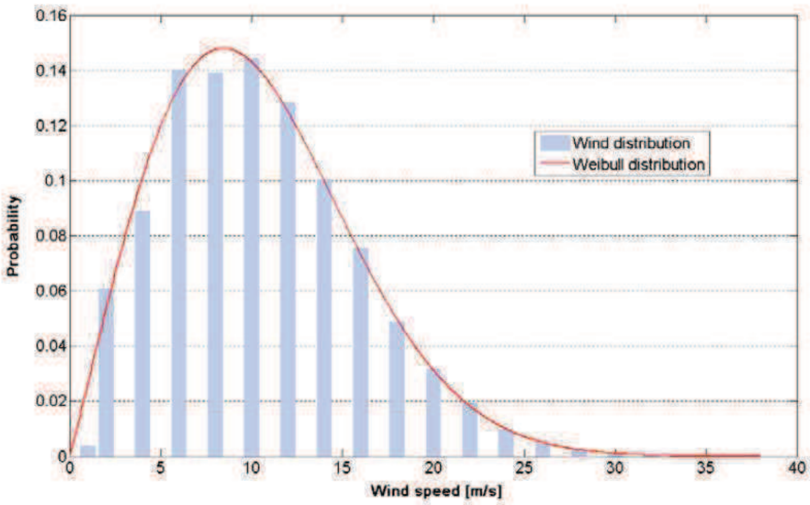


Figure 89: "Probability distribution for wind speeds"

Its relevant Weibull parameters are A=11,75 m/s and k=2,04, which leads to an annual mean wind speed on hub height of 10,05 m/s.

Wind loads are obtained using FAST software, which has been certified by German Lloyd for bottom founded wind turbines design.

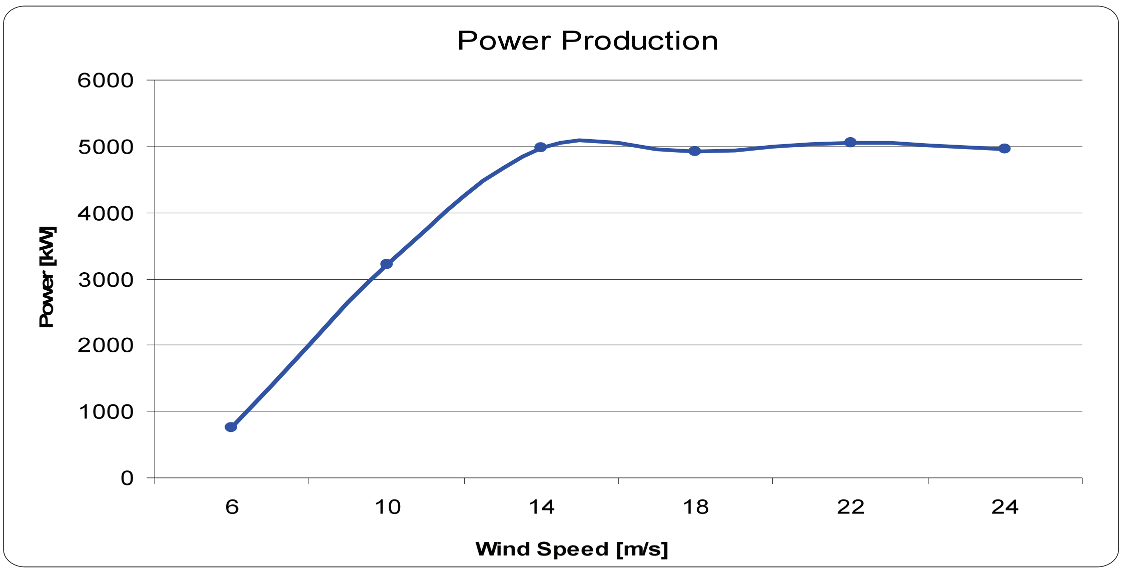


Figure 90: „Energy obtained from a wind turbine"

Figure 90 shows how for winds lower than 5-6 m/s, profitable wind energy is low and therefore production is off.
Also for winds higher than 24-25 m/s wind production is stopped for structural security reasons.
For this reason, only the interval between them will be studied in the Design Load cases, table 27 shows the wind speed cases:

Table 27: "Wind Speed cases"

6 m/s
10 m/s
14 m/s
18 m/s
22 m/s
24 m/s

Despite that wind speed is defined as a fixed value, simulation software recreates a random wind model where the median wind speed as that value, see figure 91:

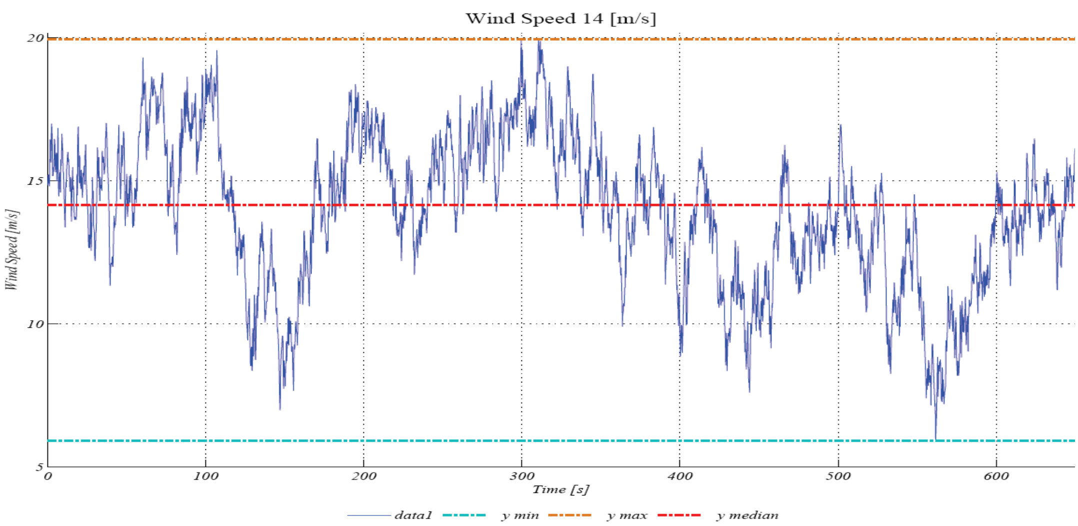


Figure 91: "Wind speed distribution for a medium velocity of 14 m/s"

Wind Extreme Values

The extreme wind speed is determined as the maximum wind speed that occurs with a certain return period.The resulting equation (48) and its projection, figure 92, are:

$$V_{hub,10miin}(T_{return}) = 2{,}5536\ln(x) + 32{,}736 \qquad (48)$$

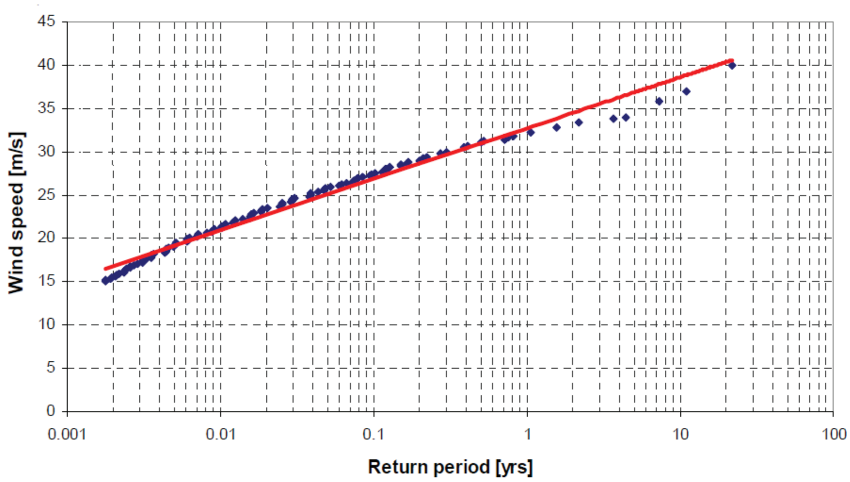


Figure 92: "Extreme Wind speeds return periods projection"

From this point, the maximum wind speeds averaged to 10 min wind speeds at hub height for different returns periods can be obtained, table 28, following the procedure according to [53]. From this extreme wind speed the one for 50 years will be chosen for the survival case.

Table 28: "Extreme wind speeds as a function of the return period"

T_{retrun} [yr]	V_w (10 min) [m/s]
1	32,74
5	36,85
10	38,62
50	42,73
100	44,50

In order to get a better understanding of the wind power production, wind force cases compilation are shown in figure 93, followed by the power production associated to it.

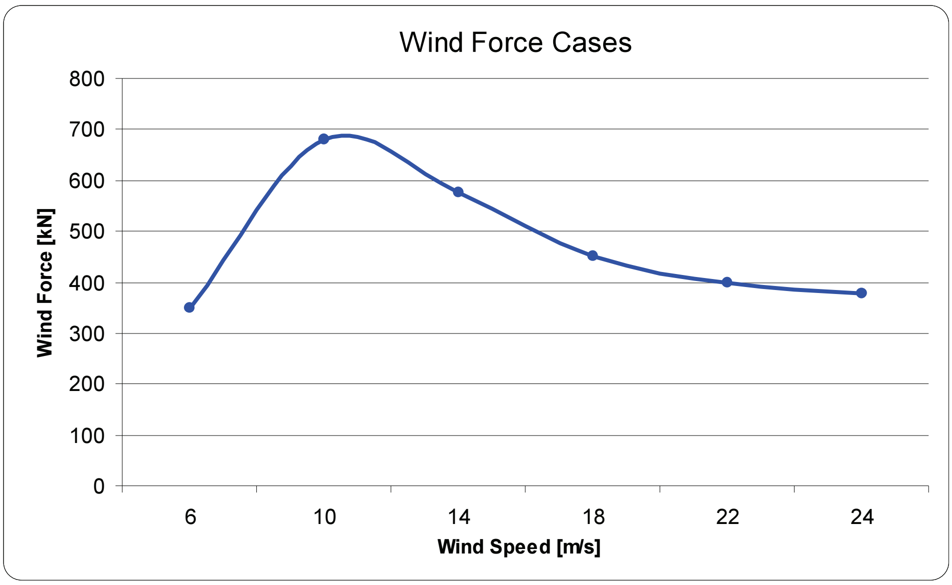


Figure 93: „Wind force over rotor"

Despite what could be thought, maximum wind forces do not correspond with the stronger winds, that is caused by the blade's angle of attack which for strong operative winds reduce the blades surface on the wind, reducing efforts but maintaining energy production. This wind production continues stable at the maximum generator capacity until 24 m/s. For stronger winds, the blades' angle of attack is set to get the minimum wind drag.

8.5 Waves

The wave data are used to determine design parameters. These data give us information of the frequencies of different wave height groups and also the wave periods and directions.
Wave's loads calculation is realized using FAST and ANSYS software, depending of the parameter required.

Also I get the most common *H*s, *Tp*, for the waves related to those wind speeds:

Table 29: "Significant wave heights and peak periods for wind speeds in design loads cases"

Wind speed (m/s)	Hs (meters)	T_p (seconds)
6	0,5	5
10	1,48	5,74
14	1,91	6,07
18	2,5	7
22	2,5	7
24	3,5	8

Also for extreme design load cases, different values for wind speed, wave height and wave period have to be determined. From [55] [68] and using a JONSWAP spectrum with a peak enhancements factor of 3.3 and T_{period} combined with the above mentioned extreme wave heights, equation results (49)

$$11{,}1\sqrt{\frac{H_s(V)}{g}} \leq T \leq 14{,}3\sqrt{\frac{H_S(V)}{g}} \qquad (49)$$

Table 30: "Significant wave heights and peak periods for wind speeds in survival loads cases" [68]

Return Period (years)	H_s (m)	H_{Max} (m)	H_{Red} (m)	T_p (secs)	V (m/s)
50	9,40	17,48	10,34	10,87-14,00	42,73

8.6 Current

The values available for the currents from [55] are taken from "*Noordzeewind OWEZ"* study which is close to the studied location.
For normal current loads an average value of 0,6 m/s at surface level is taken and for the extreme case 1,2 m/s.

As for wave states, on current state analysis there are:

For this study a 50 years return period will be used and considered as a Survival Current Model (SurCM)

Table 31: "Current value for design load cases"

Case	Wind speed (m/s)	Current speed (m/s)
Design Load	6-24 m/s	0,6
Survival Load	42,73	1,2

CHAPTER 9: STRUCTURAL BASIC ANALYSIS

9.1. Introduction

In this chapter structure displacements, load combinations and efforts are studied.

9.2 Structural Model

Platform has been simulated computing a transient structural analysis using ANSYS software.

On it, platform is represented by a line composed of pipes and beams sections.
The basic difference between these sections is that over pipes hydrodynamic loads can be simulated. Therefore pipes sections have been used. For each pipe, radius and material rugosity are defined. Then structure mass, upper mass and ballast mass have been introduced as single points, each of them in their own center of masses with their own mass and inertia. Also fixation points for mooring lines have been introduced at structures center of masses, see figure 94.

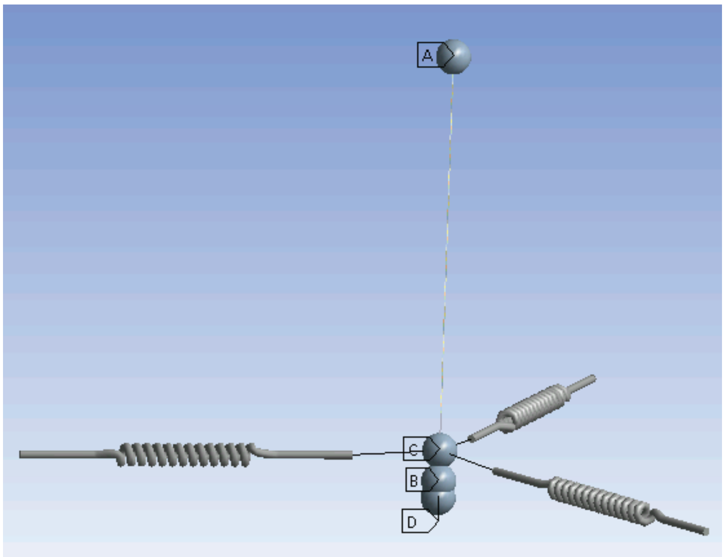


Figure 94: "Structural model in ANSYS"

<u>*Loads modeling*</u>:

Wind force over rotor has been modeled as a vector force in x axis and located on top of tower.
Rotor torque caused by wind turbine has been introduced on tower top.
Distributed wind force over tower bole has been computed for each 10 meters representing wind distributed pressure.
See figure 95.
Wave forces have been introduced trough OCEAN command. Wave type selected has been a random (but repeatable) combination of linear Airy wave components. To generate those waves a Pierson-Moskowitz spectrum has been chosen.
Currents have been modeled with an uniform velocity along all water depth.

Drags coefficients for structure have been 0,6 for x and y axis and 2.1 on z axis.[69]

Mooring lines have been modeled in xy plane using spring connectors. In order to avoid vertical components springs have been installed horizontally at structure center of masses height.

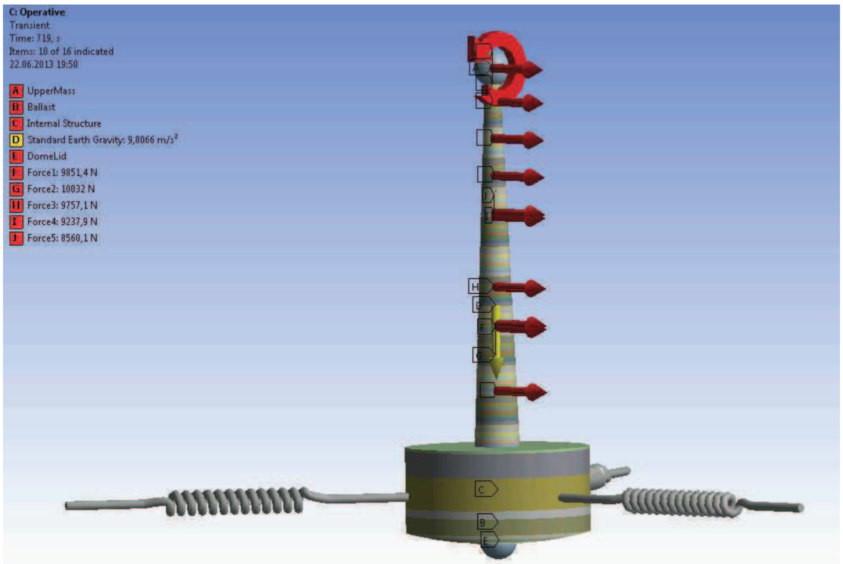


Figure 95: "Loads model in ANSYS"

Due spring characteristics it has been necessary to avoid compression state on them. As a solution a tension preload of 857500 N has been introduced. Therefore when structure displaces some springs increase their tension and other decreases simulating the mooring line vertical displacement with sea bottom.

A 1000 second computing time has been used.

9.3 Mooring Lines distribution

In order to study how mooring lines distribution affects to structure behavior three mooring lines distributions are studied, figure 96.

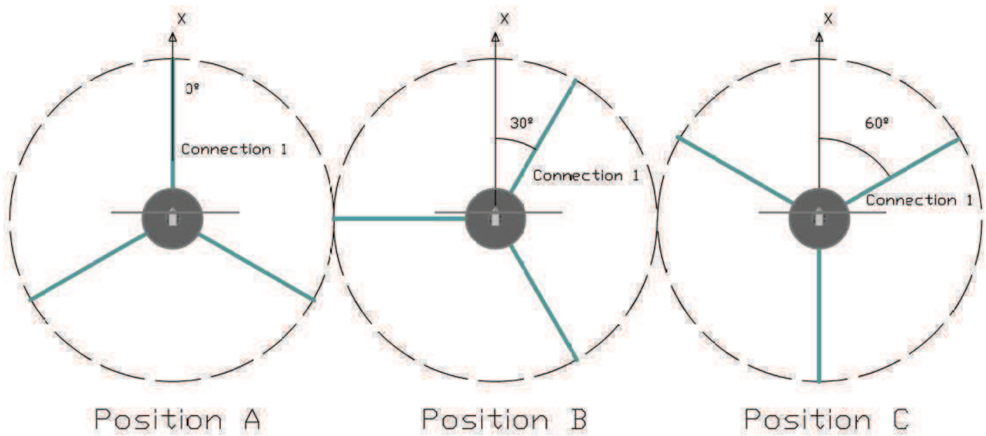


Figure 96: "Mooring lines cases"

Due to symmetry it is not necessary to analyze more positions.

Mooring lines position in Z axes would require a deep analysis because of non-linear mooring lines behavior. Some positions as the extreme cylinder position over the center of masses could create stabilizing moments against the disturbing forces but also reduce the platform stiffness, creating more instability. In absence of that study mooring lines have been fixed at the center of masses of the global structure because in a first approximation, it would be the place where the mooring lines create the least effect to the tilting, working only against platform's displacements.

Table 32: "Connection angle with X axis"

Case	Connection 1	Connection 2	Connection 3	Connections Location in Platform
A	0°	120°	240°	-27,15 m under SwL
B	30°	150°	270°	-27,15 m under SwL
C	60°	180°	300°	-27,15 m under SwL

Sea state modeled has been the one for 10 m/s wind speed, that means wave spectrum of H_s= 1,48 m, T_p=5,74 s and +90° deviation with wind and a current speed of 0,6 m/s and -90° deviation with wind.

Degrees of motion to be analyzed will be heave, pitch and surge because are considered to be the most important for operation.

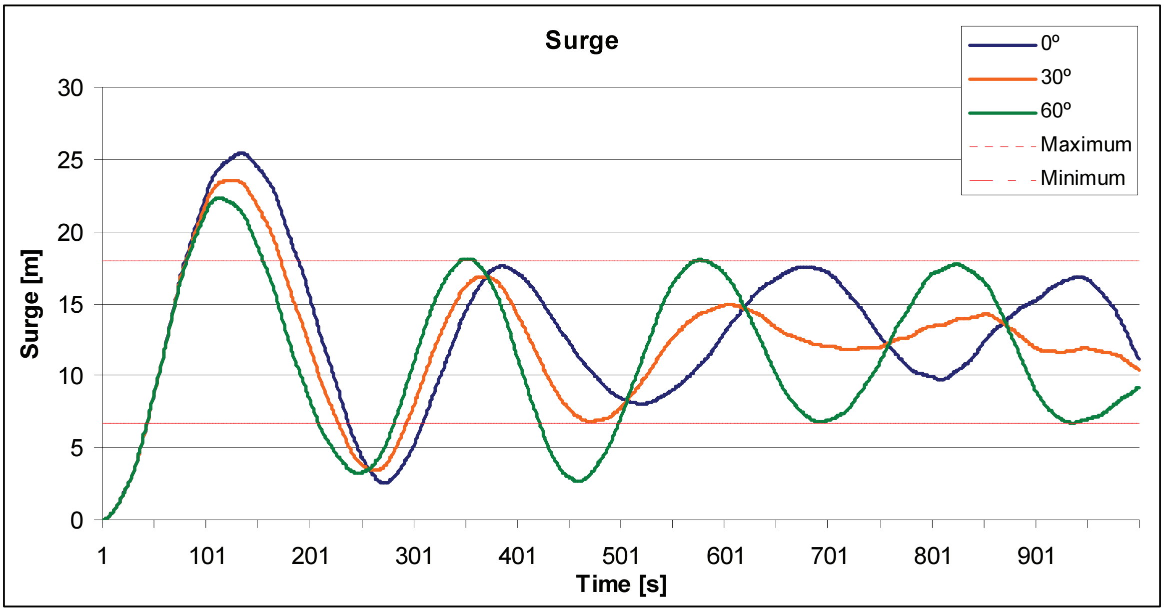


Figure 97: "Platform surge 10 m/s"

On surge figure 97shows that 60 ° mooring lines configuration creates a 67% more surge than the second biggest surge which is 0° case.

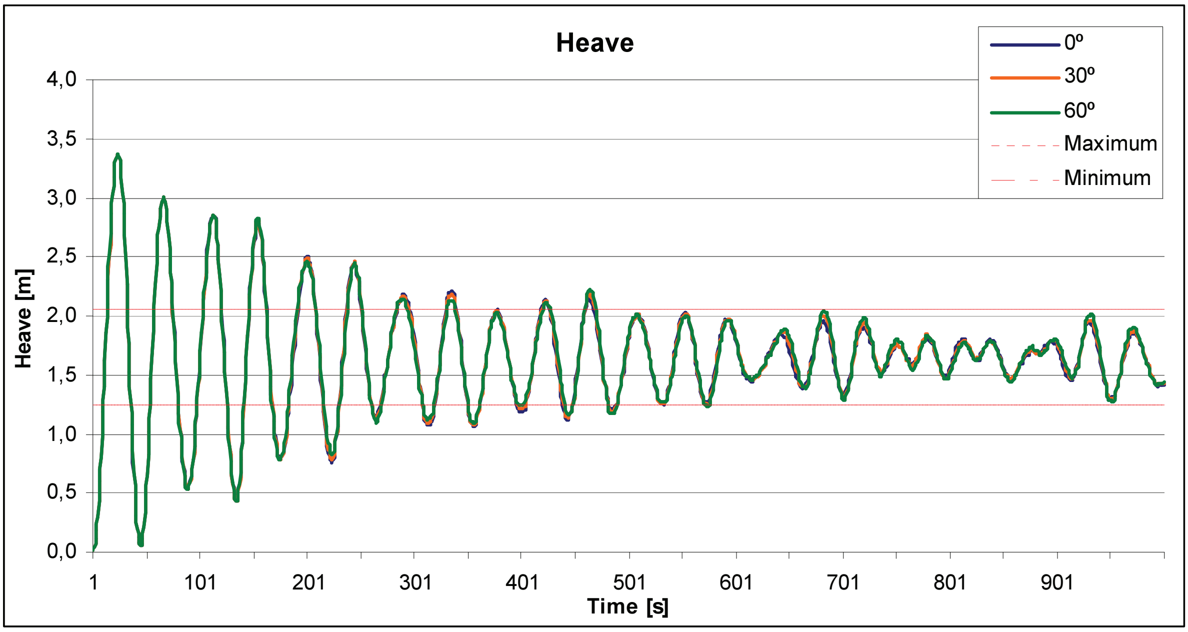


Figure 98: "Platform heave for 10 m/s"

On heave figure [99] it can be seen how there is no difference between mooring lines configurations. The explanation is that model was created with mooring lines acting only in xy plane.

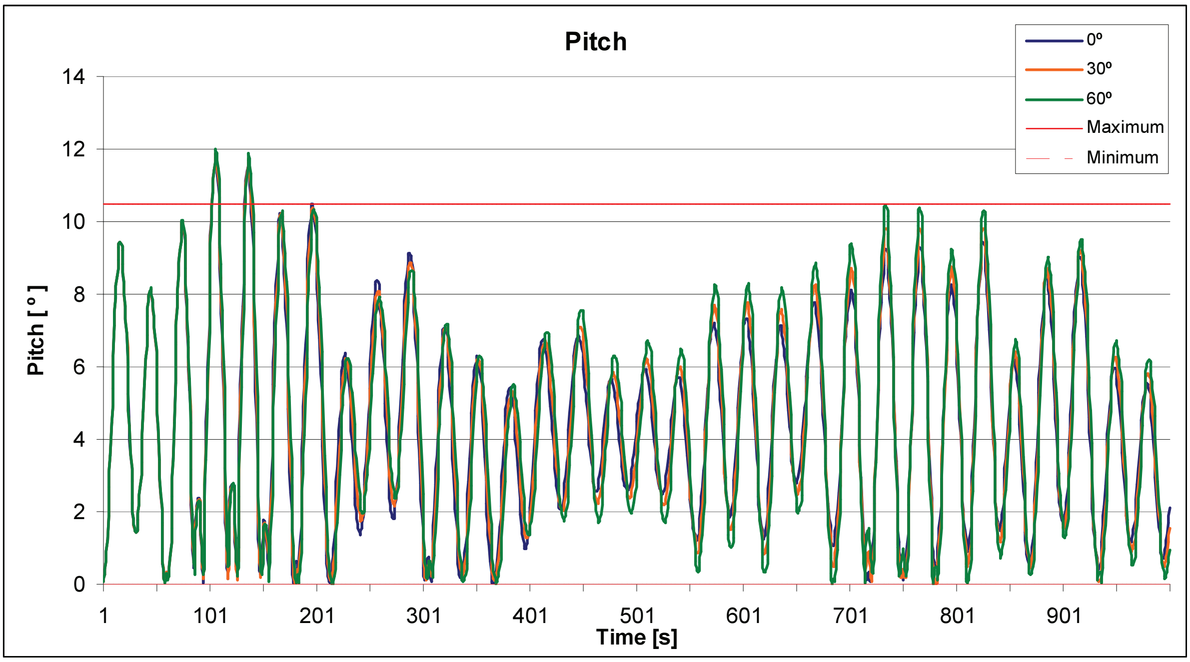


Figure 99: "Platform pitch for 10 m/s"

On figure 99 pitch shows that it is not influenced by mooring lines configurations due their relative low weight, being only useful on xy plane.

9.4 Service Limit State

6 Design cases and 1 survival case have been computed in order to see platform behavior in pitch, heave and surge.

Table 33: "Study Cases

Cases	Wind Condition	Waves		Wind and Wave Directionality	Sea Currents		Water Level
	V_{hub} (m/s)	NSS		MIS, wind direction change	NCM		MSL
		H_s (m)	T_p (sec)		$V_{Current}$	$\Theta_{Current}$	
Design loads	6	0,5	5	Θ_{Wind} +90°	0,6	Θ_{Wind} -90°	±0
	10	1,48	5,74				
	14	1,91	6,07				
	18	2,5	7				
	22	2,5	7				
	24	3,5	8				
Surviva l loads	42,3	10,8	12,44	Θ_{Wind} +90°	1,2	Θ_{Wind}-90°	+5,66

Mooring lines configuration used is the most unfavorable.

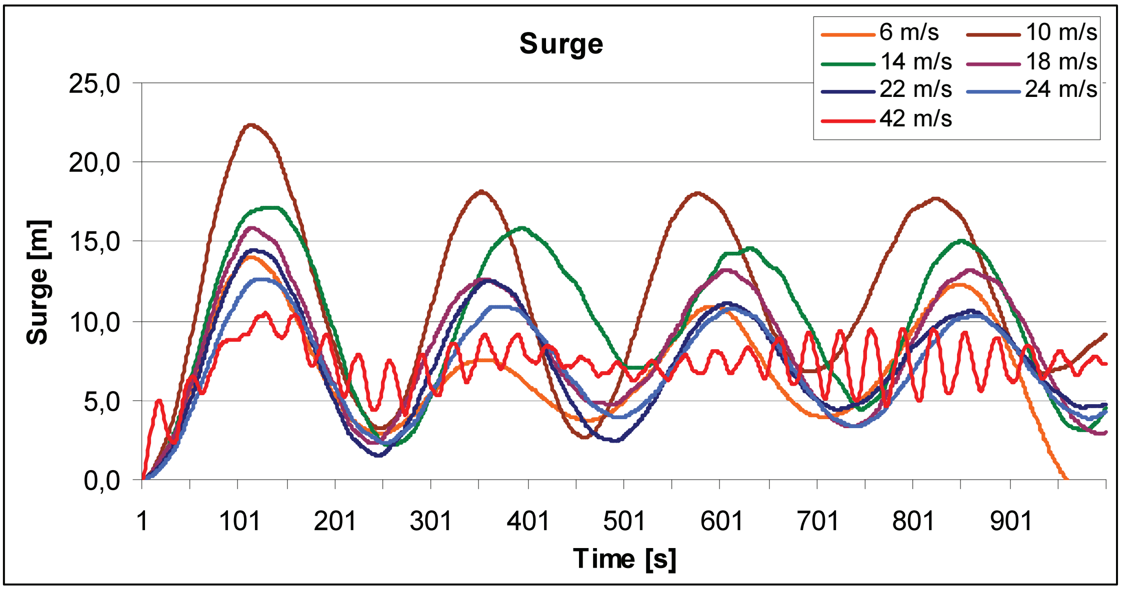


Figure 100: "Platform surge"

On surge, figure 100 it can be seen how the biggest surge is for 10 m/s wind speed which is consistent with the forces obtained in chapter 8 where it was observed that the maximum force generated by wind was for 10 m/s.
Also an excitation problem for survival case is seen.

It is easily to see the difference between the design load cases where the main load acting is wind and the survival one where wind turbine is not operative and its blades have a minimum resistance to wind, letting waves to be the main load. It is clear how wind and waves surge excitation periods are different.

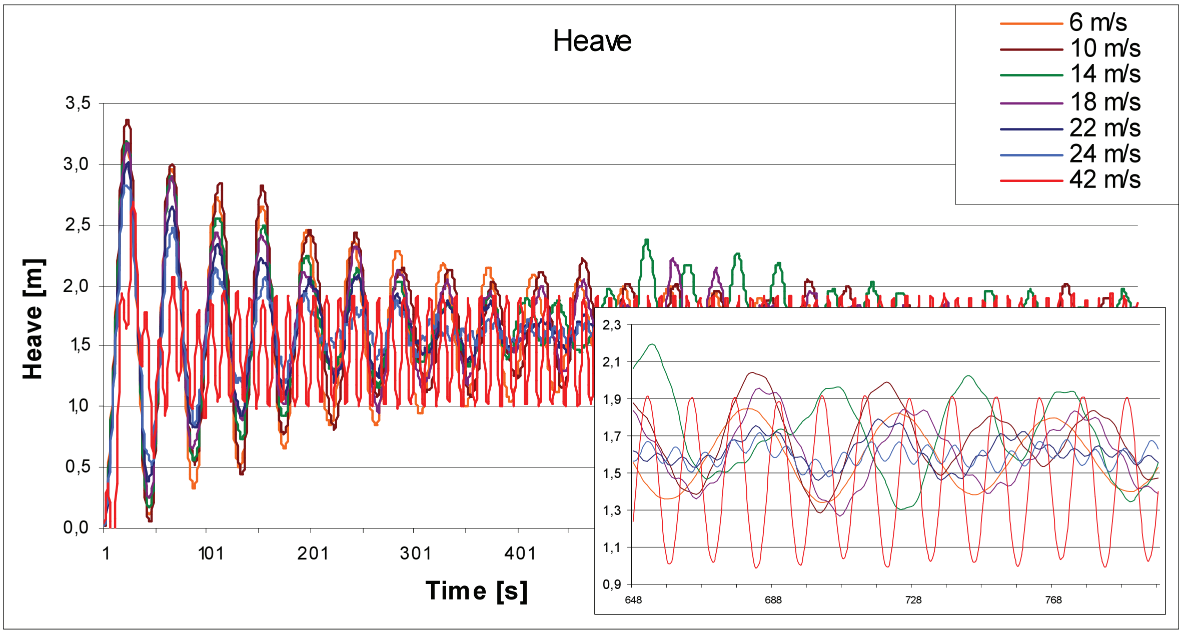


Figure 101: "Platform heave"

On heave, figure 101 for survival case, platform behavior is controlled by waves as in contrast with the design load cases where heave is controlled by wind loads. This wave induced movement important, the reason may be that natural platform excitation on heave is too close from the wave period for 42 m/s case. To solve it more damping needs to be added. A possible way would be adding damping plates around the external face of cylinder. This solution was adopted in Windfloat prototype see figure [20]. For design load cases no problems are appreciated.

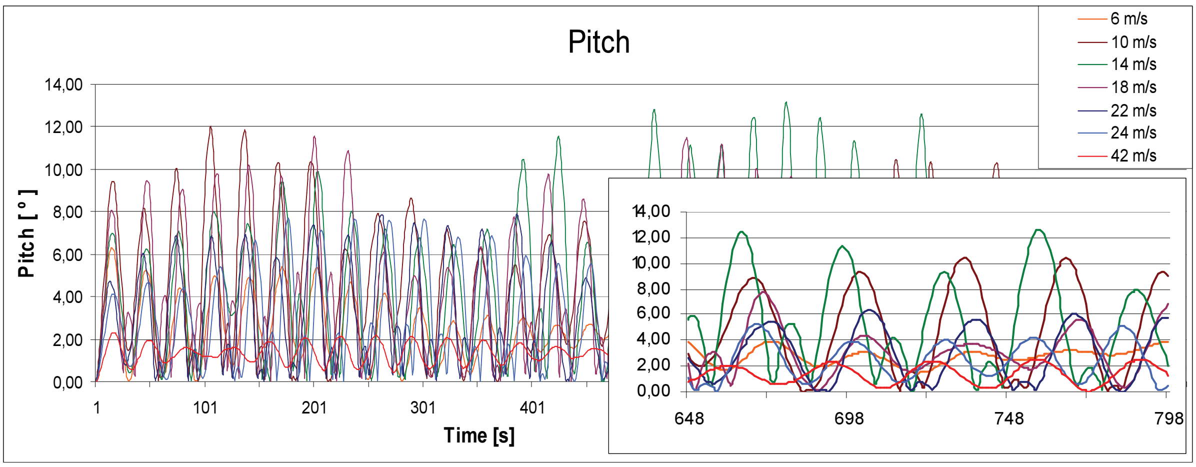


Figure 102: "Platform pitch"

On pitch, figure 103 shows how survival case is in this case the one which less excitation induce to platform. The reason is that wind force due to absence of an operative rotor, is much lower than in design load cases where maximum pitch angle condition specified in chapter 5 is largely exceeded.

9.5 Ultimate Limit State

Case for structural design will be the Ultimate limit state. The loads factors used will be the ones recommended in "*Guideline for offshore floating wind turbines structures*" Det Norske Veritas :

Table 34: "Load factors γ_f for the ULS and the ALS" [18]

Load factor set	Limit state	Load categories						
		G		Q		E		D
		Favourable Load	Unfavourable Load	Favourable Load	Unfavourable Load	Normal safety class	High safety class	
(a)	ULS	1.25		1.25		0.7	0.7	1.0
(b)	ULS	0.9	1.0	0.9	1.0	1.35	1.53	1.0
(c)	ULS for abnormal load cases	0.9	1.0	0.9	1.0	1.1	1.24	1.0
(d)	ALS	1.0		1.0		1.0	1.0	1.0
Load categories are: G = Permanent load Q = Variable functional load, normally relevant only for design against ship impacts and for local design of platforms E = Environmental load D = Deformation load								

It is considered that the case which creates the biggest moments over the structure is the one with the largest pitch angle because creates bigger restoring moments over the structure.

Load factor used has been the one for ULS and normal safety class, table 34 $\gamma_f=1,35$
Therefore the 14 m/s wind speed case is studied.

Shear Force

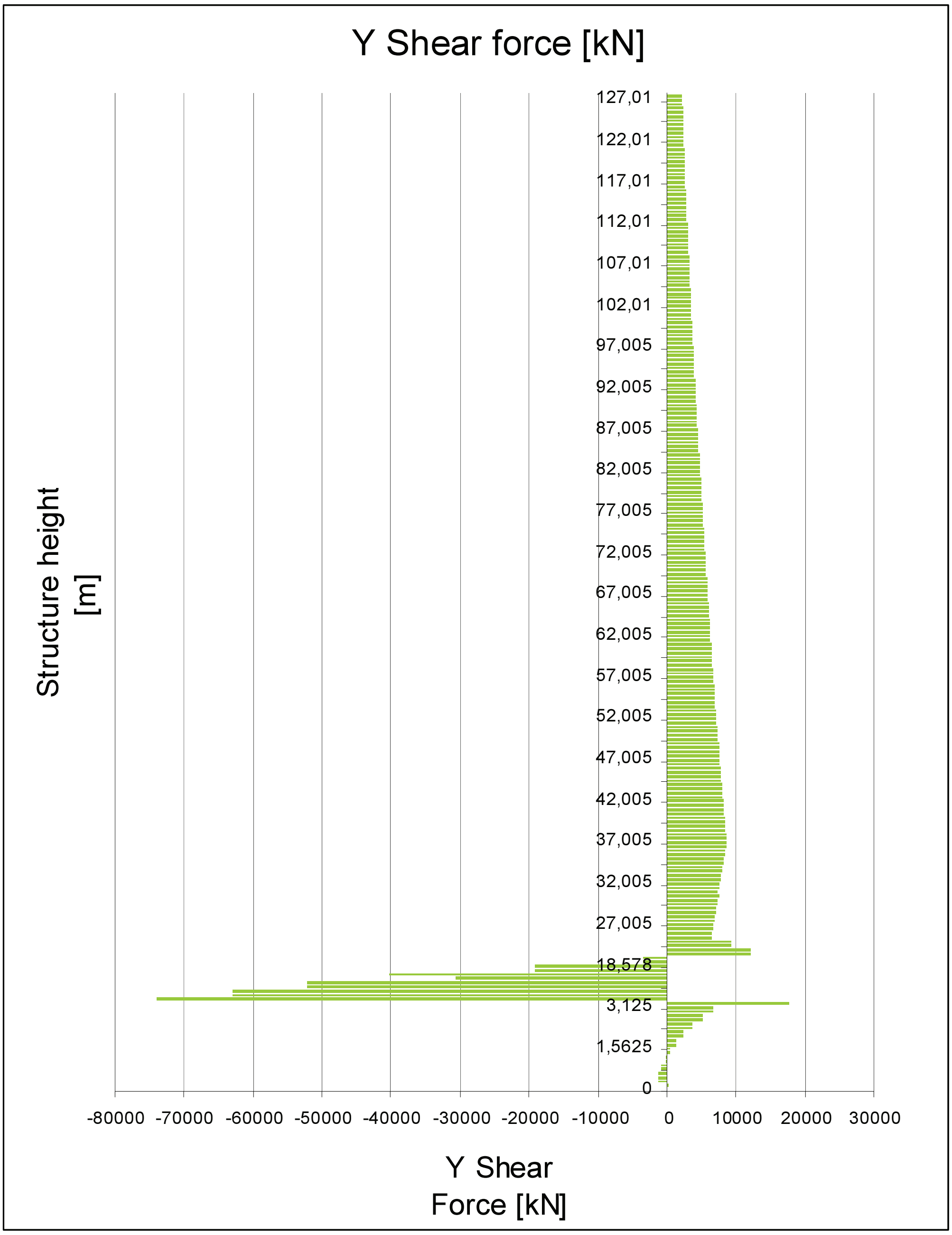


Figure 104: "Shear force"

Figure 104 shows how share force increases from tower top until arrive to cylinder (25 meters) on platform where due to a great concentrated mass (ballast) an abrupt change is observed. On this zone results are unrealistic and a 3D analysis should be used.

Bending Moment

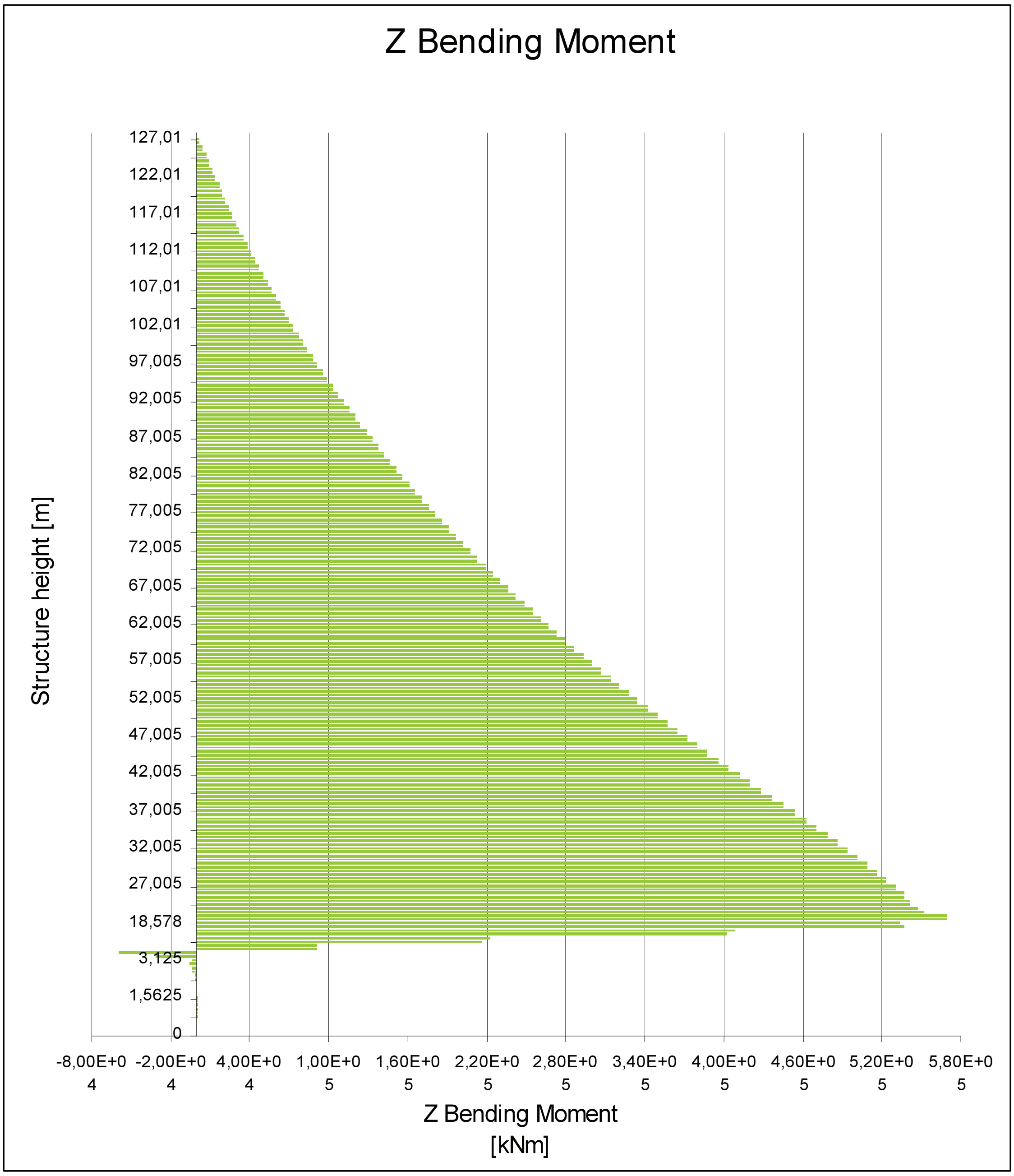


Figure 105: "Bending moment"

Bending moment, figure 105, over tower is caused by wind force over rotor and bole. This diagram shows a classical diagram showing combination of a distributed force (wind over bole) and a punctual moment on the cantilever beam extreme (wind over rotor).

Then diagram losses reliability when arrives to platform because of 3D effects and internal ballast which can not be described using 1D elements.

For correct platform efforts modeling 3D software should be used.

Results summary

From results can be observed how wind force over rotor creates the most critical displacements and moments.

Pitch
Pitch angle it is seen how that huge oscillation because the high wind speed variation and absence of rotor controller would induce important accelerations over rotor that may result unaffordable for existing wind turbines on market.

There are three reasons for this:

1. Wind speed modeled is not constant, therefore important variations along time see figure [103] change significantly the wind force over rotor amplifying oscillation.
2. Absence of a rotor controller: Floating wind platforms due pitch angle movements experiment variations over the incidence angle and velocity of wind over rotor. This dynamic effect creates an oscillatory movement that in absence of a controller over blades angle of attack can increase seriously pitch problems. Software used on this minor thesis to computing the structure behavior was no able to modeling it.
3. A dynamic modeling is used and therefore effects which weren't able to be modeled in the static analysis are here considered resulting in greater oscillation.

Surge
Relative to surge no problems are observed about accelerations or extreme displacements in design load cases. For survival cases excitation is observed but as wind turbine is not operating.

Heave
Main problems appear for survival case because the most important forces acting over it come from waves and heave excitation period is near the natural waves period.
Despite that for survival case the wind turbine wouldn't be operative, fatigue on their components materials and even in concrete could appear. Great safety factors should be used in the platform structural design.

Shear force
Results are reliable from tower top until the cylinder radius where due 3D effects unable to be modeled using 1D software and a concentrated in just one point ballast mass which is nearly 40% of the total structure mass, create significant unrepresentative results. From the reliable zone it is obtained the maximum shear force which is around 15000 kN.

Bending moment
Results as in shear force are reliable from tower top until de cylinder. From the reliable zone it can be concluded that the maximum bending moment has a value around 550000 kNm.

CHAPTER 10: CONCLUSIONS

After this analysis, the following conclusions about low draft ballasted platforms and the use of concrete as main material have been obtained:

- The use of concrete is feasible. Many marine structures have been built using this material. And the forces expected to act on the structure would are affordable with concrete after a good structural design.

- Concrete floating platforms offers more stiffness than the steel one due to their higher weight.

- For deeper drafts stability is improved. A specific market study should be done in order to fix the most optimal platform draft to use.

- The most disturbing load is wind over rotor, therefore the platform will suffer higher forces in operation than in survival conditions despite that the wave heights could be more than three times bigger than in operation cases.

- The most critical section is in the radius change section between platform tower bottom and the cylinder lid. A research using 3D modeling should be done there and in the entire platform to check the distribution of forces.

- Maximum tilting in pitch has been bigger than expected in predesign because of use of safety factors and absence of rotor controller. In a real prototype this angle would be smaller. More research should be done in this aspect.

- Problems with damping for frequencies close to survival case should be solved adding damping plates or changing platform geometry in order to move natural platform excitation period on heave further from natural wave periods.

- Influence of mooring lines on shallow waters is more difficult to model than in deep waters because mooring stiffness changes sharply due their short length. Software used for modeling was not able to accurately simulate such behavior because mooring lines had to be introduced as linear springs. More research on this field should be developed.

- It is necessary more research in floating platforms adapted to shallow waters, in order to develop accurate methods and software tools for a reliable modeling.

REFERENCES

[1] Global Wind Energy Council (GWEC) http://www.gwec.net/ Last retrieved June 4th, 2013

[2] "Renewable Global Status Report 2012" Renewable Energy Policy Network for the 21st Century http://www.ren21.net/REN21Activities/GlobalStatusReport.aspx Last retrieved, June 1st, 2013

[3] "Global Wind Statistics 2012 " Global Wind Energy Council (GWEC) (2013)

[4] International Energy Agency (IEA) http://www.iea.org/ Last retrieved June 4th, June 2013

[5] The European Wind Energy Association (EWEA) http://www.ewea.org/ Last retrieved April 24th 2013

[6] Jet Propulsion Laboratory, N.A.S.A http://www.jpl.nasa.gov/news/news.php?release=2008-128 Last retrieved November 18th, 2012

[7] "The European offshore wind industry, key trends and statistic 2012" European Wind Energy Agency (EWEA), 2013

[8] "U.S. Offshore Wind Market and Economic Analysis " U.S. Department of Energy & Navigant Consulting, 2013

[9] "The World of Wind Atlases" by Risø National Laboratory http://www.windatlas.dk/Europe/oceanmap.html, 1989

[10] "Der Spiegel Online" 2009
http://cdn2.spiegel.de/images/image-82451-galleryV9-mspj.jpg Last retrieved May 3rd, 2013

[11] "A Guide to an Offshore Wind Farm" The Crown Estate, 2011

[12] National Renewable Energy Laboratory (NREL), http://www.nrel.gov/gis/wind.html Last retrieved April 25th 2013

[13] "Energy Department to Underwrite 7 Wind Projects" J. Hurdle, The New York Times, December 2012

[14] "Renewable Energy World" J. Montgomery, http://www.renewableenergyworld.com/rea/news/article/2013/04/progress-report-seven-us-offshore-wind-demonstration-projects. April 29th, 2013

[15] "China: An Emerging Offshore Wind Development Hotspot" Qin Haiyan et al. World Wild Life, 2010

[16] “Floating Offshore Wind Foundations: Industry Consortia and Projects in the United States, Europe and Japan“ Main(e) International Consulting LLC, 2012

[17] “Fukushima Floating Offshore Wind Farm Demostration Project” T. Ishihara, The University of Tokyo 2011.

[18] “Guideline for offshore floating turbine structures”, Det Norske Veritas, 2009

[19] “Blue H” Blue H Technologies BV http://www.bluehgroup.com/ Last retrieved 4th June 2013

[20] Statoil, http://www.statoil.com/en/TechnologyInnovation/NewEnergy/RenewablePowerProduction/Offshore/Hywind/Pages/HywindPuttingWindPowerToTheTest.aspx. Last retrieved 1st March, 2012

[21] Sway, http://www.sway.no/?page=206 Last retrieved: 30 th April, 2013

[22] “WindFloat: A floating foundation for offshore wind turbines “ by Dominique Roddier et al. Journal of renewable and sustainable energy, 2010.

[23] “Principle Renewable Energy Delivered” http://www.principlepowerinc.com/products/windfloat.html Last retrieved 1st December, 2012

[24] United States Department of Energy, http://energy.gov/ Last retrieved 14th June 2013

[25] The University of Maine, http://umaine.edu/news/blog/2013/05/30/the-launch-of-volturnus-18/ Last retrieved 4th June, 2013

[26] 4Coffshore http://www.4coffshore.com/windfarms/kyushu-university-wind-lens-project---phase-1-japan-jp12.html Last retrieved 5th May 2013

[27] Poseidon Floating Power http://www.floatingpowerplant.com/?pageid=336 Last retrieved 20th May 2013

[28] Oil Rig Photos, http://www.oilrig-photos.com/ Last retrieved 12th March

[29] “Offshore Structures-A new challenge“ by Knut Sandvik et al. *XIV National Conference on Structural Engineering*, Acapulco, 2004

[30] “Establecimiento de comunidades autónomas en alta mar: opciones presentes y evolución futura“ by M. L. Pardo, Universidade Da Coruña, A Coruña, 2011.

[31] ELF, http://www.elf.com.pl/odyssee/us/dev/nkossa/index.htm, Last retrieved 26th November

[32] “Heidrun Tension Leg Platform”, E. Microsilica, 2000

[33] „Floating Breakwater Built in Algeciras for the Port of Monaco" by Juan Barceló Llauger et al. *Revista de Obras Públicas,* 2003

[34] "Concrete Construction Engineering Handbook" by E. G. Nawy, 1997

[35] "Design of Offshore Steel Structures, General (LRFD Method)" Det Norske Veritas, Oslo 2011

[36] "Design of steel structures" Lysaker, 2004

[37] "Estudio, caracterización y comparación de tipologías de plataformas para soporte de aerogeneradores en alta mar" Sara Ferreño González et al., 2011

[38] "Eurocode 2: Design of Concrete Structures", European Committee for Standarization, 2004

[39] "La Corrosión del Concreto en Ambiente Marino " by Miguel Cotera, *I Congreso Nacional de Ingeniería Estructural y Construcción*, Peru, 1998

[40] "Concrete in the Marine Environment" by P. Metha, Elsevier Science Pulishers, New York 1991

[41] "Investigación y recomendaciones para la construcción de cajones portuarios de hormigón armado " by Maria Pilar Alaejos Gutiérrez, Revista *Puertos*Nr. 45-57, 2006.

[42] "Maritime Structures - Part 1: Code of practice for general criteria - 6349 - 1" British Standards, 2000

[43] "Prestressed Concrete Design" by M. Hurst, Oxon, 2003.

[44] "Offshore concrete structures - C502" Det Norske Veritas, 2010

[45] "Durability design of concrete structures in severe environments" by O. E. Gjorv, Published by Taylor & Francis, New York, 2009

[46] Anchor Industries Inc, http://www.anchors.co.za/offshore-mooring-products.htm Last retrieved 2nd June 2013

[47] HEXICON http://www.hexicon.eu/ Last retrieved 14th May, 2013

[48] „Mapping the Future in Offshore Wind - Wind Turbine Installation Ships and Wind Farm Service Vessels" Germanischer Lloyd, 2010

[49] "Electric Arc Furnace Slag - a product not waste: saving or earning money by using slag as a building material" by D.J. Apfel, Badische Stahl-Engineering GmbH

[50] "Estudio del comportamiento de hormigones con áridos siderúrgicos de horno eléctrico" by J.C. Gallart, Universitat Politècnica de Catalunya, Barcelona, 2012

[51] "Waves in the Ocean" Florida Center for Instructional Technology, 2006

[52] Offshoremoorings.org http://www.offshoremoorings.org. Last Retrieved 21th June 2013

[53] “Floating Offshore Wind Turbine Installations. Guide for building and classing floating offshore wind turbine installation” American Bureau of Shipping (A.B.S), 2013

[54] “International Standard Wind Turbines Part 3: Design requirements for offshore wind turbines“ International Electrotechnical Commision (IEC), 2009.

[55] “Upwind Design Basis, WP4: Offshore Foundations ans Support Structures“ by T. Fischer et al. Project UpWind, Stuttgart 2010.

[56] American Wind Energy Association (AWEA) http://www.awea.org Last retrieved 10th March

[57] “Position Mooring - OS - E301“, Det Norske Veritas, 2010

[58] “Environmental Conditions and Environmental Loads - RP - C205“, Det Norske Veritas, 2010

[59] “Design of Offshore Wind Turbine Structures - DNV-OS-J101“, Det Norske Veritas, 2010

[60] “Guide for Building and Classing Bottom-Founded Offshore Wind Turbine Installations” American Bureau of Shipping, 2013.

[61] “Round 3 Zones: High-Level Risk Review of Physical Processes“ The Crown Estate, 2009

[62] “Offshore Hydromechanics” by W. Massie, Delf University of Technology, Delf, 2001.

[63] “Wind Energy and Solar Energy Resources Evaluation“ C.M. Administration, Beijing 2011

[64] “Responses of Floating Wind Turbines to Wind and Wave Excitation” by K. H. Lee, Massachusetts Institute of Technology, 2005.

[65] “Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine” by J. Jonkman, National Renewable Energy Laboratory, 2007.

[66] “Definition of a 5-MW Reference Wind Turbine for Offshore System Development“ by J.M. Jonkman et al. National Renewable Energy Laboratory, 2009

[67] ”Definition of the Floating System for Phase IV of OC3“ by J.Jonkman, National Renewable Energy Laboratoty, 2010

[68] “Model Development and Loads Analysis of a Wind Turbine on a Floating Offshore Tension Leg Platform” by J.Jonkman et al., National Renewable Energy Laboratoty, 2010

[69] “Definition of the Semisubmersible Floating System for Phase IV of OC3” by J.Jonkman, National Renewable Energy Laboratoty , 2012

[70] “Floating Offshore Wind Turbines for Shallow waters” B.H. Bulder et al., 2009

[71] “Directional Wave Data Recorded in the Southern North Sea “ by C.H. Clayson and J.A. Ewing, Institute of Oceanographic Sciences, Deacon Laboratory, Deacon, 1988

[72] “Handbook of Offshore Engineering” by S.K. Chakrabarti. Published by Elsevier, 2005

[73] “Dynamic Analysis of Offshore Floating Wind Turbines” by H. Bagbanci, Universidade Técnica de Lisboa, 2011

[74] “A Floating Wind Tower Is Launched in Maine” by M.L. Wald, The New York Times p. B3, 1 June 2013