İSTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

STRUCTURAL ANALYSIS OF OFFSHORE WIND TURBINE SUPPORT STRUCTURE UNDER HYDRODYNAMIC AND AERODYNAMIC LOADS

M.Sc. THESIS

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Offshore Engineering Programme

AUGUST 2019

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<u>ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ</u>

HİDRODİNAMİK VE AERODİNAMİK YÜKLERİN ALTINDAKİ RÜZGAR TÜRBİNİ DESTEK YAPISININ YAPISAL ANALİZİ

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FOREWORD

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August 2019 Murtala MUSA

Mechanical Engineer

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ABBREVIATIONS

OWT	: Offshore Wind Turbine
DNV	: Det Norske Veritas
NREL	: National Renewable Energy Laboratory
API	: American Petroleum Institute
MSL	: Mean Sea Level
OCS	: Offshore Continental Shelf
CFD	: Computational Fluid Dynamics
RotThrust	: Rotor Thrust
RNA	: Rotor Nacelle Assembly
LC 1	: Load case 1
LC 2	: Load Case 2
SS	: Support Structure

SYMBOLS

H	: Wave Height
T	: Wave Period
L	: Wave Length
K	: Wave Number
H	: Sea Depth
ρ_w	: Water density
ρ	: Air Density
a	: Induction Factor
A	: Swept Area of Rotor Blade
C_p	: Power Coefficient
P	: Power Extracted from Wind
V	: Mean Wind Speed
t	: time
U(t)	: Water Particle Velocity
$U_a(t)$	: Water Particle Acceleration
C_M	: Inertia Coefficient
C_D	: Drag Coefficient
ζ	: Wave Amplitude
ω	: Wave Angular Speed
Z	: Elevation
$F_{inertia}$	: Inertia Force
F_{Drag}	: Drag Force
Re	: Reynolds Number
Z_o	: Terrain Roughness
$V_{(T,Z)}$	: Basic Wind Speed
C	: Shape Coefficient
q	: Basic Wind Pressure
S	: Projected Area Normal to Wind
α	: Angle between wind and Member
K_t	: Terrain Factor
σ_v	: Von Mises stress
σ_y	: Yield Strength
σ_1	: Principal Stress in x Direction
σ_2	: Principal Stress in y Direction
σ_3	: Principal Stress in x Direction
F_T	: Thrust Force
C_T	: Thrust Coefficient

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STRUCTURAL ANALYSIS OF OFFSHORE WIND TURBINE SUPPORT STRUCTURE UNDER HYDRODYNAMIC AND AERODYNAMIC LOADS

SUMMARY

We live in a changing world, and the world energy demands changes with it. The increase in population and a greater environmental awareness means engineers has to produce more energy than ever and more sustainably. This has led engineers to find alternatives to meet those demands. Ultimately it is technology that will make the difference. Wind energy engineering is among the forefront of making this change happen. Today, offshore engineers set out to move some the onshore wind turbine offshore in other to increase effectiveness of wind turbines. To do that, engineers are integrating new technology into existing fleet to give them access to a higher performance.

Engineers believe wind technology will change the future phase of world energy demand for the benefit of all. Wind energy is already a proven technology, it has shown lots promise and potential over the years. According to a press release from world wind energy association energy (WWEA), "The total capacity wind turbines installed around the world at the end of 2018 will get to almost 600 GW, as shown by statistics published by WWEA. About 54,000 Megawatt were integrated to the commercial grid in the year 2018, which is relatively more than what is expected in the year 2017 when about 52'552 Megawatt were constructed. Similarly, in 2018 the growth has continued to increase, there are new installations although, it's at a lower rate of about 9.8 %, after 10.8% growth the previous year. As pointed out by data, wind turbines constructed by end of 2018 can reach up to 7% of worldwide electric power demand" (Gsänger, 2019).

Due to the dynamic complication of offshore wind turbine OWT and their subjection to various internal and external loading, offshore wind turbine is especially constantly subjected to environmental loadings especially aerodynamic and hydrodynamic loads. Therefore, the environmental load is an important design criterion that should be considered during the design of support structure of OWT.

Due to the dynamic complication of offshore wind turbine (OWT) and their subjection to various internal and external loading, OWT are especially constantly subjected to environmental loadings especially aerodynamic and hydrodynamic loads. Therefore, the environmental load is an important design criterion that should be considered during the design of support structure of OWT.

In this research, the main objective is to investigate the response and influence of various environmental loads subjected on the support structure of offshore wind turbine under extreme aerodynamic and hydrodynamic load. In order to do this, it is very important to

analyze the unstable aerodynamic wind as well as the hydrodynamic wave that is subjected on the offshore wind turbine (OWT) support structure.

The first chapter of the thesis give the introduction about OWT in general, the benefit of offshore wind turbine, the type support structure in the OWT industry. It went further to give literature review of past research done other researchers in similar field.

National renewable energy laboratory (NREL) wind turbine is selcted for the research, and the second chapter presents the specification of the NREL 5MW wind turbine and the monopile. Furthermore, the chapter presents the scope and limitations of the thesis necessary assumptions are made in order to simplify the problem for instance the soil monopile interaction is neglected and it is assumed the monopile has a static fixed support at the sea bed.

In chapter 3, necessary theoretical background related to the problem of the thesis is presented and it is followed by calculations of the loads. To make the calculations more reliable, renowned recommended standard practices are used to calculate the aerodynamic and hydrodynamic loads. One of the standards used in this thesis is the American petroleum institute (API) standard, it is applied in the calculations for the wave loads. Recommended practice by Det Norske Veritas (DNV) is used for the wind load calculations on the tower while the rotor thrust load calculations is as giving by the NREL 5MW wind turbine. However, an alternative rotor theory solution was given for calculating the rotor thrust.

In chapter 4 the loads calculated in the previous chapter and constrains on the support structure are defined and it is set up on the support structure model. Using finite element analysis software ANSYS APDL the calculations of the response of the support structure is carried out. Load cases is assumed (Load case 1 & Load case 2) in order to see the response of the support structure under a maximum worst-case scenario. Afterwards, results of the simulations are presented and analyzed. Two main areas are looked at, the displacement of the support structure and the stresses field in the support structure. From the results, it is evident the load case 1 create higher displacement of the support structure. The maximum displacement for the load case 1 is about 0.97m however, when the application is change to load case 2, the max displacement decreases by 11.9%. On the other hand, the Von Mises stress remain the same for both load cases which is about 0.131E+09pa (131Mpa). This means the change of wave load direction has no effect on the Von Mises stress. From the result of the Von Mises stress it is evident the Von Mises stress are higher at the tower when compared to the monopile. This means that failure will begin at tower before the monopile when the load is increased. Therefore, in order to reduce the stresses in the tower two alternative solutions are proposed.

1. Increase in the thickness of the tower will reduce the stresses in the tower. however, this will come with economical expenses and should be done in a logical way
2. Decrease the tower height. This will reduce the overall aerodynamic load on the wind turbine consequently it will reduce stresses on the tower. However, there's a drawback to this, the wind power extracted by the wind turbine will compromised since lower altitude means low wind speed.

HİDRODİNAMİK VE AERODİNAMİK YÜKLERİN ALTINDAKİ RÜZGAR TÜRBİNİ DESTEK YAPISININ YAPISAL ANALİZİ

ÖZET

Değişen bir dünyada yaşıyoruz ve bununla birlikte dünya enerji talepleri de değişiyor. Nüfustaki artış ve daha fazla çevre bilinci, mühendislerin her zamankinden daha fazla enerji üretmeleri gerektiği anlamına geliyor. Bu, mühendisleri bu talepleri karşılamak için alternatifler bulmaya yönlendirdi. Sonunda fark yaratacak teknolojidir. Rüzgar enerjisi mühendisliği, bu değişikliklerin gerçekleştirilmesinde ön plandadır. Bugün açık deniz mühendisleri, rüzgar türbinlerinin etkinliğini artırmak için bazı kıyı rüzgar türbinlerini açık denizde hareket ettirmeye karar verdiler. Bunu yapmak için, mühendisler daha yüksek performansa erişebilmeleri için yeni teknolojiyi mevcut filoya dahil ediyorlar.

Mühendisler, rüzgar teknolojisinin, herkesin yararına olacak şekilde dünya enerji talebinin gelecekteki aşamasını değiştireceğine inanıyor. Rüzgar enerjisi zaten kanıtlanmış bir teknolojidir, yıllar boyunca pek çok umut ve potansiyel göstermiştir. Dünya rüzgar enerjisi birliği enerjisinden (WWEA) yapılan bir basın bültenine göre, “2018 sonunda dünyaya kurulan toplam kapasite rüzgar türbinleri, WWEA tarafından yayınlanan istatistiklerle gösterildiği gibi yaklaşık 600 GW'a ulaşacak. 2018 yılında ticari şebekeye yaklaşık 54.000 Megawatt entegre edildi; bu, 2017 yılında, 52.555 Megawatt inşa edildiğinde beklenenden daha fazladır. Benzer şekilde, 2018'de büyüme artmaya devam etti, ancak yeni tesisler var, ancak önceki yıla göre %10,8 artıştan sonra yaklaşık %9,8 daha düşük bir oranda. Verilerin belirttiği gibi, 2018'in sonunda inşa edilen rüzgar türbinleri dünya elektrik enerjisi talebinin %7'sine ulaşabiliyor” (Gsänger, 2019).

OWT'nin dinamik komplikasyonları ve çeşitli iç ve dış yüklemelere maruz kalmaları nedeniyle, OWT özellikle sürekli olarak özellikle aerodinamik ve hidrodinamik yüklerde çevresel yüklere maruz kalır. Bu nedenle, çevresel yük OWT'nin destek yapısının tasarımında göz önünde bulundurulması gereken önemli bir tasarım kriteridir.

Açık deniz rüzgar türbininin (OWT) dinamik komplikasyonları ve çeşitli iç ve dış yüklemelere maruz kalmaları nedeniyle, açık deniz rüzgar türbinleri özellikle sürekli olarak özellikle aerodinamik ve hidrodinamik yüklerde çevresel yüklere maruz kalmaktadır. Bu nedenle, çevresel yük, açık deniz rüzgar türbininin destek yapısının tasarımında göz önünde bulundurulması gereken önemli bir tasarım kriteridir.

Bu araştırmada asıl amaç, aşırı aerodinamik ve hidrodinamik yükler altında açık deniz rüzgar türbininin destek yapısına maruz kalan çeşitli çevresel yüklerin tepkisini ve etkisini

araştırmaktır. Bunu yapmak için, dengesiz aerodinamik rüzgarın yanı sıra açık deniz rüzgar türbini destek yapısına maruz kalan hidrodinamik dalgayı analiz etmek çok önemlidir. Tezin ilk bölümü, genel olarak OWT hakkında, OWT endüstrisinde tip destek yapısı olan OWT'nin yararına giriş niteliğindedir. Benzer alandaki diğer araştırmacılar tarafından yapılan geçmiş araştırmaların literatür taramasının yapılması daha da ileri gitti.

Ulusal yenilenebilir enerji laboratuarı (NREL) rüzgar türbini bu araştırma için seçildi ve ikinci bölüm NREL 5MW rüzgar türbini ve tekel özelliklerini açıkladı. Ayrıca, bölüm, tezin kapsamını ve sınırlamalarını sunmaktadır, örneğin toprağı monopile etkileşiminin ihmal edildiği ve monopilin deniz yatağında statik bir sabit desteğe sahip olduğu varsayıldığı için sorunu basitleştirmek için gerekli varsayımlar yapılmıştır.

Bölüm 3'te, tez problemiyle ilgili gerekli teorik arka plan sunulmuş ve yüklerin hesaplamaları takip edilmiştir. Hesaplamaları daha güvenilir yapmak için, aerodinamik ve hidrodinamik yükleri hesaplamak için bilinen standart uygulamalar kullanılır. Bu tezde kullanılan standartlardan biri Amerikan petrol enstitüsü (API) standardı olup, dalga yükü hesaplamalarında uygulanmaktadır. Det Norske Veritas (DNV) tarafından önerilen uygulama kuledeki rüzgar yükü hesaplamaları için kullanılırken rotor itme yükü hesaplamaları NREL 5MW rüzgar türbini tarafından yapılır. Bununla birlikte, rotor itişini hesaplamak için alternatif bir rotor teorisi çözümü verilmiştir.

4. bölümde, önceki bölümde hesaplanan yükler ve destek yapısındaki kısıtlamalar tanımlanmış ve destek yapı modelinde düzenlenmiştir. Sonlu elemanlar analizi yazılımı ANSYS APDL kullanılarak, destek yapısının tepkisi hesaplamaları yapılır. Destek yapısının azami en kötü durum senaryosunda yanıtını görmek için yük durumları varsayılır (Yük durumu 1 ve Yük durumu 2).

Daha sonra simülasyonların sonuçları sunuldu ve analiz edildi. Destek yapısının yer değiştirmesi ve destek yapısındaki gerilmeler alanı olmak üzere iki ana alana bakılır. Sonuçlardan, yük durumu 1'in destek yapısının daha yüksek yer değiştirmesi yarattığı açıktır. Yük kasası 1 için azami yer değiştirme yaklaşık 0,97 m'dir, ancak uygulama yük kasası 2'ye geçtiğinde, azami yer değiştirme %11,9 azalır. Öte yandan, Von Mises stresi, yaklaşık 0.131E + 09pa (131Mpa) olan her iki yük durumu için aynı kalır. Bu, dalga yükü yönündeki değişimin Von Mises stresini etkilemediği anlamına gelir. Sonunda, kuledeki gerilmeleri azaltmak için iki alternatif öneride bulunulmuştur

Von Mises stresi arsalarından, Von Mises stresi kulede monopile kıyasla daha yüksek olduğu açıktır. Bu, yük arttıkça başarısızlığın tekelden önce kulede başlayacağı anlamına gelir. Bu nedenle, kuledeki gerilimleri azaltmak için iki alternatif çözüm önerilmiştir.

1. Kulenin kalınlığındaki artış, kuledeki gerilmeleri azaltacaktır. Ancak, bu ekonomik giderler ile gelecek ve mantıklı bir şekilde yapılması gereken

2. Kule yüksekliğini azaltın. Bu rüzgar türbini üzerindeki genel aerodinamik yükü azaltacaktır, dolayısıyla kule üzerindeki baskıları azaltacaktır. Ancak, bunun bir dezavantajı var, rüzgar türbininin çıkardığı rüzgar gücü düşük irtifa düşük rüzgar hızı anlamına geldiğinden tehlikeye girer.

1 INTRODUCTION

1.1 Overview of Offshore Wind Turbine (OWT)

We live in a changing world, and the world energy demands changes with it. The increase in population and a greater environmental awareness means engineers has to produce more energy than ever and more sustainably. This has led engineers to find alternatives to meet those demands. Ultimately it is technology that will make the difference. Wind energy engineering is among the forefront of making this change happen. Today, offshore engineers set out to move some the onshore wind turbine offshore in other to increase effectiveness of wind turbine. To do that, engineers are integrating new technology into existing fleet to give them access to a higher performance.

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Due to the dynamic complication of OWT and their subjection to various internal and external loading, OWT are especially constantly subjected to environmental loadings especially aerodynamic and hydrodynamic loads. Therefore, the environmental load is an important design criterion that should be considered during the design of support structure of OWT.

The main objective of this thesis is to investigate the response and influence of various load subjected on monopile supported OWT under extreme aerodynamic and hydrodynamic load. In order to do this, it is very important to analyze the unstable aerodynamic wind as well as the hydrodynamic wave that is subjected on the offshore wind turbine (OWT) support structure. To be precise, the support structure comprises of the monopile, transition unit and the tower. Most of the support structure for OWT are monopiles. Monopile are by far the most common support structure foundation used for OWT today. In this thesis, the support structure of standard NREL 5Mw wind turbine will be investigated and analyze to see its response under extreme environmental loading of wave, wind and internal dead load.

So, to do this, meteorological data for a proposed location will be taken from Meteorological Service. Wave data (period, height) and wind data are collected and using relevant standards, the hydrodynamic and aerodynamic loads are calculated. Individual environmental loads will be calculated separately and its coupled effect on the support structure will be investigated using ANSYS CAD Software

1.2 Benefits of Offshore Wind Energy

Even though offshore wind farms can sometime be expensive, but not only that it might be difficult to build and maintain as well, there are number of benefits which are associated with the development of offshore wind farms. For instance, the wind speeds at offshore farm locations are evidently faster and more effective as compared to onshore wind turbine, thus, improving energy output at these locations. Some of the advantages of offshore wind turbine are listed below.

- The wind speed offshore is considerably faster than on land. Consequently, Small increases in wind speed gives large increases in energy harvested in that in that location: a turbine in a 15-mph wind can generate twice as much energy as a turbine in a 12-mph wind.

- The wind speed offshore tends to be steadier than onshore. This means offshore wind turbine is more reliable energy source and more consistent than onshore turbine.
- Because population of coastal regions are high, construction of offshore wind turbine gives an opportunity tap energy from nearby source. Thus, enabling government to meet up with the energy demands of the rejoin.
- Just like onshore wind turbine offshore wind turbine has some similar benefits just as the onshore wind turbine. They (OWT) do not emit co_2 like conventional energy sauces. Moreover, wind energy is free therefore making OWT a cheap source of energy. In addition, construction of OWT creates more jobs.

1.3 Types of Offshore Wind Turbine Support Structure

In the construction of offshore wind turbine, there are various type of support structure that can be employed to support the turbines over the sea water level. Usually, the support structure chosen depends on the sea depth as well as the geological property of the sea bed. The main goal of the support structure is to carry turbine above sea so it'll exploit the potential of wind in an open sea. The foundation also give stability against various environmental loads acting in the sea. However, the installation of offshore wind farms foundation isn't an easy task. One of the biggest problems lies in installation of the support structure and elevating wind turbines and substations above the sea level and anchoring them to the sea bed. The types of support structure available will be presented in this section. The offshore wind turbine support structure is classified into two, the **bottom fixed** and the **floating** structures.

1.3.1 Bottom fixed support structures

The bottom fixed foundations as the name implies are foundations which are fixed to the sea bed and has a very little or no movement at all. They are common design for shallow water regions usually with depth less than 50 meters, this is the most common available and it is already in use in various OWT farms around the world. There are four common types of the bottom fixed foundation.

- **Gravity based support structure:** This type of foundation creates stability to the turbine by simply placing it on the sea bed. As a result, this foundation structure doesn’t penetrate the sea bed. Usually weight is added to give stability, the additional weight for the stability usually comes in the form boulders, sand or some heavy steel. This type of foundation is usually applicable for sea depth less than 15m. Note that the gravity-based foundation needs a flat and a stable sea bed and it is only practical in very shallow waters. (Dolores & Vicente, 2019).
- **Monopile support structure:** This foundation type is a long tubular steel structure with a huge diameter. Unlike the gravity-based foundations monopoles penetrates the sea bed to create stability, it is hammered into the seabed by some special hammer or vibrator. This type of foundation is well suited for sea depth ranging between 0-30m. Monopiles are the most common foundation type, this is however because of the fact that they are easy to manufacture and install, at the moment they make up to 70% of all installed OWT support structures. Some monopiles under development for the future turbines is believed to be up to 10m in diameters. In this thesis the structural analysis will carried out using monopile foundation. Figure 1 shows a good example of a monopile.

- **Tripods:** This offshore foundation type consist of a vertical tube at the center, connected to three wide legs that extends to the seabed. The legs just usually small in diameter compared to monopiles are driven into the sea bed to give it more stability. This kind of turbine used in water depth ranging between 0-50m. The large base is necessary to give a stable leg that is able to manage with huge bending moments. At the moment about 6% of OWT are installed using tripod structure (Fred , 2013).

- **Jacket structure:** This foundation structures considered to be suited in water depth between 20-60m. The minimum depth applied is about 4m at the South Korean OWT farm Tamra, the maximum operational depth ever achieved with this structure is 45m on the Beatrice OWT project located in the UK. Just like the tripods the legs are piled into the sea bed to give it optimum stability for the structure (Fred , 2013). This structure is shown in the figure 1.1 below

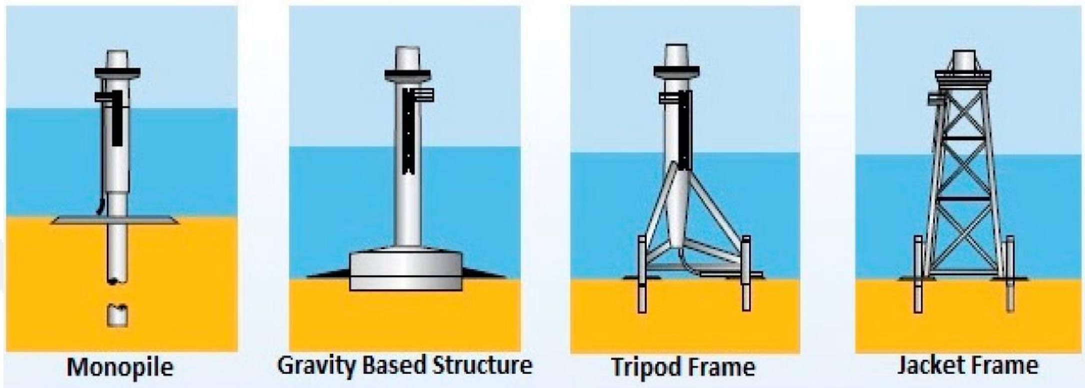


Figure 1.1: Bottom fixed OWT support structure. (Jorge, 2019).

1.3.2 Floating support structures

The floating foundation as the name implied is floating in the sea. This foundation is feasible when bottom fixed foundation is not applicable or economical. This is OWT support structure are design for water depth up to **80m**. The floating OWT support are at the moment under operation in Europe specifically wind farms in the UK, though, they are still under research and development stage. Some of the types of this support structure are listed below.

- **Spar-Buoy:** this foundation type is a slender, steel cylindrical buoy which floats in an upright manner. The center of gravity of this type of support structure is controlled by ballasting the buoy. Mooring cables are used to control and secure the turbine. The first practical display of this structure in a MW scale is presented in 2009 by the company Hywind. See figure 1.2 below
- **Semi-Submersibles structure:** This type of foundation is a bit submerged structures and has a wide base in order to give stability for the whole OWT. The support structure is kept in place by means of a mooring line. However, the mooring line are in a loose form.

- **Tension Leg Platform (TLP):** This support structure is moored vertically unlike the spar-buoy and the semi-submersibles. The mooring lines is tensioned vertically as seen in the figure 1.2 below and it is anchored to the sea bed. Usually, the support structure is design to have high buoyancy which is almost 4 times the weight of the platform. This support structure is still in research phase and currently there is no operational offshore wind farm using support structure

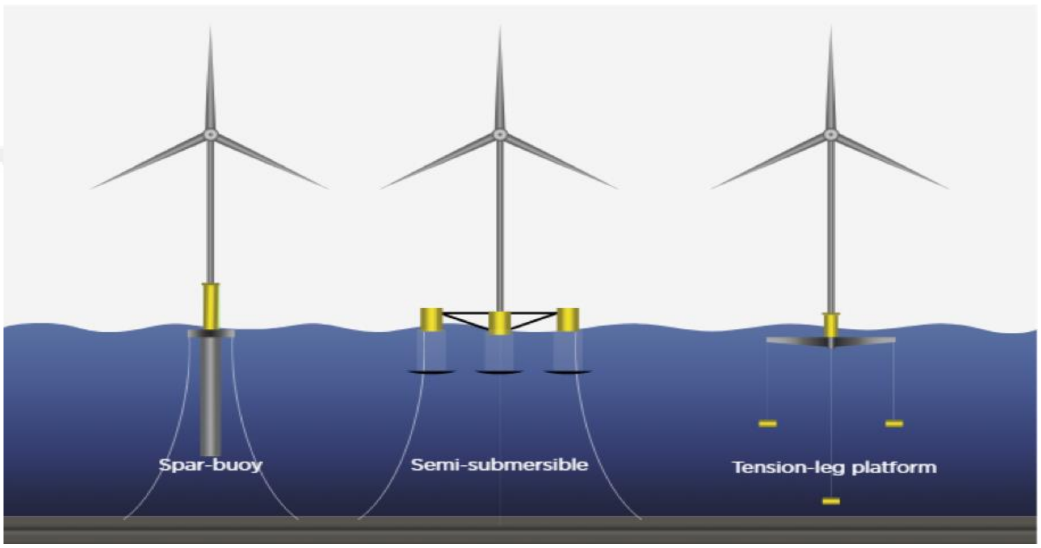


Figure 1.2: A depiction of floating foundations. (agci.org, 2019).

1.4 Literature Review

In order to design OWT, an engineer need to t comprehend he environmental loads which are subjected on the overall system. This section will go through various research carried out by some scientist and engineers in the past. Some of the research include the wind, wave, tidal current, as well as ice loading.

Morisons et al. formulated the famous Morison equation that is still used today to estimate wave forces exerted on piles. Morison's equation can be used to estimate hydrodynamic wave load on individual cylindrical pile. Back in the days, the equation had only been given in the form of horizontal wave force; after sometimes, it was rewritten in form of force which is normal to the axis of the pile structure (Morison, Johnson, & O'Brien, 1950, pp. 149-154). A research by Wanli Yang and Qiao Li presented that the typical Morison equation is limited as it unable to estimate dynamic pressure exerted by the wave on inner surface of hollow pile tubes. Consequently, they derived another version of Morison equation, which is applicable for such a problem of hydrodynamic pressure resulting from inner water and outer water (Wanli & Qiao , 2012, p. 79).

Paolo Boccotti estimated the Wave Forces on 3D lattice support structure, he formulated new technique of optimizing the Morison equation, and it is evident from his two recent experiments on wave forces on horizontal submerged cylinders as well as truncated vertical cylinders (Paolo, 2014, pp. 227-243). In the University of Hawaii, Zhida Yuan and Zhenhua Huang estimated the hydrodynamic coefficients for transverse force on oscillating cylinder moving in still water. Zhida Yuan and Zhenhua Huang believes estimating of the transverse force is very important for design of support structure of marine structures especially in the oil and gas industry. In their results, they conclude that, the transverse force subjected on an oscillating cylinder is directly proportional related to the wakes shedding behind cylinder. This is true in relating to past research which shows that repeated vortex pattern can occur depending on the amplitude of the flow. (Zhida & Zhenhua , 2015, pp. 111–117)

To increase the accuracy of calculation of wave forces, Zhang and Paterson investigated forces of on offshore platform. They utilize computational fluid dynamics and Morison equation in the process. In their initial phase of the study, they focused on applying of Morison's equations to estimate the forces the three-dimensional platform. And later on, they utilize CFD to compute the forces and empirical coefficients. Moreover, they utilize 3D RANS to simulate the wind turbine platform in regular sinusoidal waves. In conclusion Simulation results from full 3D simulation will be compared to the results from Morison's equation (Zhang, D. & Paterson, E., 2015, pp. 39-56). In technical university Hamburg, Israa Al-Esbe, investigated in her dissertation, the combined hydrodynamic and aerodynamic loads on OWT. Israa's goal is to estimate the response of fixed OWT support structure under coupled hydrodynamic and aerodynamic load. The investigation was done on standard NREL 5MW wind turbine as reference turbine. In the course of Israas research various types wind turbine support structure is investigated. These are: monopile, tripod and jacket (Israa , 2016, p. 1).

1.5 Background and Motivation

The inspiration behind this thesis is based on the fact there is need for more reliable load estimation in order to design an economically feasible and sustainable support structures for OWT's. Wave and wind loads is one of the most important criteria for the design of support structure of OWT. The fact is that support structure is one of the major components that contributes to the overall cost of an OWT, therefore, it is very vital to optimize the design of the support structure with regards to the various environmental loads subjected on the turbine.

In addition, the OWT industry has gradually increase size of turbine and consequently, moving into deeper waters for high efficiency. The increase of energy demand lead to the trend of increased in sizes of turbines. Therefore, there is huge economic benefit for enlarging the sizes of the OWT capacity, this is especially if the production and installation costs is reduced. This development has led engineers to focus more on the accuracy of the design loads. However, there is a drawback to large turbine, the bigger the turbines, the bigger the mass on top of the tower and will transmit into the support structure. This will as a result increase the size of the support structure therefore, more load due to wave wind (Trøen L, 2016, p. 3).

1.6 Problem Formulation and Objective

Environmental loads play vital role in the performance of offshore wind turbine (OWT) structural stability. To understand the complexity of the structural stability, it is vital to analyze the unstable hydrodynamic wave and aerodynamic wind loads on the offshore wind turbine (OWT) support structure. The support structure comprises of the monopile, transition unit and the tower. The main objective of this thesis it to analyze the response of NREL 5mw turbine under effect of some certain environmental loading. The support structure chosen for the analysis is the monopile foundation.

Estimating the hydrodynamic wave and aerodynamic wind loads on support structure is necessary because it reduce the risk that might arise from failure due to poor design of the machine, and moreover, it reduces the cost of manufacturing, development, maintenance of the machine as well as to increase a better performance of the OWT. Usually, oil and gas industries are the pioneers in the design of offshore structures, oil and gas industries has design platforms in deep waters and they seem to perform very well without problems. In this thesis, such methods used by the oil and gas industries will be used to predict wave and wind loads on OWT support structure. The main objective of the thesis is listed below and is depicted in the flow chart of figure 1.3 below

- In this research the load of hydrodynamic wave with extreme characteristics is calculated using API standard rules for environmental load on structure.
- Aerodynamic loads due to wind drag on the tower and thrust on the rotor blade are calculated using theoretical formulations and DNV standard rules available.
- In addition, a structural analysis will be carried out on the support structure of the turbine using ANSYS. And the main target of the structural analysis is to find the bending moment, shear stress and analyze the von misses stress response due to the hydrodynamic and aerodynamic loads on the turbine support structure. Below is flow chart giving the detail of the report.

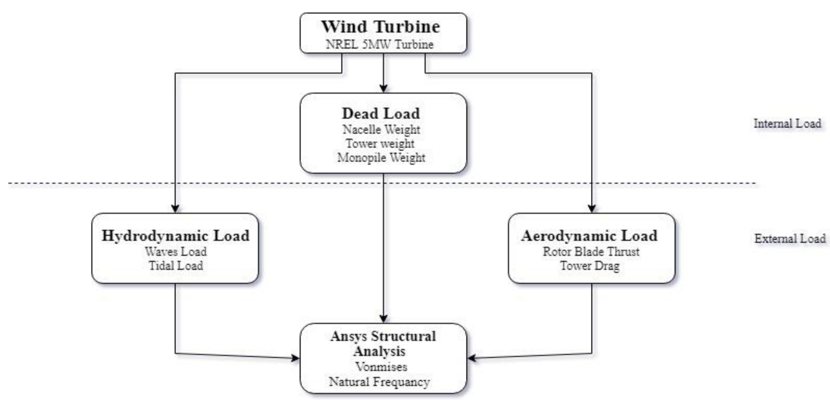


Figure 1.3: Flow chart showing the main objective of the thesis.

1.7 Structure of the Report

The subsequent chapters in this thesis, it is organized as follows. The scope and limitation of the thesis is presented in Chapter 2. The subsequent section defines the model as well as the dimensions of offshore wind turbine chosen for the thesis research. In addition, the chapter will also define offshore wind turbine terms that will be used throughout this thesis. Chapter 3 introduce the relevant theoretical background information required to comprehend the thesis. This include hydrodynamic wave theories and wave load formulations additionally, in the same chapter aerodynamics loads theory will be presented. In Chapter 4, calculation of hydrodynamic and aerodynamic load is presented. This calculation will be based on the theoretical background given in Chapter 3. The subsequent chapter 5 will give the numerical simulation using ANSYS workbench for structural analysis. And in chapter 6, the numerical results will be compared with the theoretical calculations made in chapter 4. This is followed by conclusions on the results obtained as well as suggestions future studies.

2 SCOPE AND LIMITATION

2.1 Overview

This chapter will present the scope and limitation as well as the terminologies that will be used throughout this thesis. It is important to clarify the terminologies because some of the terminologies in offshore wind turbine ((OWT) differs in literature. In addition it will present the limitations and the reference dimension for the selected turbine.

2.2 System Definitions and Terminology

The terms that will be used often in this thesis is shown in the figure 2.1 below. The Figure 2.1 depicts image of an OWT along with the parameters relevant to the study of the total system load which is important for many design estimation

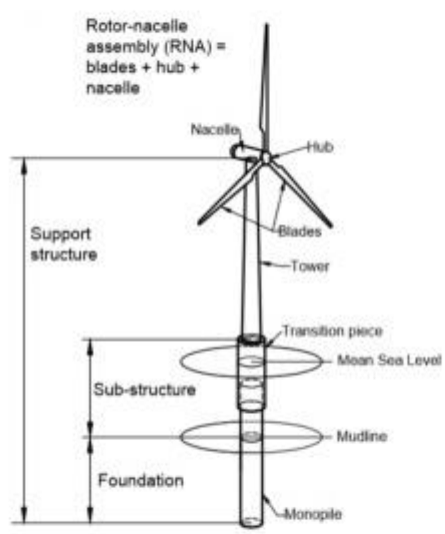


Figure 2.1: OWT Components terminology. (Laszlo & John , 2016).

The image shows various component that makes up OWT and their definitions. As seen on figure 2.1 above, the definition of **tower, substructure, support**

structure, foundation, **mudline**, **transition piece,** and **mean sea level** are all depicted on the image**.** These definitions will be used constantly throughout this thesis therefore their definition is necessary so as not cause confusion of the terms. The **rotor nacelle assembly** (**RNA)** is the sum of the rotor blade, nacelle and the hub of the turbine. For clarity, the **support structure** is the sum of the **tower** and **monopile** that supports the heavy turbine, that is, the components that carry the **RNA** which includes the **tower**, **substructure** and **foundation**. The **foundation** is the part of the support structure that is penetrated in the ground below the **mudline** to give stability to the whole OWT system. The **tower** is the part that is above the sea water, and it transfer weight of the RNA into the monopile, usually, the tower is a tubular tapered column. Similarly, the parameters are represented by signs. The parameters and their symbols are shown below.

2.3 Dimensions and Model Specification

The United States National Renewable Energy Laboratory (NREL) has sponsored a research of OWT which is suited for deep and shallow waters off the shore continental shelf (OCS) of the US and other offshore sites around the world. In order to do this, realistic and standardized data is needed. Therefore, the NREL came up with some reference designs. One of this designs the "NREL offshore 5-MW baseline wind turbine". The main goal is to establish a standardize specifications of a large wind turbine which is represents a conventional utility-scale land- and sea-based multi megawatt turbines, and suitable for deployment in deep waters (Butterfield & Jonkman, 2009)

In the following thesis an offshore wind turbine equipped with the 5MW NREL turbine will be used for the structural analysis of the environmental load calculations and ANSYS simulations. The geometry of this wind turbine model is shown in Figure 2.2 and remaining dimensions is summarize in table 2.2 below. The type of foundation type and its dimensions is not giving by NREL Butterfield & Jonkman baseline report, this is because the support structure (faundation) depends on the installation site, and the properties varies due difference in water depth, geological property o f the sea bed, wave and wind wind load. From the meteorlogical data the turbine will be installed at a location with a water depth of 20m. The overall height of the support structure from the seabed of 143.1 m. other dimensions wind turbine features are given in table 2.2 below

An overview of the structural dimension is given in figure 2.2. For more details on the turbine structural properties the reader should refer (Butterfield & Jonkman, 2009). The transition piece is not modelled in Butterfield & Jonkman report thus, in this thesis the monopile is modelled up to the tower for the ANSYS Workbench simulation.

Table 2-1: Properties chosen for the NREL 5-MW baseline wind turbine.

Wind Turbine Properties	
Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Rotor, Hub Diameter	126 m, 3 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Rated Tip Speed	80 m/s
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Hub Mass	56,780 kg
Tower Mass	347,460 kg
Monopile Height	60 m
Elevation of Yaw Bearing above SWL	87.6 m
Vertical distance above yaw bearing and shaft axis	1.962 m
Hub Height above SWL	90 m
Monopile + Hub Height above SWL	146 m
Tower Base Diameter, thickness	6 m, 0.027m
Tower Top Diameter, Thickness	3.87 m, 0.019m
Tower Height	90m
Monopile Outer Diameter, Thickness	6 m, 90mm

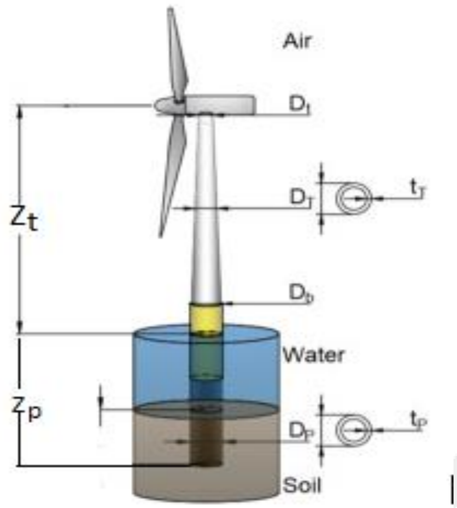


Figure 2.2: Figure of the 5 MW turbine.

2.4 Meteorological and Environmental Data

Meteorological data from climatology and weather forecast is very vital for design of offshore structure especially wind turbines. This is because meteorological data give both short and long-time data of a region. The data is carried out on a regular basis for hundreds of years and statistical operation is done on those data to give medium term as well as long term condition of the region.

In this thesis meteorological data is assumed to be taken from a certified Meteorological Service, and long term atmospheric and marine data will be used for the analysis of the OWT. The atmospheric and marine data necessary for the analysis in this thesis are wave and wind data.

2.4.1 Wave data

According to American petroleum Institute (API), the wave data that is required for estimating wave load on offshore structures is 100-year wave Height (**H**) with its associated Period (**T**). Statistically, a **100 years wave** is a sea wave with wave Height that is met or exceeded once in 100 years. This simply means the probability of reaching such

Height is **0.01**. Therefore, the OWT is design to withstand loads from such wave data. In this report the associated 100 years wave data assumed for analysis is given in table 2.3 below. Note that, the wave height, period and depth are the major data necessary. The remaining data are dependent on the major data therefore, can be calculated using appropriate wave kinematics. For instance the wave length is calculated from dispersion relation of linear wave theory.

Table 2-2: 100-year wave data.

100-year Wave Data	Symbol (unit)	Magnitude
Wave Height	H (m)	11.5
Wave period	T (s)	9
Wave length	L (m)	163.57
Wave number	K rad/m	0.038393
Sea depth	h (m)	30
Water density	ρ_w (Kg/m^3)	1025

2.4.2 Wind data

Just like the wave data discussed previously, the wind data is also a meteorological data that is estimated over short term or long-term statistics. Short term wind conditions may refer to 10 minutes or even less while long term wind condition may go as 10 years or more. One of the most common standard accepted is the 10-minute mean speed measured at to 10m height above sea level or ground. In this thesis, Der Norske Veritas (DNV) standard for environmental loads and conditions will be employed to estimate the wind load. Therefore, the DNV criteria for estimating wind conditions will be employed

The DNV suggest 10-minute mean wind speed with return period usually in years to be used for design of offshore structures. In this thesis the return period chosen is 50 years. This simply means that the 10-minute mean speed has a probability of exceedance once in 50 years i.e. 0.02. This is denoted as $\mathbf{V_{10,\,50years}}$. The assumed $\mathbf{V_{10,\,50years}}$ for estimation of the wind is **30m/S**

$$\mathbf{V_{10,\,50years} = 30m/s}$$

2.5 Limitation

In this thesis, the effect of current load will not be considered in the analysis. Although, in reality they also add load on to the offshore wind turbine. Moreover, the presence of current will also influence the wave particle speed by stretching or compressing it depending on the direction of the wave and current. This phenomenon is known as Doppler Effect and it has serious effect on the wave length of the sea wave. Therefore, for simplicity the current effect is neglected. It is also important to note that wave loads changes by season, in this thesis however that is neglected, it is regarded that the wave load throughout the season remain constant and therefore, seasonal changes is neglected in this research.

Another thing to consider in full analysis is the soil and monopile interaction, since the monopile is embedded in the seabed, the soil acts as a damper and might allow slight movement. However, in this thesis soil and monopile interaction is neglected and it is assumed the monopile has a fixed support at the base. This will be explained in more detail in chapter 4.

3 THEORETICAL BACKGROUND & LOADS CALCULATIONS

3.1 Overview

This chapter presents the theoretical background for the thesis followed by loads calculations. The theory will be based on the loads acting on the support structure of the OWT that will be considered. There are many types of loads acting on an offshore wind turbine, these loads are listed below.

- **Gravity loads:** this arises due to weight of the component that makes up the wind turbine (dead load), these include weight of the rotor, hub, nacelle, and self-weight of the support structure.
- **Live loads:** the live loads is the operational loads, such as weight of a person climbing the turbine and maintenance equipment. The live loads keep changing from time to time. But it is sometime necessary to be considered in structural analysis.
- **Ice loads:** in region where the sea is covered by seasonal ice, it is crucial to consider the temperature changes and loads due to movement of ice on the offshore structure
- **Aerodynamic loads:** the loads due to the wind action on the OWT is one of the vital loads that must be considered in the structural analysis of OWT.
- **Hydrodynamic loads:** wave loads and current loads if it exists in the region are also a very important loads of that must be considered in structural analyses of OWT.

In order to simplify the problem of this thesis some of the loads listed above are neglected. Therefore, the loads that will be taken into consideration are the **Dead loads**, **Aerodynamic loads** and **hydrodynamic loads**. To do this, the theoretical background of these loads will be giving followed by the calculation to estimate these loads.

3.2 Dead Loads

The dead loads are kind of gravity loads that is static and constant on the overall support structure of the OWT. The dead loads are predominantly due to weight of the component that makes up the wind turbine and these loads does not change over time.

For the sake of this thesis the dead loads are due to individual components of the OWT and the resultant dead load is the summation of the individual component dead loads. These components are giving below.

Table 3-1: Dead loads of various components.

	Component	**Mass**	**Position from MSL (m)**	**Weight**
Group 1	Rotor	110000	90	1079100
	Nacelle	240000	90	2354400
	hub	56780	90	557012
	Total			3990512
Group 2	Component	Mass	Height (m) with respect to MSL	Weight
	Transition Piece	172800	0	169517
	Total			169517
Group 3	Component	Mass	Height (m) with respect to MSL	Weight
	Tower	347460	Distributed	3408583
	Monopile	800000	Distributed	7848000
	Total			1.1E+07

The mass of the individual component is taken from NREL 5MW wind turbine manual (Butterfield & Jonkman, 2009). The weight of the components in group 3 i.e. **tower** and **monopile** is automatically calculated by ANSYS APDL software. This is done by inserting the density of structural steel that will be used for the design. In this thesis the density of the structural steel is assumed to be **8500kg/m^3** rather than the usual 7750kg/m^3, this is done to accommodate the weight of bolts, flanges and welds on the support structure. The weight of the monopile is not given on NREL 5MW wind turbine manual, therefore is assumed to be 800tonnes as most of the standard turbine in market today is around that much. The weight of the transition piece is also not given so, it is also assumed that the weight of the transition piece is around 22% of the monopile weight.

Another thing to consider is the respected position of individual components above mean sea level (MSL). The group 1 components are all located 90m above MSL therefore, the total dead loads is applied 90m above MSL. Likewise, the transition piece is added at the MSL (0m). Since the tower and the monopile weight is calculated by ANSYS there is no need to add its dead weight on the model structure. It is also important to note that the dead load act downward due to gravity. This is shown in figure 3.1 below

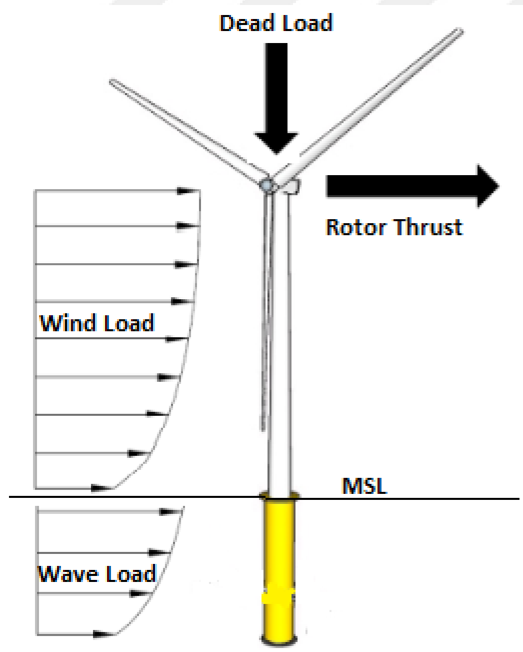


Figure 3.1: Various loads acting on an OWT.

3.3 Aerodynamic Loads

The aerodynamic loads are the wind load acting on the Wind turbine. The aerodynamic loads depend mainly on wind speed and shape of the structure. All components of the OWT above the MSL is subjected to aerodynamic load. In this thesis the aerodynamic loads is classified into two part: aerodynamic on rotor known as the **rotor thrust** and aerodynamic loads on the tower known as the **tower drag**. These two loads will be elaborated in more details in the following section.

3.3.1 Rotor thrust

The thrust due to the wind load exerted on the rotor blades create substantial amount of bending moment in the foundation of the support structure. The report manuals of the NREL 5MW wind turbine has included the characteristics of the power curve and rotor thrust, this is shown in figure 3.2 bellow. As it can be seen in the figure 3.2 below, the **maximum rotor thrust** is around **800kN**

Maximum rotThrust = 800kN

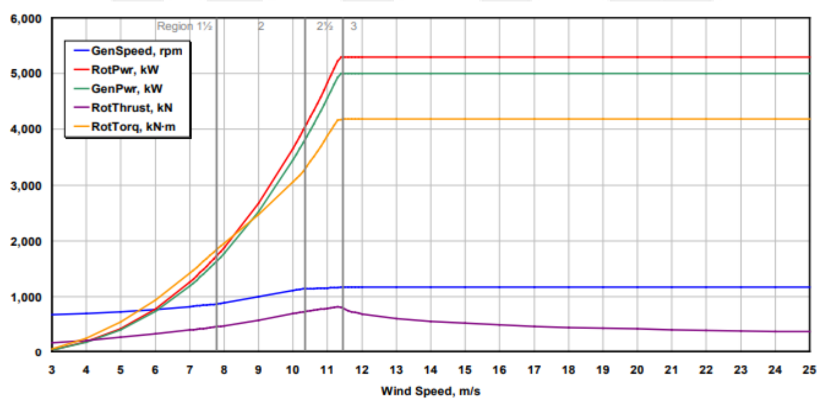


Figure 3.2: Power and thrust curve. (Butterfield & Jonkman, 2009).

However, in order to calculate a more accurate rotor thrust of a particular turbine, power curve and rotor theory can be used as follows. As shown by (Pramod , 2011) the power of the wind turbine is giving by,

$$P = \frac{1}{2} C_P \rho A V^3 \tag{3.1}$$

Where,

P: Power extracted from wind

C_P: Power coefficient

ρ: Density of the flowing air (1.225kg/m^3)

A: swept area of the turbine blade

V: wind speed. Hence,

$$C_P = 4a(1-a)^2 \tag{3.2}$$

a: induction factor

Substitute 3.2 into 3.1

$$P = 2a(1-a)^2\rho AV^3 \tag{3.3}$$

Since the power with its associated velocity can be tracked on the power curve in figure 3.2, the induction factor can be calculated with equation 3.3 substituting the associated power and wind velocity, while the thrust coefficient and thrust force is calculated by 3.4 and 3.5 respectively

$$C_T = 4a(1-a) \tag{3.4}$$

$$F_T = \frac{1}{2}C_T\rho AV^2 \tag{3.5}$$

$$F_T = 2a(1-a)\rho AV^2 \tag{3.6}$$

Where,

$F_T =$ Thrust Force,

$C_T =$ Thrust Coefficient

3.3.2 Tower drag

The wind blowing on the tower also contribute substantial amount of load in addition to the rotor thrust, this is called tower drag. The tower drags exist all over the tower and change with respect to elevation. In this thesis the tower drag is calculated in accordance with DNV recommended practice (DNV-RP-C205, ENVIRONMENTAL CONDITIONS) a similar approach is practiced by BS-EN 1991-1-4:2005+A1 standard action on structures (European Committee For Standardization, 2010) .

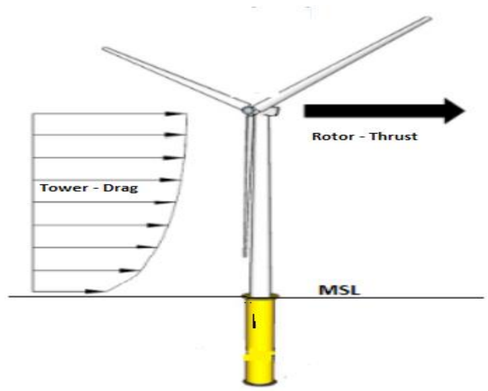


Figure 3.3: Tower drag and rotor thrust.

According to the DNV recommended practice the basic wind pressure is defined by the following equation 3.7 below

$$q = \frac{1}{2}\rho V_{T,Z}^2 \tag{3.7}$$

Where,

q = Basic wind pressure

ρ = Density of the flowing wind (1.225kg/m^3)

$V_{T,Z}$ = Basic wind velocity at height average over time interval T and height z it is giving by 3.8

$$V_{(T,Z)} = V_{10,50yr} K_t ln\frac{Z}{Z_o} \tag{3.8}$$

$\mathbf{V_{10,\,50yr}}$ = Basic Wind Velocity ($\mathbf{V_{10,\,50yr}}$ **= 30m/s** assumed wind to be velocity at 10m height)

Z_o = Terrain Roughness (**Zo = 0.001** for sea terrain)

K_t = Terrain factor, is giving by equation below

$$K_t = 0.19(\frac{Z_o}{0.05})\text{^}0.001 \tag{3.9}$$

Substituting **Zo = 0.001** for sea terrain

$$K_t = 0.19(\frac{Z_o}{0.05})\hat{}0.001 = 0.14$$

The wind force is giving by

$$F_W = CqSsin\alpha \qquad (3.10)$$

Where,

C = shape coefficient (**taken as 0.8**) is a function of Reynolds number (Re)

q = Basic wind pressure

S = projected area of the structure normal to the force of wind

α = angle between wind direction and axis of the structural member

The Reynolds Number is giving by

$$Re = \frac{DV_{T,z}}{\mu} \qquad (3.11)$$

Where,

$V_{T,Z}$ = Wind Speed

D = diameter of the structural member

μ = Kinematic Viscosity

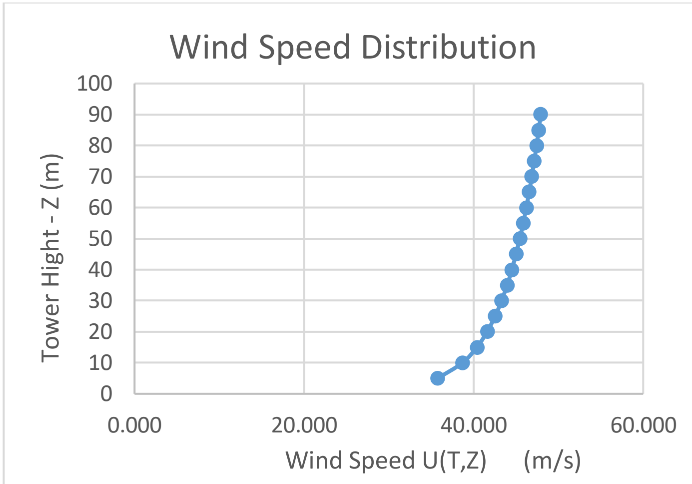
DNV suggest some constant values of shape coefficient C for some common shape cross section and in the case of this thesis the shape coefficient is taken

The calculation for the force on the whole tower is done in segments of 5 m length. The tower is 90m tall so, dividing by 5m length gives 18 segments. Therefore, wind load on each segment is calculated and the summation of all the loads on each segment gives the total force on the tower. In order to increase the accuracy of the calculation smaller segment can be employed. Table 3.2 below is the calculation of the force on tower and the total drag force on the tower is about **426kN**

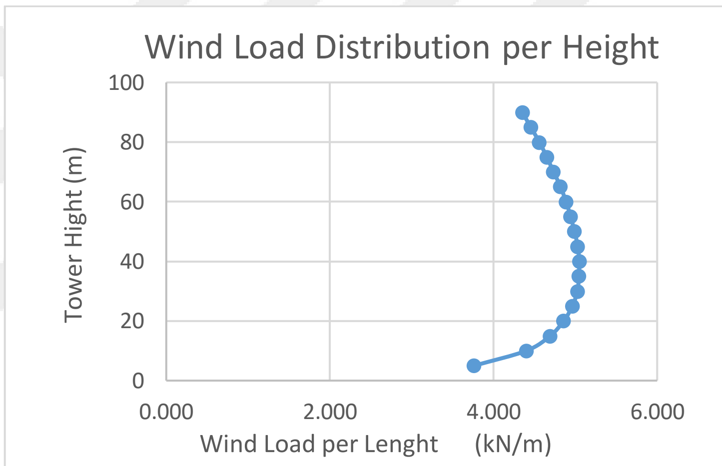
Table 3-2: Calculation for wind load.

Wind Load on Tower DNV Standard									
S/N	**Z (m)**	**D (m)**	**$V_{T,z}$ (m/s)**	**q (kN/m^2)**	**S (m^2)**	**Re [-]**	**C [-]**	**F_w (kN)**	**F_w/h (kN/m**
1	5	6.000	35.772	0.784	30.000	14802294.374	0.8	**18.8109**	**3.762**
2	10	6.000	38.683	0.917	30.000	16006936.371	0.8	**21.9972**	**4.399**
3	15	5.870	40.386	0.999	29.350	16349521.952	0.8	**23.4571**	**4.691**
4	20	5.730	41.595	1.060	28.650	16437057.341	0.8	**24.2882**	**4.858**
5	25	5.600	42.532	1.108	28.000	16426094.039	0.8	**24.8189**	**4.964**
6	30	5.470	43.298	1.148	27.350	16333646.788	0.8	**25.1236**	**5.025**
7	35	5.330	43.945	1.183	26.650	16153588.371	0.8	**25.2181**	**5.044**
8	40	5.200	44.506	1.213	26.000	15960724.315	0.8	**25.2350**	**5.047**
9	45	5.070	45.001	1.240	25.350	15734676.687	0.8	**25.1542**	**5.031**
10	50	4.930	45.443	1.265	24.650	15450643.390	0.8	**24.9430**	**4.989**
11	55	4.800	45.843	1.287	24.000	15175736.789	0.8	**24.7150**	**4.943**
12	60	4.670	46.209	1.308	23.350	14882426.640	0.8	**24.4305**	**4.886**
13	65	4.540	46.545	1.327	22.700	14573399.595	0.8	**24.0973**	**4.819**
14	70	4.400	46.856	1.345	22.000	14218448.940	0.8	**23.6676**	**4.734**
15	75	4.270	47.146	1.361	21.350	13883690.690	0.8	**23.2533**	**4.651**
16	80	4.140	47.417	1.377	20.700	13538395.029	0.8	**22.8053**	**4.561**
17	85	4.000	47.672	1.392	20.000	13150815.848	0.8	**22.2714**	**4.454**
18	90	3.870	47.912	1.406	19.350	12787486.944	0.8	**21.7651**	**4.353**
Total								**426.0516**	**[-]**

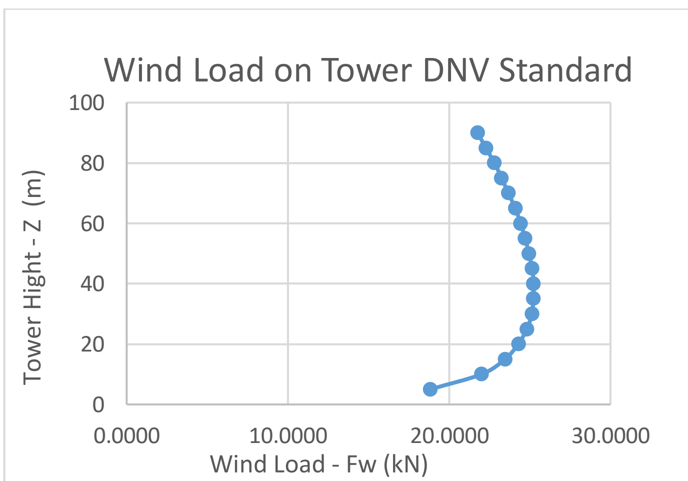
Three graphs are plotted from the resulting table 3.2, wind speed distribution with the elevation, wind load per height and finally the concentrated wind load on tower.



A.



B.



C.

Figure 3.4: A-C wind speed and wind load distribution on tower.

3.4 Hydrodynamic Load

This section presents hydrodynamic loads on the monopile of the support structure. The hydrodynamic loads on the OWT support structure arises due to motion of water particles as a result of waves or sea current. In this thesis however, load due to ocean current is neglected and only the sea wave load is assumed to be present. In other to calculate load due to wave crushing on the monopile, standard recommended practice has been employed from (American Petroleum Institute , 2002).

The estimation waves force exerted on a cylindrical object as recommended by API can be done by Morisons load formula. The Morison's formula being the sum of drag force which is proportional to the square of velocity and inertia force which is proportional to the acceleration. Usually, the Morison equation is valid when wave length (L) is less than 5 time the diameter (D). According to API recommended practice the wave load on a fixed slender structure is giving by

$$F(t) = F_{inertia} + F_{Drag} \tag{3.12}$$

$$F(t) = \frac{\pi}{4}\, \rho_w\, C_M D^2 * U_a(t) \; + \frac{1}{2}\, \rho_w\, C_D D U(t)|U(t)| \tag{3.13}$$

Where,

ρ_w = Density of the fluid (1025 kg/m^3 for sea water)

C_M = Inertia coefficient (C_M = 1.6 for smooth Monopile)

C_D = Drag coefficient (C_D = 0.65 for smooth monopile)

D = Diameter of the Monopile (D = 6m)

$U_a(t)$ = Fluid particle acceleration

$U(t)$ = Fluid particle velocity

t = Time

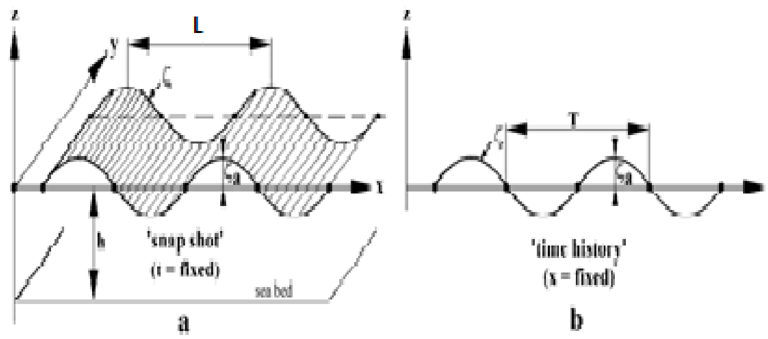


Figure 3.5: Wave displacement and time history. (Journée & Massie, 2001, pp. 5-4).

The velocity and acceleration is a function of elevation and time giving by following equations

$$U(z,t) = \zeta\omega \frac{\cosh k(h+z)}{sinh\ kh} \cos(\mathrm{kx} - \mathrm{wt}) \tag{3.14}$$

Since the monopile is a fixed structure, it can be assumed the monopile is in the origin therefore *kx* can be dropped and the equation becomes

$$U(z,t) = \zeta\omega \frac{\cosh k(h+z)}{sinh\ kh} \cos(-\mathrm{wt}) \tag{3.15}$$

Similarly, differentiating the velocity gives the acceleration which is giving by,

$$U_a(z,t) = \zeta\omega^2 \frac{\cosh k(h+z)}{sinh\ kh} \sin(-\mathrm{wt}) \qquad (3.15)$$

Where,

ζ = amplitude

ω = Angular frequency

K = wave number

t = time

h = water depth

z = elevation

3.4.1 Selection of coefficients C_M and C_D

Many researches have shown that the values of C_M & C_D depend on some flow conditions. Some of these conditions are Reynolds number, Keulegan Carpenter Number and surface condition of the cylinder (smooth or rough). Consequently, it is very common and reasonable to present C_M and C_D in a graph depending on some independent parameters. For instance, changing the roughness of the cylinder changes the value of C_M and C_D. A good example is shown below in figure 3.5,

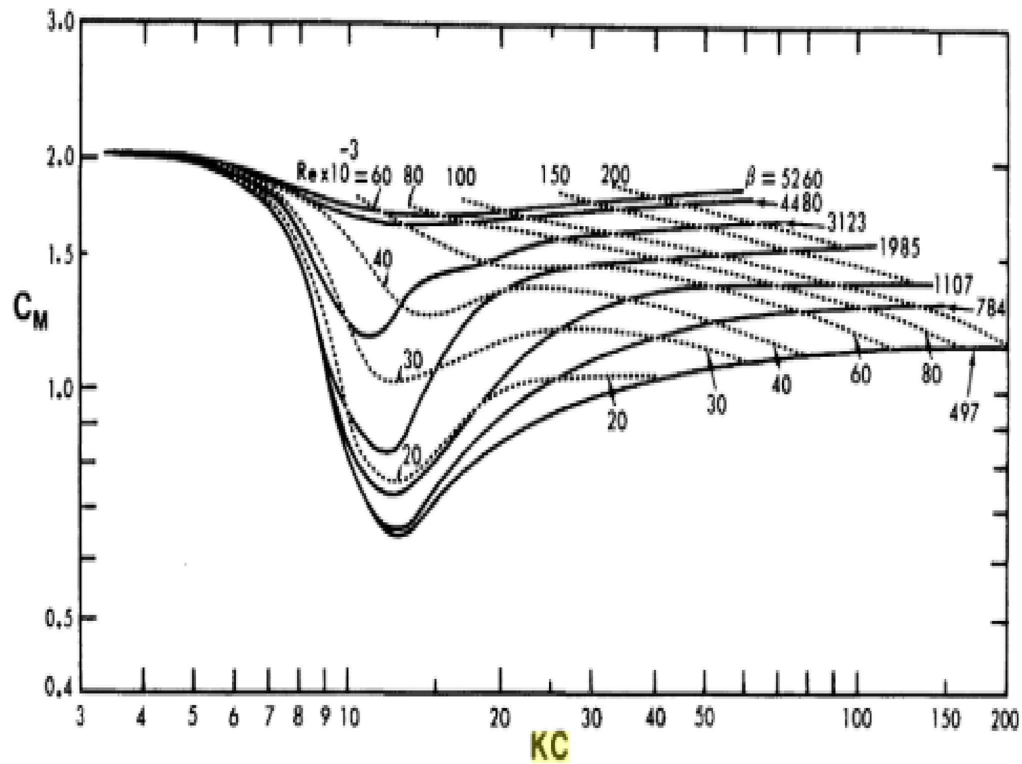


Figure 3.6: C_M vs KC (Sarpkaya & Isaacson , 1981).

There are many standard design codes or regulation used by engineers to specify the appropriate C_M & C_D Values. One of the most widely used codes are those published by (American Petroleum Institute , 2002). According to API recommended practice, standard values of C_M and C_D are constant values and it only depends surface texture i.e. smooth or rough. These standard values are listed in the table below

Table 3-3: Suggested API's values for C_M & C_D.

Smooth Cylinder		Rough Cylinder	
C_D	C_M	C_D	C_M
0.65	**2.0**	**1.0**	**1.8**

In the calculation of this thesis it will assumed that the monopile is smooth and new. This means the effect of marine growth on the monopile is not present. Therefore, the values of inertia and drag coefficients that will be used in this thesis is for smooth case giving above,

3.4.2 Wave data

According to American petroleum Institute (API), the wave data that is required for estimating wave load on offshore structures is 100-year wave Height (**H**) with its associated Period (**T**). Statistically, a **100 years wave** is a sea wave with wave Height that is met or exceeded once in 100 years. This simply means the probability of reaching such Height is **0.01**. Therefore, the OWT is design to withstand loads from such wave data. In this report the associated 100 years wave data assumed for analysis is given in table 2.3 below. Note that, the wave height, period and depth are the major data necessary. The remaining data are dependent on the major data therefore, can be calculated using appropriate wave kinematics. For instance the wave length is calculated from dispersion relation of linear wave theory.

Table 3-4: 100 Year wave data.

100 year Wave Data	Symbol (unit)	Magnitude
Wave Height	H (m)	11.5
Wave period	T (s)	9
Wave length	L (m)	163.57
Wave number	K (rad/m)	0.038393
Sea depth	h (m)	30
Water density	ρ_w (Kg/m^3)	1025

3.4.3 Procedure for calculating the wave load

The Morison's seems simple but one dig into it, it's a bit complicated equation. The velocity and acceleration are 90º out of phase and so do the inertia and drag coefficient. As a result, it makes the calculation of the coefficients tasking. Another problem with the equation is that the velocity and acceleration vary with space and time consequently, the total force also varies with time. The following steps will present the procedure for calculating the maximum wave load.

- Divide the wave period into several time steps
- The submerged portion of the monopile is divided into several segments. The higher the number of segments the higher the accuracy of the calculation.
- Use the Morison's equation to calculate the load on each segment.
- Use numerical integration to calculate the total load for all the segments for this time step.
- Repeat the procedure above for each of the time steps.
- The maximum load of all the time steps calculated is the maximum wave load on the monopile.

3.4.4 Calculation result

In order to make it the calculation easy, Microsoft excel is used to carry out the calculations. Although there are several wave solver software's such as ANSYS AQWA, ASHES etc. Micro soft excel is the best choice for this occasion. The calculation is done in time steps (0-9s) and for each time step the distributed load is found. The calculation is repeated for all the time step and eventually the maximum load is found. The calculation is done on a spread sheet and it is giving in the table 3.5-3.14 below

Table 3-5: Wave load on monopile (Time Step 0s).

	Z	D	ω	L	K	H	C_M	C_D	U(z,t)	U_a(z,t)	$F_{inertia}$	F_{drag}	F_{total}	integral
S/N	**(m)**	**(m)**	**rad/s**	**(m)**	**(rad/m)**	**(m)**	**[-]**	**[-]**	**(m/s)**	**(m/s^2)**	**(N/m)**	**(N/m)**	**(kN/m)**	**(kN)**
1	0	6	0.697778	163.57	0.038393	11.5	1.6	0.65	4.90	0	0	48045.26924	48.04526924	-209.03561
2	-5	6	0.697778	163.57	0.038393	11.5	1.6	0.65	4.22	0	0	35568.97351	35.56897351	-156.96338
3	-10	6	0.697778	163.57	0.038393	11.5	1.6	0.65	3.69	0	0	27216.37886	27.21637886	-122.39363
4	-15	6	0.697778	163.57	0.038393	11.5	1.6	0.65	3.30	0	0	21741.07332	21.74107332	-100.1677
5	-20	6	0.697778	163.57	0.038393	11.5	1.6	0.65	3.03	0	0	18326.00704	18.32600704	-86.968939
6	-25	6	0.697778	163.57	0.038393	11.5	1.6	0.65	2.87	0	0	16461.56837	16.46156837	-80.827764
7	-30	6	0.697778	163.57	0.038393	11.5	1.6	0.65	2.82	0	0	15869.53733	15.86953733	
Total														-756.35702

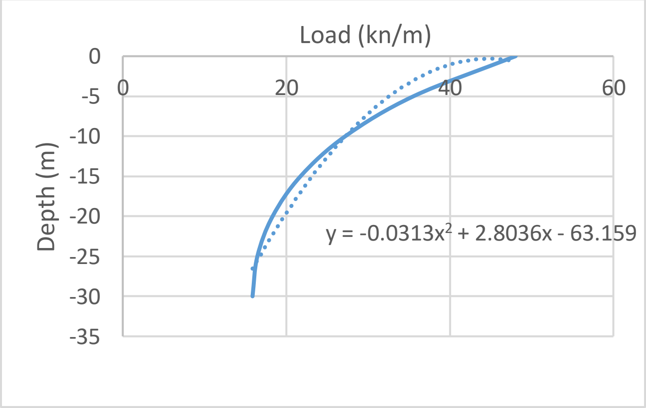


Figure 3.7: Depth vs wave load (t = 0s).

Table 3-6: Wave load on monopile (Time Step 1s).

S/N	t (S)	Z (m)	D (m)	ω rad/s	h	K (m)	ζ (m)	C_M [-]	C_D [-]	U(z,t) (m/s)	U_a(z,t) (m/s^2)	$F_{inertia}$ (N/m)	F_{drag} (N/m)	F_{total} (kN/m)	integral (kN)
1	1	0	6	0.69778	30	0.038393	5.75	1.6	0.65	3.76	-2.19813	-101875.3742	28211.17888	-73.664195	351.0862792
2	1	-5	6	0.69778	30	0.038393	5.75	1.6	0.65	3.23	-1.89132	-87655.76145	20885.44507	-66.770316	318.6638545
3	1	-10	6	0.69778	30	0.038393	5.75	1.6	0.65	2.83	-1.65442	-76676.24437	15981.01896	-60.695225	291.1503741
4	1	-15	6	0.69778	30	0.038393	5.75	1.6	0.65	2.53	-1.47867	-68530.97755	12766.05334	-55.764924	269.8074984
5	1	-20	6	0.69778	30	0.038393	5.75	1.6	0.65	2.32	-1.35758	-62918.88047	10760.80531	-52.158075	255.3113382
6	1	-25	6	0.69778	30	0.038393	5.75	1.6	0.65	2.20	-1.28667	-59632.50833	9666.04819	-49.96646	247.9960597
7	1	-30	6	0.69778	30	0.038393	5.75	1.6	0.65	2.16	-1.26332	-58550.38411	9318.420364	-49.231964	
TOTAL															1734.015404

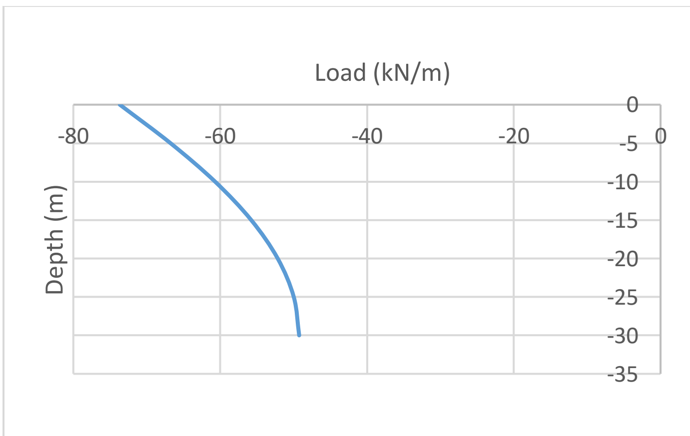


Figure 3.8: Depth vs wave load (t=1s).

Table 3-7: Wave load on monopile (Time Step 2s).

	t	Z	D	ω	h	K	ζ	C_M	C_D	U(z,t)	U_a(z,t)	$F_{inertia}$	F_{drag}	F_{total}	integral
S/N	**(S)**	**(m)**	**(m)**	**rad/s**	**(m)**	**(rad/m)**	**(m)**	**[-]**	**[-]**	**(m/s)**	**(m/s^2)**	**(N/m)**	**(N/m)**	**(kN/m)**	**(kN)**
1	2	0	6	0.69778	30	0.038393	5.75	1.6	0.65	0.854768	-3.36872	-156128.1806	1460.344705	-154.66784	719.81
2	2	-5	6	0.69778	30	0.038393	5.75	1.6	0.65	0.735461	-2.89852	-134336.0421	1081.129904	-133.25491	624.84
3	2	-10	6	0.69778	30	0.038393	5.75	1.6	0.65	0.643339	-2.53546	-117509.4828	827.2534978	-116.68223	552.62
4	2	-15	6	0.69778	30	0.038393	5.75	1.6	0.65	0.574998	-2.26612	-105026.528	660.8315969	-104.3657	500.59
5	2	-20	6	0.69778	30	0.038393	5.75	1.6	0.65	0.52791	-2.08054	-96425.75955	557.0304283	-95.868729	466.89
6	2	-25	6	0.69778	30	0.038393	5.75	1.6	0.65	0.500337	-1.97187	-91389.25973	500.3605964	-90.888899	450.34
7	2	-30	6	0.69778	30	0.038393	5.75	1.6	0.65	0.491257	-1.93609	-89730.86008	482.3657279	-89.248494	
TOTAL															3315.09

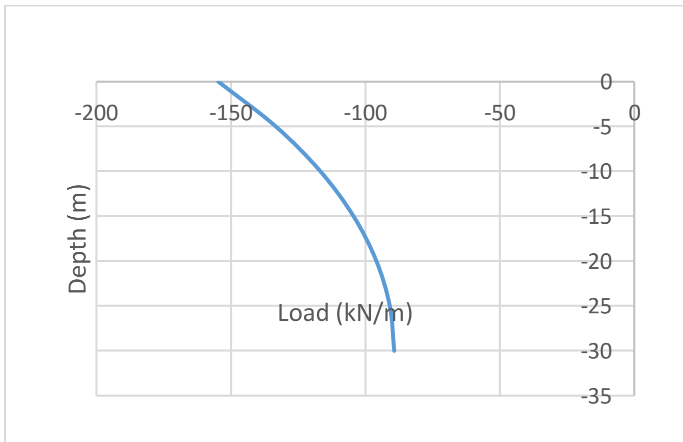


Figure 3.9: Depth vs wave load (t=2s).

Table 3-8: Wave load on monopile (Time Step 3s).

	t	Z	D	ω	h	K	ζ	C_M	C_D	U(z,t)	U_a(z,t)	$F_{inertia}$	F_{drag}	F_{total}	integral
S/N	**(S)**	**(m)**	**(m)**	**rad/s**	**(m)**	**(rad/m)**	**(m)**	**[-]**	**[-]**	**(m/s)**	**(m/s^2)**	**(N/m)**	**(N/m)**	**(kN/m)**	**(kN)**
1	3	0	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.44695	-2.96458	-137397.4528	-11967.62	-149.36507	691.1118111
2	3	-5	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.10541	-2.55079	-118219.7214	-8859.93	-127.07965	593.1772387
3	3	-10	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.84169	-2.23128	-103411.8476	-6779.40	-110.19124	520.0831934
4	3	-15	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.64605	-1.99425	-92426.47531	-5415.56	-97.842033	468.1611919
5	3	-20	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.51125	-1.83094	-84857.54268	-4564.90	-89.422443	434.8705096
6	3	-25	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.43231	-1.73531	-80425.27271	-4100.49	-84.52576	418.6115266
7	3	-30	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.40632	-1.70382	-78965.83158	-3953.02	-82.91885	
TOTAL															3126.015471

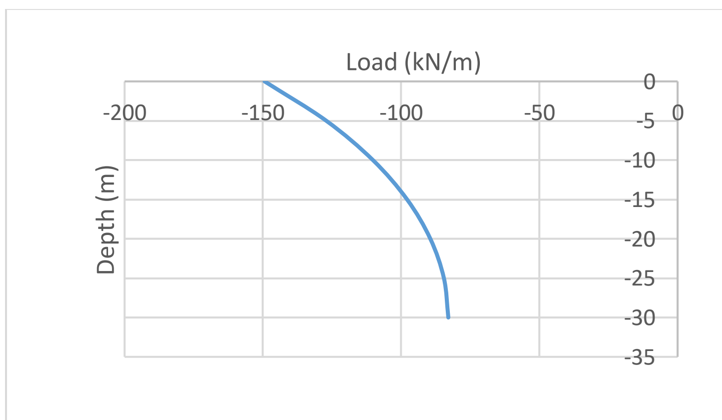


Figure 3.10: Depth vs wave load (t=3s).

Table 3-9: Wave load on monopile (Time Step 4s).

S/N	t (S)	Z (m)	D (m)	ω rad/s	h (m)	K (rad/m)	ζ (m)	C_M [-]	C_D [-]	U(z,t) (m/s)	U_a(z,t) (m/s^2)	$F_{inertia}$ (N/m)	F_{drag} (N/m)	F_{total} (kN/m)	integral (kN)
1	4	0	6	0.69778	30	0.038393	5.75	1.6	0.65	-4.60482	-1.17461	-54439.03943	-42382.14898	-96.821188	437.5956962
2	4	-5	6	0.69778	30	0.038393	5.75	1.6	0.65	-3.96208	-1.01066	-46840.51953	-31376.57055	-78.21709	357.9976537
3	4	-10	6	0.69778	30	0.038393	5.75	1.6	0.65	-3.4658	-0.88407	-40973.40623	-24008.56515	-64.981971	301.9536641
4	4	-15	6	0.69778	30	0.038393	5.75	1.6	0.65	-3.09763	-0.79015	-36620.82834	-19178.6659	-55.799494	263.9688465
5	4	-20	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.84396	-0.72545	-33621.89776	-16166.14661	-49.788044	240.4382015
6	4	-25	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.69542	-0.68756	-31865.76244	-14521.47378	-46.387236	229.1849286
7	4	-30	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.64651	-0.67508	-31287.50883	-13999.2264	-45.286735	
TOTAL															1831.138991

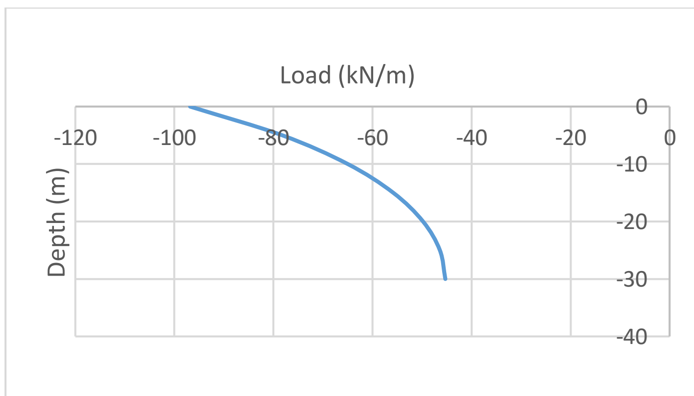


Figure 3.11: Depth vs wave load (t=4s).

Table 3-10: Wave load on monopile (Time Step 5s).

	t	Z	D	ω	h	K	ζ	C_M	C_D	U(z,t)	U_a(z,t)	$F_{inertia}$	F_{drag}	F_{total}	integral
S/N	**(S)**	**(m)**	**(m)**	**rad/s**	**(m)**	**(rad/m)**	**(m)**	**[-]**	**[-]**	**(m/s)**	**(m/s^2)**	**(N/m)**	**(N/m)**	**(kN/m)**	**(kN)**
1	5	0	6	0.69778	30	0.038393	5.75	1.6	0.65	-4.61012	1.815041	84120.61996	-42479.86316	41.6407568	-206.4275883
2	5	-5	6	0.69778	30	0.038393	5.75	1.6	0.65	-3.96665	1.5617	72379.18934	-31448.91081	40.9302785	-200.4488341
3	5	-10	6	0.69778	30	0.038393	5.75	1.6	0.65	-3.4698	1.366086	63313.17322	-24063.91811	39.2492551	-191.5345711
4	5	-15	6	0.69778	30	0.038393	5.75	1.6	0.65	-3.1012	1.220968	56587.45663	-19222.88328	37.3645733	-182.7864649
5	5	-20	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.84724	1.120981	51953.43109	-16203.41848	35.7500126	-176.0871599
6	5	-25	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.69852	1.06243	49239.80511	-14554.95377	34.6848513	-172.499054
7	5	-30	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.64955	1.043151	48346.27259	-14031.50232	34.3147703	
TOTAL															-1129.783672

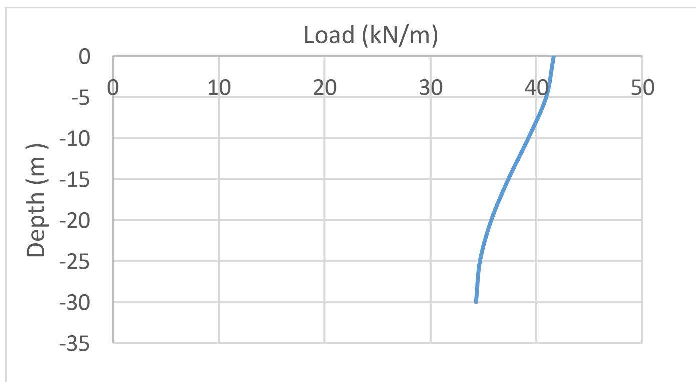


Figure 3.12: Depth vs wave load (t=5s).

Table 3-11: Wave load on monopile (Time Step 6s).

	t	Z	D	ω	h	K	ζ	CM	CD	U(z,t)	Ua(z,t)	Finertia	Fdrag	Ftotal	integral
S/N	**(S)**	**(m)**	**(m)**	**rad/s**	**(m)**	**(rad/m)**	**(m)**	**[-]**	**[-]**	**(m/s)**	**(m/s^2)**	**(N/m)**	**(N/m)**	**(kN/m)**	**(kN)**
1	6	0	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.46038	2.959157	137146.2838	-12099.40547	125.046878	-585.2324859
2	6	-5	6	0.69778	30	0.038393	5.75	1.6	0.65	-2.11697	2.546122	118003.6101	-8957.494098	109.046116	-513.53718
3	6	-10	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.8518	2.227202	103222.8059	-6854.049914	96.3687559	-457.8776952
4	6	-15	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.65509	1.990608	92257.51535	-5475.193229	86.7823221	-417.1739315
5	6	-20	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.51955	1.827594	84702.41908	-4615.16859	80.0872505	-390.549651
6	6	-25	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.44018	1.732136	80278.25151	-4145.641586	76.1326099	-377.3938492
7	6	-30	6	0.69778	30	0.038393	5.75	1.6	0.65	-1.41405	1.700703	78821.47831	-3996.54856	74.8249297	
TOTAL															-2741.764793

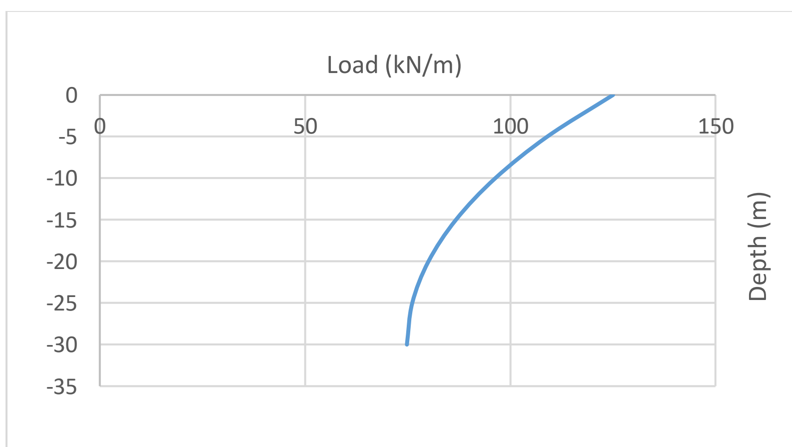


Figure 3.13: Depth vs wave load (t=6s).

Table 3-12: Wave load on monopile (Time Step 7s)

S/N	t (S)	Z (m)	D (m)	ω rad/s	h (m)	K (rad/m)	ζ (m)	C_M [-]	C_D [-]	U(z,t) (m/s)	$U_a(z,t)$ (m/s^2)	$F_{inertia}$ (N/m)	F_{drag} (N/m)	F_{total} (kN/m)	integral (kN)
1	7	0	6	0.69778	30	0.038393	5.75	1.6	0.65	0.839483	3.370594	156214.8965	704.2908276	156.218267	-726.5795538
2	7	-5	6	0.69778	30	0.038393	5.75	1.6	0.65	0.722309	2.900131	134410.6543	521.4042083	134.413554	-629.9771015
3	7	-10	6	0.69778	30	0.038393	5.75	1.6	0.65	0.631835	2.536869	117574.7493	398.9654283	117.577286	-556.661037
4	7	-15	6	0.69778	30	0.038393	5.75	1.6	0.65	0.564715	2.267379	105084.8613	318.7039545	105.087129	-503.9213155
5	7	-20	6	0.69778	30	0.038393	5.75	1.6	0.65	0.51847	2.0817	96479.31582	268.6430266	96.4813975	-469.8084729
6	7	-25	6	0.69778	30	0.038393	5.75	1.6	0.65	0.491389	1.972969	91440.01865	241.3124637	91.4419916	-453.0615667
7	7	-30	6	0.69778	30	0.038393	5.75	1.6	0.65	0.482472	1.937167	89780.6979	232.6339505	89.7826351	
TOTAL															-3340.009047

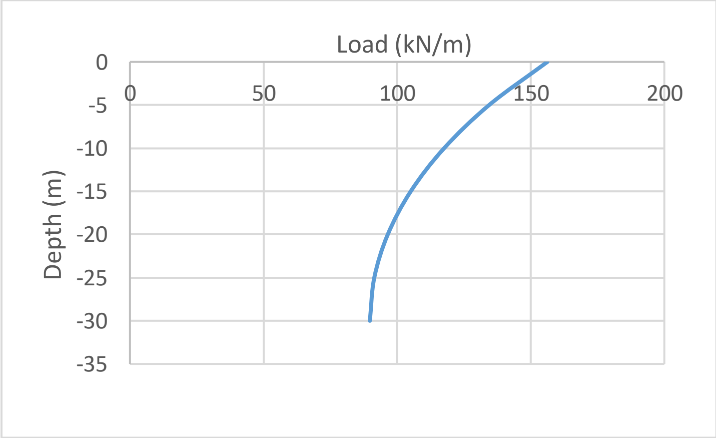


Figure 3.14: Depth vs wave load (t=7s).

Table 3-13: Wave load on monopile (Time Step 8s).

	t	Z	D	ω	h	K	ζ	C_M	C_D	U(z,t)	U_a(z,t)	$F_{inertia}$	F_{drag}	F_{total}	integral
S/N	**(S)**	**(m)**	**(m)**	**rad/s**	**(m)**	**(rad/m)**	**(m)**	**[-]**	**[-]**	**(m/s)**	**(m/s^2)**	**(N/m)**	**(N/m)**	**(kN/m)**	**(kN)**
1	8	0	6	0.69778	30	0.038393	5.75	1.6	0.65	3.746925	2.206416	102259.4388	28061.34472	130.320784	-597.7038038
2	8	-5	6	0.69778	30	0.038393	5.75	1.6	0.65	3.223935	1.898448	87986.21892	20774.51907	108.760738	-504.055472
3	8	-10	6	0.69778	30	0.038393	5.75	1.6	0.65	2.820114	1.660653	76965.30966	15896.14117	92.8614508	-435.872593
4	8	-15	6	0.69778	30	0.038393	5.75	1.6	0.65	2.520535	1.484243	68789.33563	12698.25075	81.4875864	-388.3683014
5	8	-20	6	0.69778	30	0.038393	5.75	1.6	0.65	2.314125	1.362697	63156.08124	10703.65292	73.8597342	-358.3294101
6	8	-25	6	0.69778	30	0.038393	5.75	1.6	0.65	2.193254	1.29152	59857.31965	9614.710237	69.4720299	-343.7801862
7	8	-30	6	0.69778	30	0.038393	5.75	1.6	0.65	2.153454	1.268084	58771.11589	9268.928719	68.0400446	
TOTAL															-2628.109767

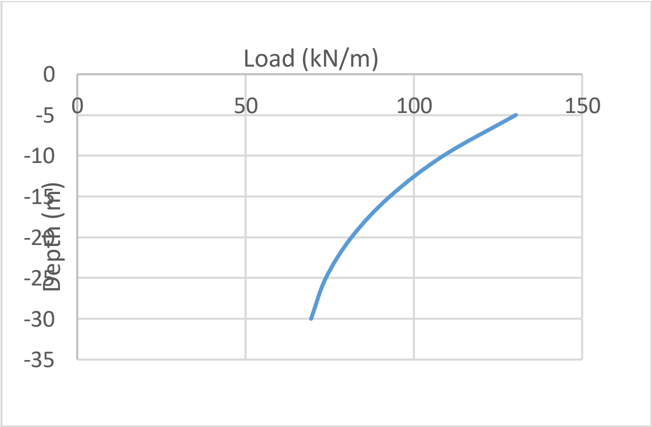


Figure 3.15: Depth vs wave load (t=8s).

Table 3-14: Wave load on monopile (Time Step 9s).

S/N	t (S)	Z (m)	D (m)	ω rad/s	h (m)	K (rad/m)	ζ (m)	C_M [-]	C_D [-]	U(z,t) (m/s)	U_a(z,t) (m/s^2)	$F_{inertia}$ (N/m)	F_{drag} (N/m)	F_{total} (kN/m)	integral (kN)
1	9	0	6	0.69778	30	0.038393	5.75	1.6	0.65	4.902833	0.010829	501.8789183	48045.49928	48.5473782	-211.3712419
2	9	-5	6	0.69778	30	0.038393	5.75	1.6	0.65	4.218503	0.009317	431.8274077	35569.29117	36.0011186	-158.9889659
3	9	-10	6	0.69778	30	0.038393	5.75	1.6	0.65	3.690105	0.00815	377.7379066	27216.72986	27.5944678	-124.1837752
4	9	-15	6	0.69778	30	0.038393	5.75	1.6	0.65	3.298108	0.007285	337.6110582	21741.43126	22.0790423	-101.7884187
5	9	-20	6	0.69778	30	0.038393	5.75	1.6	0.65	3.028021	0.006688	309.963619	18326.36155	18.6363252	-88.48004181
6	9	-25	6	0.69778	30	0.038393	5.75	1.6	0.65	2.869862	0.006339	293.7736329	16461.91793	16.7556916	-82.28504753
7	9	-30	6	0.69778	30	0.038393	5.75	1.6	0.65	2.817784	0.006224	288.4426553	15869.8848	16.1583275	
TOTAL															-767.097491

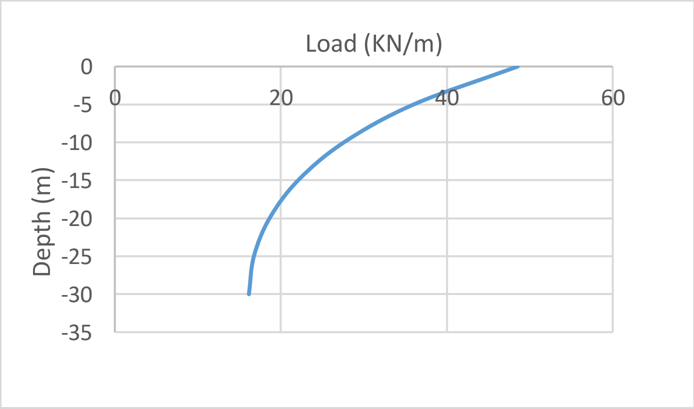


Figure 3.16: Depth vs wave load (t=9s).

Table 3-15: Summary of the total wave load on monopile for each time step.

Time (s)	Total Load (kN)	Absolute (kN)
0	-756.357022	756.357022
1	1734.0154	1734.0154
2	3315.09	3315.09316
3	3126.01547	3126.01547
4	1831.13899	1831.13899
5	-1129.78367	1129.78367
6	-2741.76479	2741.76479
7	-3340.00905	3340.00905
8	-2628.10977	2628.10977
9	-767.097491	767.097491

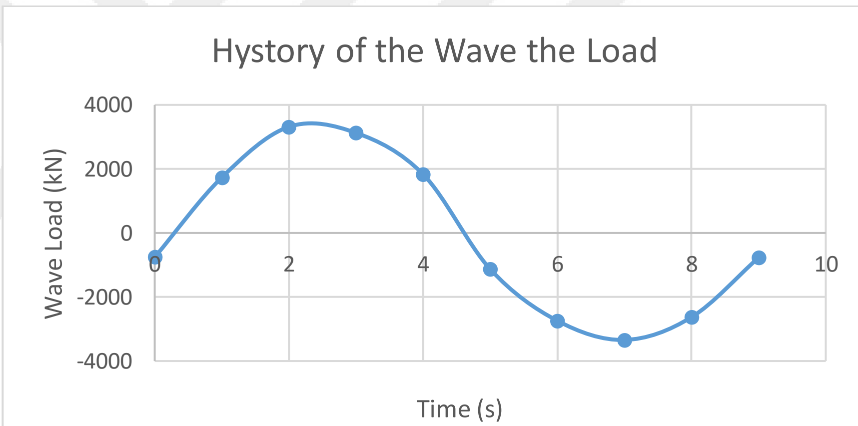


Figure 3.17: History of the wave Load.

Maximum Load = 3340.00 kN

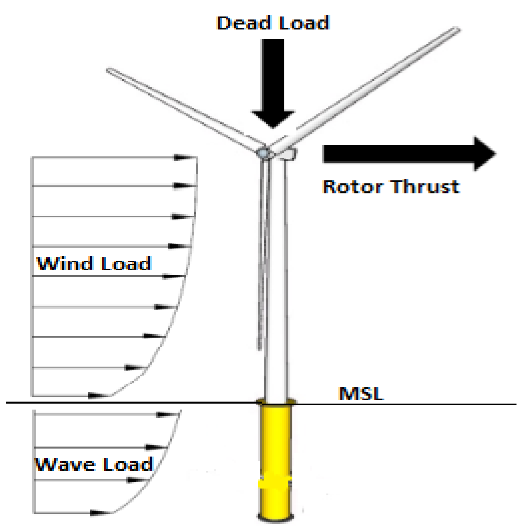
The maximum wave load occurs at the 7s step which is about **3340kN** and the distributed load of this step will be used for further analysis on ANSYS APDL to investigate the response of the support structure. This will be presented in the next chapter.

4 SIMULATION ANALYSIS AND RESULTS

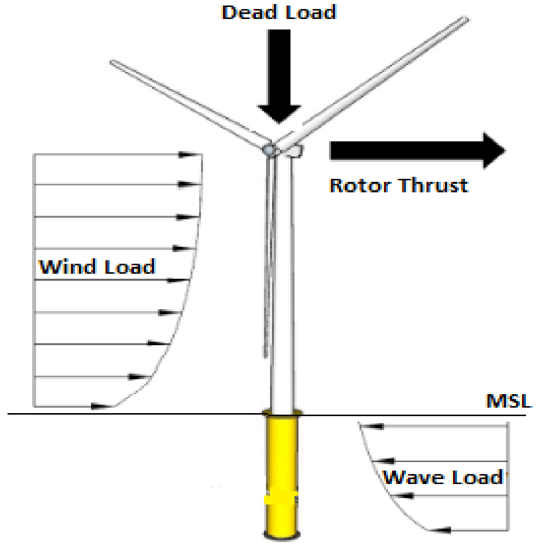
4.1 Overview

Since the dimension of the support structure is known its geometry can be modelled. The loads calculated in the previous chapter and constrains on the support structure will be defined to set up on the support structure. Using finite element analysis software ANSYS APDL the calculations of the response of the support structure will be carried out. Load cases is assumed in order to see the response of the support structure under a maximum worst case scenario. The two load cases that will be investigated are

- **Load Case 1:** The aerodynamic loads as well as the hydrodynamic loads are acting in the same direction on the support structure and it is assumed the loads are collinear. The dead load acts due to gravity therefore, it acts downward in all cases. Figure 4.1A depicts this case.
- **Load Case 2:** The aerodynamic and hydrodynamic loads are acting in opposite direction on the support structure. It is also assumed the loads are collinear as well. The dead acts downward in this case as well. This is shown in figure 4.1B bellow



A



B

Figure 4.1: Two load cases that will be considered in the investigation

4.2 ANSYS Modelling

The first thing to do before the simulation is to model the support structure geometry. The whole support structure geometry is modelled using beam188 element, the dimensions is as giving in chapter 2. Constraints are also defined; fixed support structure is assigned at the bottom of the monopile. Note that, in this thesis the soil monopile interaction is ignored therefore, the embedded region of the monopile is not modelled. Consequently, the support structure is modelled in similar way as a cantilever beam. The figure 4.2 below depicts the modelled support structure on ANSYS. All the loads as calculated in chapter 3 were applied as point loads on the nodes of the model depending on the loading cases proposed.

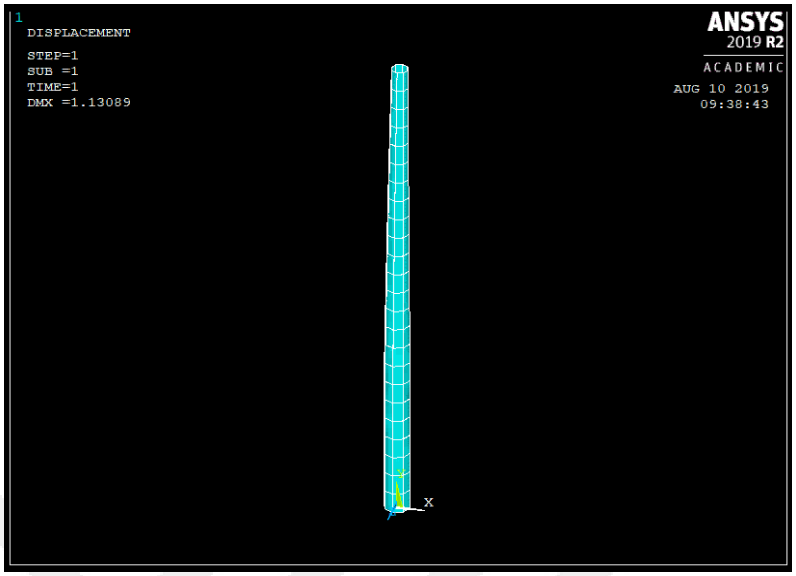


Figure 4.2: Support structure model geometry

4.3 Load Application

Now that the support structure is modelled, it is time to apply load calculated in the previous chapter 3. Because the distributed loads cannot be applied on the on beam 188 element, the concentrated load of each segment of the support structure is used instead. The load of each segment is applied at the top node of each segment. The figure 4.3 and 4.4 below shows how the loads are applied for each case defined earlier in section 4. The wind and wave load are applied in the horizontal x direction while the dead load is applied vertically downward in negative direction. All loads is as calculated in chapter 3.

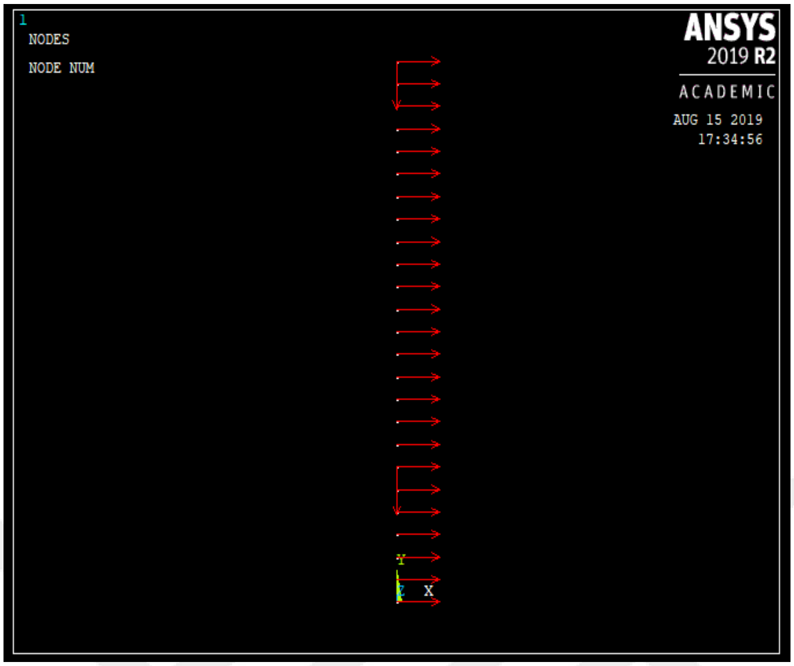


Figure 4.3: Case 1 load application on nodes

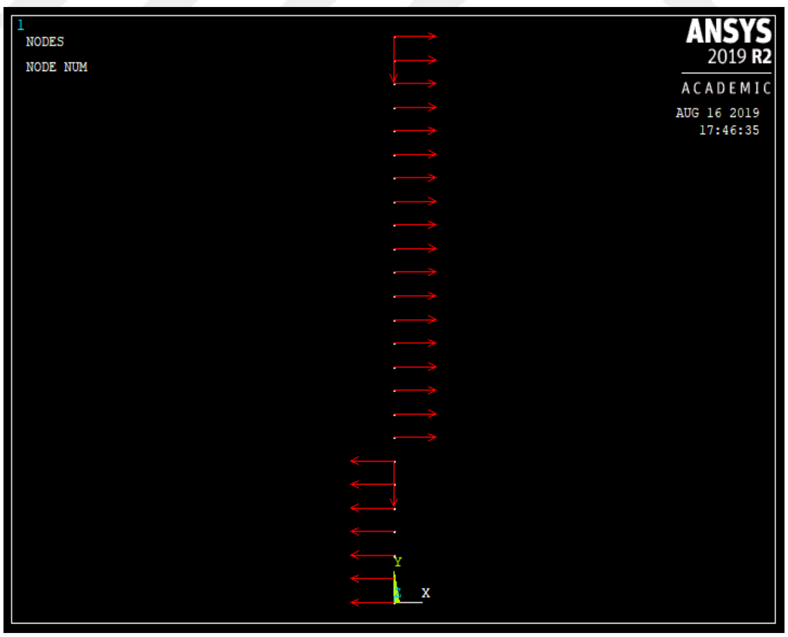


Figure 4.4: Case 2 load application on nodes

4.4 Simulation Results

In this section, the result of the finite element analysis will be presented. The main goal of the thesis is to check the response of the support structure under hydrodynamic and aerodynamic loads. The key areas to look at is the distribution of the stresses in the structure and the displacement of the support structure.

The values of the displacement and Von Mises stress were obtained. This is shown in figures below. a summary of the results is also tabulated in table 4.1

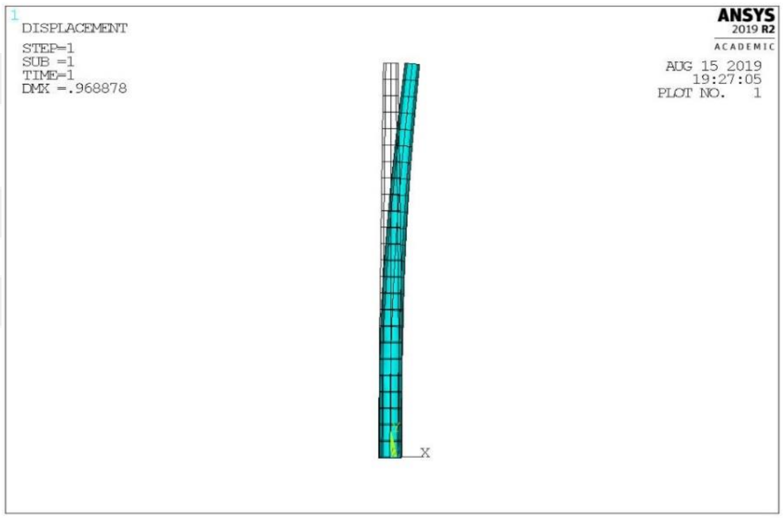


Figure 4.5: Displacement of load case 1

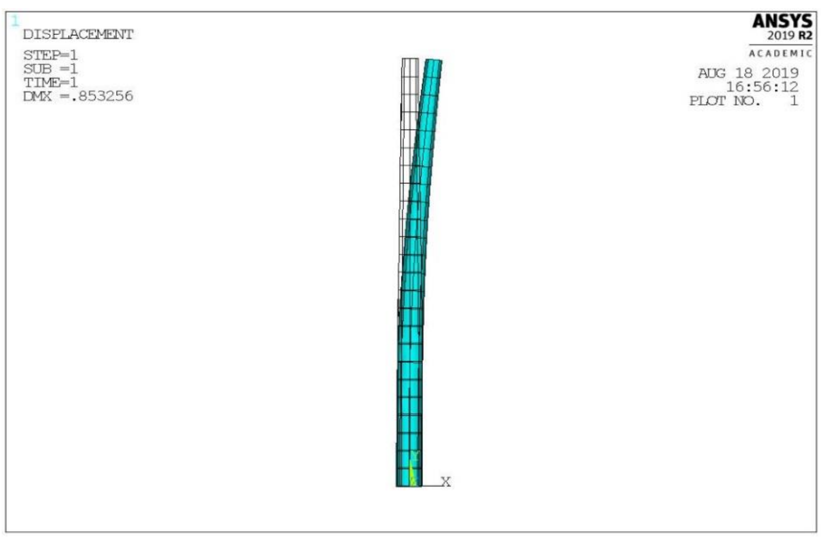


Figure 4.6: Displacement of load case 2

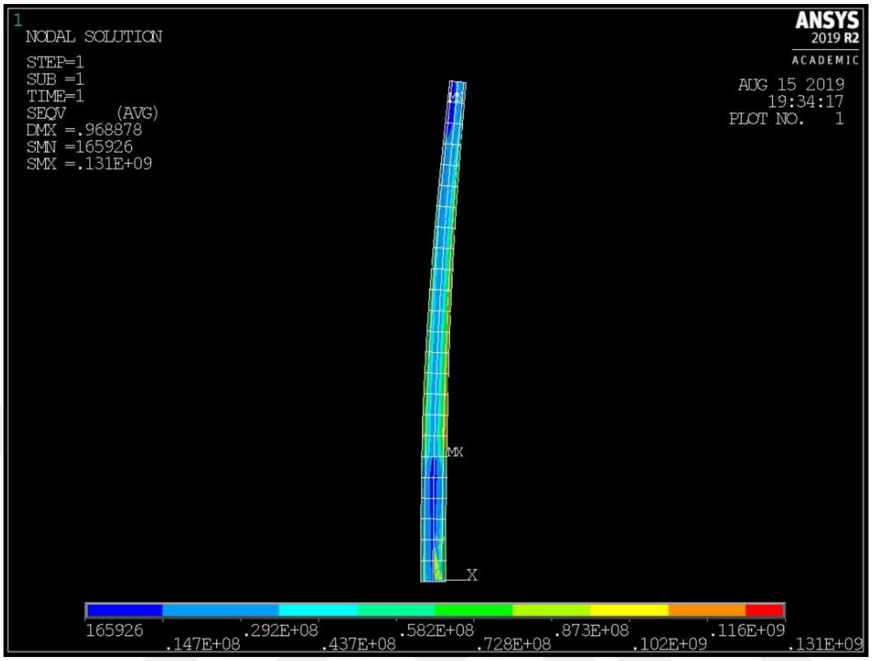


Figure 4.7: Von Mises stress of load case 1

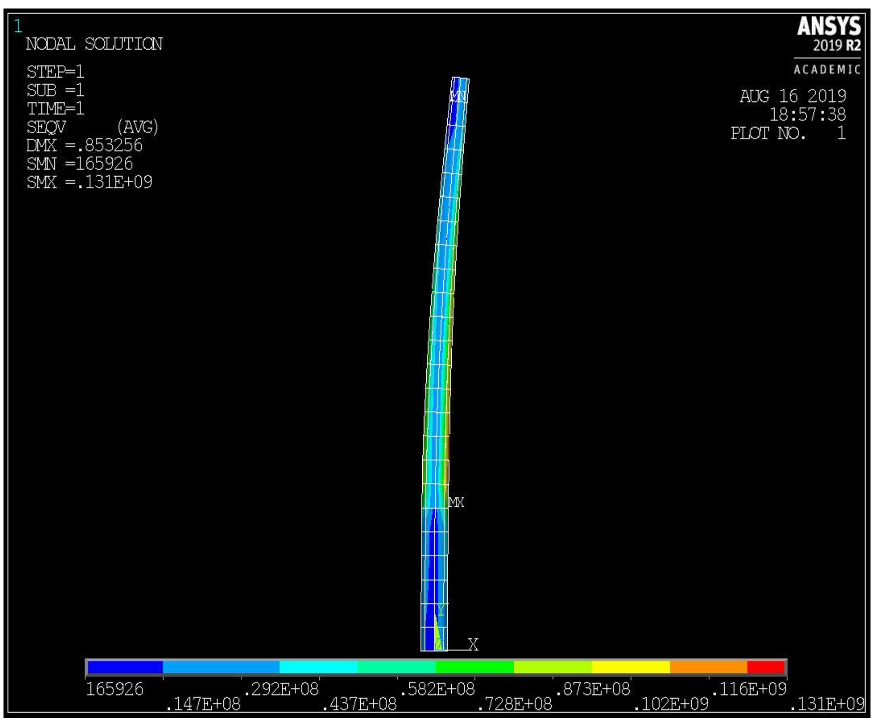


Figure 4.8: Von Mises stress of load case 1

In order to compare the load cases results easily, the results are tabulated in a table and the percent change is calculated 4.1 below

Table 4-1: Max displacement and max Von Mises stress

Load case (LC)	Max Displacement (m)	Max Von Mises (Pa)
LC 1	0.968878	0.131E+09
LC 2	0.853256	0.131E+09
% Change	-11.93 %	0

From the table 4.1 above it is evident the load case 1 create higher displacement of the support structure. The maximum displacement for the load case 1 is about 0.97m however, when the application is change to load case 2, the max displacement decreases by 11.9%.

On the other hand, the Von Mises stress remain the same for both load cases which is about 0.131E+09pa (131Mpa). This means the change of wave load direction has no effect on the Von Mises stress consequently, the percent change of the Von Mises is zero.

Most noticeably, the Von Mises stress is less than the yield strength of steel which is about 250Mpa, this is very important because Von Mises criterion states that yielding of ductile material begins when the Von Mises stress is equal or greater than the yield strength of the material. The Von Mises criterion is given by the equation 4.1 below

$$\sigma_v \geq \sigma_y \tag{4.1}$$

$$\sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \geq \sigma_y \tag{4.2}$$

Where,

σ_v = Von Mises stress

σ_y = Yield strength

σ_1 ,σ_2, σ_3= Principal Stresses

From the result of the Von Mises stress it is evident the Von Mises stress are higher at the tower when compared to the monopile. This means that failure will begin at tower before the monopile when the load is increased. Therefore, in order to reduce the stresses in the tower two alternative solutions are proposed.

3. Increase in the thickness of the tower will reduce the stresses in the tower. however, this will come with economical expenses and should be done in a logical way
4. Decrease the tower height. This will reduce the overall aerodynamic load on the wind turbine consequently it will reduce stresses on the tower. However, there’s a drawback to this, the wind power extracted by the wind turbine will compromised since lower altitude means low wind speed.

5 CONCLUSION

In this thesis, structural analysis is carried out on the support structure of an offshore wind turbine. In the process, standard NREL 5MW wind turbine is chosen for the analysis. The main goal of the research is to investigate the response of the turbine under some assumed environmental load conditions. The thesis is divided in chapters which will be summarized shortly.

The first chapter of the thesis give the introduction about OWT in general, the benefit of OWT, the type support structure in the OWT industry. It went further to give literature review of past research done other researchers in similar field.

The second chapter presented the specification of the NREL 5MW turbine and the monopile. Furthermore, the chapter presents the scope and limitations of the thesis, necessary assumptions are made in order to simplify the problem, for instance the soil monopile interaction is neglected and it is assumed the monopile has a static fixed support at the sea bed.

In chapter 3 necessary theoretical background related to the problem of the thesis is presented and it is followed by calculations of the loads. To make the calculations more reliable, renowned recommended standard practices are used to calculate the aerodynamic and hydrodynamic loads. One of the standards used in this thesis is the American petroleum institute (API) standard, it is applied in the calculations for the wave loads. Recommended practice by Det Norske Veritas (DNV) is used for the wind load calculations on the tower while the rotor thrust load calculations is as giving by the NREL 5MW wind turbine. However, an alternative rotor theory solution was given for calculating the rotor thrust.

In chapter 4 the loads calculated in the previous chapter and constrains on the support structure will be defined to set up on the support structure. Using finite element analysis software ANSYS APDL the calculations of the response of the support structure is carried out. Load cases is assumed in order to see the response of the support structure under a maximum worst case scenario. The two load cases that will be investigated are

- **Load Case 1:** The aerodynamic loads as well as the hydrodynamic loads are acting in the same direction on the support structure and it is assumed the loads are collinear. The dead load acts due to gravity therefore, it acts downward in all cases.
- **Load Case 2:** The aerodynamic and hydrodynamic loads are acting in opposite direction on the support structure. It is also assumed the loads are collinear as well. The dead acts downward in this case as well.

Results of the simulations are presented and analyzed. Two main areas are looked at, the displacement of the support structure and the stresses field in the support structure. Form the results, it is evident the load case 1 create higher displacement of the support structure. The maximum displacement for the load case 1 is about 0.97m however, when the application is change to load case 2, the max displacement decreases by 11.9%.

On the other hand, the Von Mises stress remain the same for both load cases which is about 0.131E+09pa (131Mpa). This means the change of wave load direction has no effect on the Von Mises stress. Two alternative suggestions are made in order to reduce the stress field in the tower. These are listed below

- Increase in the thickness of the tower will reduce the stresses in the tower. however, this will come with economical expenses and should be done in a logical way
- Decrease the tower height. This will reduce the overall aerodynamic load on the wind turbine consequently it will reduce stresses on the tower. However, there’s a drawback to this, the wind power extracted by the wind turbine will compromised since lower altitude means low wind speed.

5.1 Suggestion for further research

In regards to the limitation of thesis which are presented in the second chapter. Suggestion for further research are listed below.

- Since the study this thesis does not include sea current effect on the support structure, further research can incorporate combined effect of current as well.
- The thesis modelled the support structure as fixed in the sea be however, in reality it is not fixed. There is a soil monopile interaction which might be important to look at
- Other research can look at dynamic analysis of the support structure which involve time dependency of the loads on the support structure.
- Another important area to look at is the natural frequency of support structure, because there is a possibility of vibration that might lead to resonance.

•

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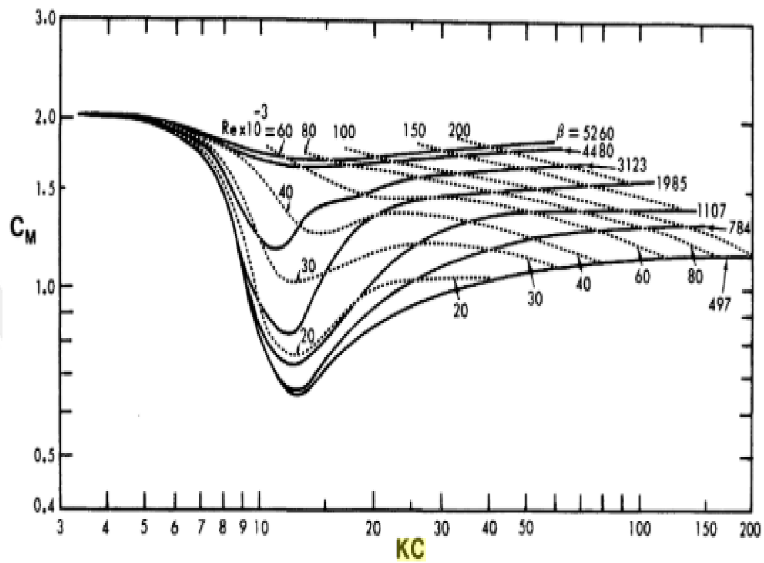
APPENDIXES

Appendix A	:DNV graph of C_M and C_D
Appendix B	:Steps for calculating hydrodynamic load as provided by API standard
Appendix C	:Support Structure Geometry
Appendix D	: Loads on Nodes for two cases

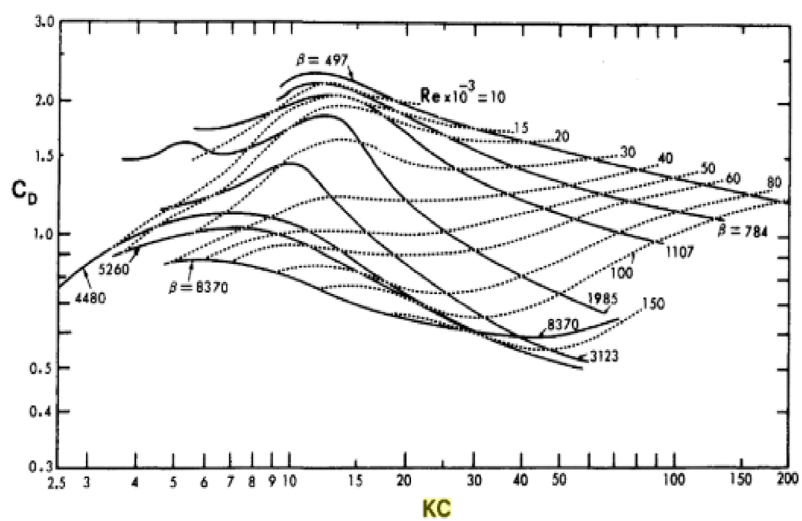
Appendix A

DNV graph of C_M and C_D



C_M vs KC for various Reynolds number or Sarpkaya Beta β

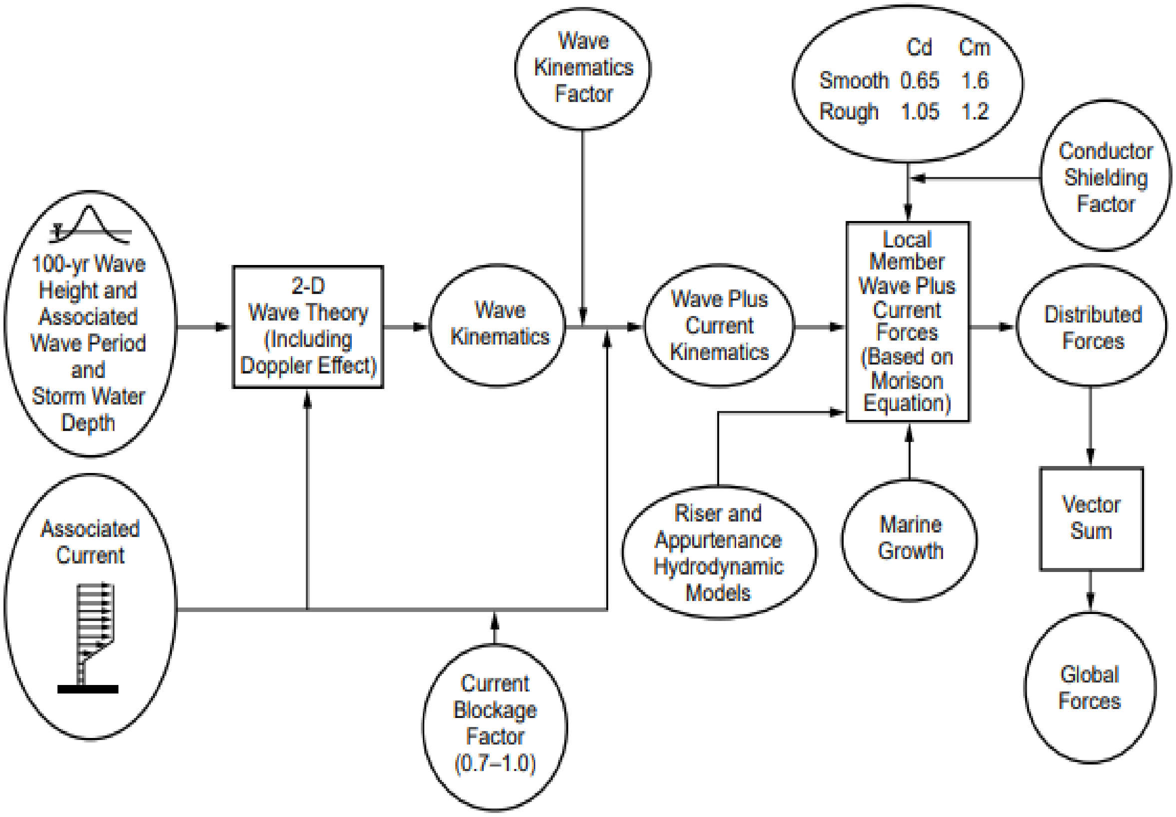
Retrieved (Sarpkaya & Isaacson , 1981)



C_D vs KC for various Reynolds number or Sarpkaya Beta. Source (Sarpkaya & Isaacson , 1981)

Appendix B

Steps for calculating hydrodynamic load as provided by API standard



Appendix C

Support Structure Geometry

Elevation	Radius	Diameter
90	1.93499	3.86998
85	2.001553	4.003106
80	2.068116	4.136233
75	2.134679	4.269359
70	2.201243	4.402485
65	2.267806	4.535611
60	2.334369	4.668738
55	2.400932	4.801864
50	2.467495	4.93499
45	2.534058	5.068116
40	2.600621	5.201243
35	2.667184	5.334369
30	2.733748	5.467495
25	2.800311	5.600621
20	2.866874	5.733748
15	2.933437	5.866874
10	3	6
5	3	6
0	3	6
-5	3	6
-10	3	6
-15	3	6
-20	3	6
-25	3	6

-30	3	6

Appendix D

list of Loads On nodes for load case 1 on the support structure Model

```
LIST NODAL FORCES FOR SELECTED NODES        1 TO       25 BY        1
CURRENTLY SELECTED NODAL LOAD SET= FX    FY    FZ    MX    MY    MZ

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01055371  VERSION=WINDOWS x64   12:51:22  AUG 20, 2019 CP=      2.406
```

NODE	LABEL	REAL	IMAG
1	FX	448913.180	0.00000000
2	FX	781091.300	0.00000000
2	FY	-169516.800	0.00000000
3	FX	457209.960	0.00000000
4	FX	482406.990	0.00000000
5	FX	525435.600	0.00000000
6	FX	587886.400	0.00000000
7	FX	672067.800	0.00000000
8	FX	21997.2000	0.00000000
9	FX	18810.9000	0.00000000
10	FX	812365.000	0.00000000
10	FY	-3990511.80	0.00000000
11	FX	23457.1000	0.00000000
12	FX	24288.2000	0.00000000
13	FX	24818.9000	0.00000000
14	FX	25123.6000	0.00000000
15	FX	25218.1000	0.00000000
16	FX	25235.0000	0.00000000
17	FX	25154.2000	0.00000000
18	FX	24943.0000	0.00000000

NODE	LABEL	REAL	IMAG
19	FX	24715.0000	0.00000000
20	FX	24430.5000	0.00000000
21	FX	24097.3000	0.00000000
22	FX	23667.6000	0.00000000
23	FX	23253.3000	0.00000000
24	FX	22805.3000	0.00000000
25	FX	22271.4000	0.00000000

list of Loads On nodes for load case 2 on the support structure Model

```
LIST NODAL FORCES FOR SELECTED NODES         1 TO        25 BY         1
CURRENTLY SELECTED NODAL LOAD SET= FX    FY    FZ    MX    MY    MZ

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01055371  VERSION=WINDOWS x64   10:03:51  AUG 20, 2019 CP=       2.438
```

NODE	LABEL	REAL	IMAG
1	FX	-448913.180	0.00000000
2	FX	-781091.340	0.00000000
2	FY	-169516.800	0.00000000
3	FX	-457209.960	0.00000000
4	FX	-482406.990	0.00000000
5	FX	-525435.640	0.00000000
6	FX	-587886.430	0.00000000
7	FX	-672067.770	0.00000000
8	FX	21997.2000	0.00000000
9	FX	18810.9000	0.00000000
10	FX	812365.000	0.00000000
10	FY	-3990511.80	0.00000000
11	FX	23457.1000	0.00000000
12	FX	24288.2000	0.00000000
13	FX	24818.9000	0.00000000
14	FX	25123.6000	0.00000000
15	FX	25218.1000	0.00000000
16	FX	25235.0000	0.00000000
17	FX	25154.2000	0.00000000
18	FX	24943.0000	0.00000000

NODE	LABEL	REAL	IMAG
19	FX	24715.0000	0.00000000
20	FX	24430.5000	0.00000000
21	FX	24097.3000	0.00000000
22	FX	23667.6000	0.00000000
23	FX	23253.3000	0.00000000
24	FX	22805.3000	0.00000000
25	FX	22271.4000	0.00000000

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