

**Modal Dynamics of Combined Offshore Wind Turbine and
Monopile Foundation System:
A Seismic Impact Assessment Study on System Dynamism**

ديناميكيات مشروطة لتوربينات الرياح البحرية المدمجة ونظام الأساس الأحادي:
دراسة تقييم التأثير الزلزالي على ديناميكية النظام

by

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**Dissertation submitted in partial fulfilment
of the requirements for the degree of
MSc STRUCTURAL ENGINEERING
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ABSTRACT

For the sustainability transition to evolve at a rapid pace, complex engineering systems are required to be reliable and effective in their operability. Even though offshore wind energy systems are a few decades old now, global adoption is not strong due to reliability issues, construction, operation, and maintenance complexities. The primary uncertainty in the structural engineering of this system lies in the dynamic behavior which is almost impossible to accurately compute. Seismic interactions at the seabed further complicate this. This dissertation conducts an in-depth modal dynamics analysis of an integrated offshore wind turbine and monopile foundation system, employing finite element analysis techniques. The study encompasses frequency domain analysis, eigenvalue extraction, and modal dynamic steps, incorporating seismic loads inspired by significant earthquake events, and the seismic impact on the system's dynamism is evaluated by evaluating system field and history outputs across system modal dynamics. Critical insights regarding the geometric variation effects on the dynamic traits of the combined system are retrieved by careful comparative evaluation.

خلاصة

لكي يتطور انتقال الاستدامة بوتيرة سريعة ، يجب أن تكون الأنظمة الهندسية المعقدة موثوقة وفعالة في قابليتها للتشغيل . على الرغم من أن أنظمة طاقة الرياح البحرية عمرها بضعة عقود الآن ، إلا أن التبني العالمي ليس قويا بسبب مشكلات الموثوقية وتعقيدات البناء والتشغيل والصيانة . يكمن عدم اليقين الأساسي في الهندسة الإنشائية لهذا النظام في السلوك الديناميكي الذي يكاد يكون من المستحيل حسابه بدقة . التفاعلات الزلزالية في قاع البحر تزيد من تعقيد هذا . تجري هذه الأطروحة تحليلا متعمقا لديناميكيات مشروطة لتوربينات الرياح البحرية المتكاملة ونظام الأساس الأحادي ، باستخدام تقنيات تحليل العناصر المحدودة . تشمل الدراسة تحليل مجال التردد ، واستخراج القيمة الذاتية ، والخطوات الديناميكية المشروطة ، ودمج الأحمال الزلزالية المستوحاة من أحداث الزلازل الكبيرة ، ويتم تقييم التأثير الزلزالي على ديناميكية النظام من خلال تقييم مجال النظام ومخرجات التاريخ عبر ديناميكيات النظام المشروطة . يتم استرجاع الأفكار النقدية المتعلقة بتأثيرات التباين الهندسي على السمات الديناميكية للنظام المدمج من خلال التقييم المقارن الدقيق .

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Chapter 1: Literature Review

A methodical approach was used to gather relevant literature on AI-enabled dynamic response prediction of offshore wind turbines under seismic activity, specifically investigating soil-model parametric dependencies, for the review. Different scholastic data sets and web crawlers were used, including however not restricted to IEEE Xplore, ScienceDirect, and Google Researcher. The inquiry watchwords included blends of terms, for example, "Simulated intelligence," "dynamic reaction expectation," "seaward wind turbines," "seismic action," and "soil-model parametric conditions." The indexed lists were separated in light of importance and materialness to the exploration point. An extensive survey of the chose articles was directed to extricate significant experiences and discoveries for the examination.

The motivation behind this audit is to examine the dirt model parametric conditions with regards to man-made intelligence empowered powerful reaction forecast of seaward wind turbines under seismic action. A thorough and thorough method of article sourcing and collection was used to accomplish this. An overview of the method used to find relevant articles and gather the necessary data is provided in this section.

- Literature Search

A thorough literature search was the first step in the process of sourcing articles. Relevant scholarly articles were identified using a variety of academic databases, including IEEE Xplore, ScienceDirect, ACM Digital Library, and Google Scholar. "AI-enabled dynamic response prediction," "offshore wind turbines," "seismic activity," and "soil-model parametric dependencies" were among the search terms and phrases used. Both friend inspected diaries and gathering procedures were considered to guarantee a complete survey of the subject.

- **Consideration and Prohibition Models**

Specific inclusion and exclusion criteria were established to maintain the review's focus. Only English-language articles were taken into consideration. The time span for consideration was set from the earliest accessible distributions until the present. The articles were required to investigate the soil-model parametric dependencies and the dynamic response prediction of offshore wind turbines during seismic activity. Excluded were studies that only dealt with onshore wind turbines or other kinds of dynamic loads.

- **Selection and screening**

A screening procedure was carried out after the initial pool of articles was retrieved. The articles' titles and abstracts were looked at to see how relevant they were to the research topic. The inclusion criteria were not met or the articles were deemed irrelevant. To determine whether they were suitable for inclusion in the review, the remaining articles were subjected to full-text analysis. The last determination of articles depended on their substance's arrangement with the exploration targets and their commitment to understanding the dirt model parametric conditions in computer based intelligence empowered powerful reaction forecast.

- **Extraction of Data**

Relevant information was extracted from each article and arranged for analysis. This included information about the authors, the year of the publication, the study's goals, the research methodology, the experimental setup, the AI methods used, and the most important results regarding parametric dependencies between soil models. After that, the extracted data were combined to discover recurring patterns, divergent results, and knowledge gaps in the existing literature.

- An Archive of Articles

The chose articles were gathered and ordered in an organized way. To maintain academic integrity and make reference easier in the future, proper citation and referencing practices were used.

By following this thorough course of article obtaining and assortment, a far reaching and very much established survey of the man-made intelligence empowered unique reaction forecast of seaward wind turbines under seismic action, with a particular spotlight on soil-model parametric conditions, was accomplished. The ensuing areas of this audit will introduce an examination of the accumulated data and feature the critical discoveries and exploration holes in the field.

1.1 Purpose of Literature Review

In any research project, including the examination of seismic analysis techniques for offshore wind turbine (OWT) foundations, the purpose of a literature review is crucial.

The following is a list of important functions performed by the literature review:

- Defining the Setting:
- Finding Studies of Relevance: Researchers can find relevant studies and research papers that are relevant to the research topic with the help of a literature review. It aids in selecting the most influential and appropriate sources that enhance comprehension of OWT foundation seismic analysis techniques. Researchers can build on existing knowledge and avoid duplicate efforts by reviewing previous studies.
- Information for Synthesizing: The literature review makes it possible to combine data from a variety of sources. In order to acquire a comprehensive comprehension of the subject, it involves analyzing, summarizing, and integrating the results of numerous

studies. Researchers can identify patterns, trends, and knowledge gaps by synthesizing the data. These findings can help advance the field and inform their own research.

- **Assessing Techniques:** Researchers can critically evaluate the methods used in previous studies with the help of a literature review. It aids in determining the advantages and disadvantages of various OWT foundation seismic analysis techniques. By looking at the methods, researchers can figure out which methods are best for their own research and how to overcome any limitations found in previous studies.
- **Finding Research Deficits:** The literature review enables researchers to pinpoint areas in which additional research is required and fill in knowledge gaps. Researchers are able to identify specific research questions and objectives that will contribute to filling these gaps by understanding the current state of research on seismic analysis methods for OWT foundations. This contributes to expanding knowledge and moving the field forward.

In a nutshell, the goal of a literature review is to establish the context, identify pertinent studies, synthesize information, evaluate methodologies, and discover research gaps. It serves as the research study's foundation, allowing researchers to build on previous knowledge, critically evaluate previous studies, and advance the field of OWT foundation seismic analysis methods.

1.2 Overview of Chapter Structure

The chapter provides a comprehensive overview of various aspects of Offshore Wind Turbine (OWT) foundation design and seismic analysis. It talks about a lot of different things, like how important seismic considerations are for OWT structures, how seismic damage has been seen in OWT structures, and the problems with seismic design that OWT wind farms

face. Monopiles are the primary focus of the discussion, which also includes a comparison to other foundation systems for OWTs [\[1\]](#). These foundation systems' performance under seismic loading is also examined. In order to accurately represent the behavior of the soil in seismic analysis, the significance of soil modeling in Soil-Structure Interaction (SSI) is emphasized. The parametric dependencies and uncertainties of linear and nonlinear soil models, as well as their advantages and disadvantages, are discussed. The choice of reasonable soil models for seismic investigation is additionally tended to.

Seismic hazard analysis, ground motion selection and scaling, a comparison of linear and nonlinear methods, static and dynamic analysis, as well as time-history and response spectrum analysis, are all explored as seismic analysis techniques for OWT foundations. Contextual Analyzes are introduced to show the use of these strategies in OWT establishment frameworks [\[2\]](#).

In addition, the chapter delves into the seismic design standards for OWT foundations, providing a summary of the relevant codes and guidelines and contrasting them with international standards. The difficulties that arise when these codes are applied to foundation systems are identified. Soil-constitutive models and cutting-edge geotechnical engineering simulation methods like the finite element method, boundary element method, mesh generation, and model simplifications are all covered in depth. Emphasis is placed on the significance of model validation and calibration. The potential for artificial intelligence (AI) and machine learning (ML) to improve dynamic response prediction is highlighted in this investigation of their use in geotechnical engineering. Case studies of AI-enabled analysis in OWT foundation systems and machine learning algorithms for dynamic response prediction are presented.

A summary of the findings of the literature review, the identification of research gaps, and justification for the proposed research round out the chapter. Seismic analysis, foundation types, soil modeling, seismic analysis methods, design standards, advanced simulation techniques, and AI applications are all highlighted in this chapter's comprehensive overview of the structure [\[3\]](#). It sets the establishment for additional exploration and examination in the field of OWT establishment frameworks under seismic action.

Chapter 2: Earthquake Effects on Offshore Structures

2.1 Importance of Seismic Considerations in OWT Structures

The foundation systems for OWTs (Offshore Wind Turbines) have a number of challenges. First, the marine environment is severe, thus they are difficult to build and engineer [4]. It takes experience to come up with solutions that are both cost-effective and reliable while withstanding wave pressures and seabed conditions [5]. Second, there is a large price tag attached to both setup and upkeep. Costs rise with the necessity of specialized vessels and equipment, as well as the regular upkeep of inspecting, cleaning, protecting, and repairing them [6]. Thirdly, there is the issue of environmental impact. Disturbance of the seafloor due to construction can have negative effects on marine life. Effective evaluations and countermeasures are essential for limiting negative outcomes [1].

Seismic variables play an important role in the design and operation of offshore wind turbines (OWTs) because of the risks posed by earthquakes. While offshore structures are more earthquake-proof than their on-land counterparts, they are nonetheless susceptible to tremors. Understanding and accounting for seismic risks is crucial for ensuring the durability, safety, and reliability of OWTs [7; 5]. The primary reason for considering seismic effects in OWT projects is the probability of earthquakes in offshore areas [5]. Even while earthquakes are more commonly associated with onshore areas, offshore seismic activity can nonetheless pose a hazard in regions with active fault lines or tectonic activity [1]. Offshore wind farms are frequently found in coastal locations, which are more prone to seismic activity since they are often located near tectonic plate borders or undersea faults [5]. In order to assess hazards and implement appropriate design measures, it is essential to conduct a seismic hazard assessment [4].

Multiple aspects of seismic safety must be considered while constructing an OWT building. The dynamic behavior of the OWT's foundation system in the presence of earthquake ground vibrations must first be evaluated [8]. Soil-structure interaction (SSI) impacts and horizontal and vertical ground accelerations are examples of seismic loads that must be described. In earthquake-prone areas, it is essential that the designs of OWTs (Offshore Wind Turbines) incorporate seismic safety measures [3]. The seismic response of OWT buildings depends on a number of elements, such as soil-structure interaction (SSI), structural dynamics, and soil properties [9].

During earthquakes, the OWT's foundation system interacts with the soil underneath it, a phenomenon known as seismic soil interaction (SSI) [8]. Stiffness, damping, and soil amplification effects are all dynamic soil properties that can have a major impact on how a building reacts. When evaluating SSI, it is important to take into account the fact that different soil types behave differently during seismic events. In order to understand the structural dynamics of an OWT, the complete system's reaction to seismic forces must be analyzed, from the tower to the transition piece to the base [9]. The structure's inherent frequencies, mode shapes, and damping properties are all taken into account in this research. The building's ability to endure seismic energy without experiencing excessive vibrations or failure is determined by analyzing its dynamic response. Both SSI and structural dynamics are highly influenced by the soil type. Ground vibrations and the forces communicated to the foundation system may be greater in soft soils like clay or loose sands because of the amplification of seismic waves. Amplification effects are reduced in soils that are stiff or thick [9]. The SSI response and the structural behavior during seismic events are both heavily influenced by the soil's qualities, such as its shear modulus, density, and damping characteristics [10; 11]. Seismic factors are taken into account by conducting in-depth geotechnical investigations to

learn about the soil properties and behavior at the OWT site. Complex numerical models and studies are then used to mimic the building's response to earthquakes using the data gathered [\[12\]](#). To make sure the OWT building is safe and resilient during earthquakes, designers take steps including optimizing the foundation design, installing dampening devices, and using the right soil-structure interaction models [\[13\]](#).

2.1.1 Soil-Structure Interaction Under Seismic Activity

The term "soil-structure interaction" (SSI) is used to describe the dynamic influence and mutual effect that the soil has on a building's or infrastructure's structure when an earthquake occurs. The soil deforms as seismic waves travel through it, which modifies the structure's response [\[14\]](#). When it comes to calculating the stresses, displacements, and vibrations that a building would feel during an earthquake, SSI is crucial. In order to guarantee the stability and performance of structures under seismic loading circumstances, it is essential that the design and analysis processes take into account the effects of SSI [\[15\]](#).

2.1.2 Soil Modeling Techniques and The OWT's Global Dynamic Response Under Lateral Excitations

For the purpose of simulating the response of OWT (Offshore Wind Turbine) structures to lateral excitations, soil modelling techniques are employed [\[16\]](#). Finite element and finite difference approaches are frequently employed, with the soil typically represented as a continuum using appropriate constitutive models. Soil features including stiffness, damping, and nonlinear behavior are taken into account by these models. Engineers can evaluate the global dynamic response of OWT structures, including the tower, the foundation, and other components, to lateral excitations by including soil models into the study (Lopez et al., 2020). The seismic and lateral loading performance of the OWT system can be better understood with the help of this research [\[16\]](#).

2.2 Structures Observed Seismic Damage in OWT Structures

The susceptibility and sensitivity of these systems under earthquake conditions have been shown by the study of seismic damage in offshore wind turbine (OWT) structures. Although OWTs are built to handle a variety of environmental pressures, including as wind and waves, the dynamic nature of earthquakes and the interaction with the offshore environment can present unique issues. Seismic damage to OWT structures has been reported on multiple occasions, demonstrating the significance of taking earthquake effects into account [\[17\]](#). Foundational issues are frequently reported as a leading cause of damage. Monopile, jacket, or gravity-based foundations interact with the seafloor and the surrounding soil to sustain OWTs [\[18\]](#). Foundation failure, soil liquefaction, or excessive strains in the supporting structure can be brought on by seismic shaking if the foundation moves laterally or vertically too much [\[19\]](#). OWTs have experienced problems with their tower and supporting structures during earthquakes. Deformations, buckling, or even collapse may occur in these parts as a result of ground motions' dynamic stress, resonance effects, and increased fatigue. Earthquakes can also increase vibrations and reduce operational efficiency by altering the dynamic behavior of the turbine blades and the rotor-nacelle assembly [\[20\]](#). There has to be strong design and mitigation techniques for OWT structures because of the seismic damage that has been documented.

Table 1: Different Components Of Offshore Wind Turbines (OWTs) and their Corresponding Effect

Component	Observed Seismic Damages	Effects
Foundations	Settlement, cracking, tilting	Reduced stability, misalignment
Towers	Structural deformation, bending	Increased stress, reduced load capacity
Supporting Structures	Weld failures, brace buckling	Loss of structural integrity, instability
Rotor-Nacelle Assemblies	Blade damage, misalignment, vibrations	Decreased efficiency, increased wear

Damage to an OWT (Offshore Wind Turbine) can be greatly affected by the soil type at the location. Soil types respond differently to various loading conditions, such as earthquakes and high winds. More settlement and lateral movement could occur in soft soils like clay or loose sands, which could compromise the integrity of the foundation or even cause structural damage. Alternatively, the risk of excessive deformations is reduced and support is improved with stiffer or denser soils [\[21\]](#). In order for engineers to build foundations and structural systems that can survive the particular soil conditions and minimize the possibility for damage to the OWT, geotechnical investigations and evaluations are essential [\[22\]](#).

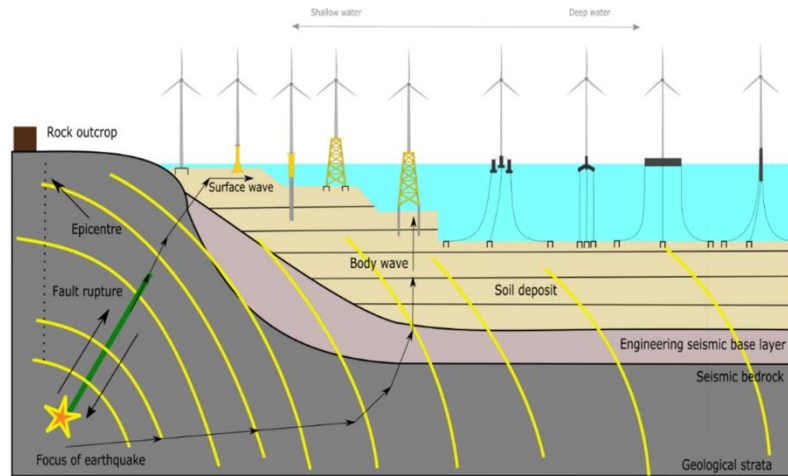


Figure 1: Seismic Damage on OWTs

2.3 Seismic Design Challenges in OWT Wind Farms

Seismic design for offshore wind farms provides unique challenges compared to onshore structures due to the complex interaction between wind turbines, their foundations, and the maritime environment [\[23\]](#). These challenges must be addressed in order for offshore wind farms to operate safely and reliably, particularly in seismically active regions. The correct characterization of seismic hazards unique to offshore environments is one of the primary design problems [\[24\]](#).

Table 2: Comparing the Characteristics of Seismic Hazards in Offshore and Onshore Environments

Characteristic	Offshore Environment	Onshore Environment	Implications for Wind Turbine Design
Ground Motion	Generally lower due to attenuation in water	Higher ground motion due to direct coupling with the ground	Offshore turbines may require less robust foundation systems compared to onshore turbines
Soil Conditions	Consistent and predictable seabed conditions	Heterogeneous and variable soil conditions	Offshore turbines may benefit from more reliable and uniform soil conditions for foundation design
Water-Soil Interaction	Water can mitigate seismic forces on the foundation	Direct interaction between soil and structure	Onshore turbines may require more robust foundation systems to account for soil-structure interaction
Wave-Induced Effects	Wave loading and wave-induced vibrations	No wave-induced effects	Offshore turbines may need to account for additional dynamic loads and vibrations caused by waves
Environmental Loads	Marine corrosion and salt spray	Less exposure to marine corrosion and salt spray	Offshore turbines may require more corrosion-resistant materials and protective coatings
Accessibility and Maintenance	Limited accessibility and more challenging maintenance	Easier accessibility and maintenance	Offshore turbines may require specialized equipment and procedures for maintenance
Offshore Infrastructure	Additional costs for offshore support structures	Existing onshore infrastructure may be readily available	Offshore turbines may have higher initial installation and maintenance costs

The seismic source characteristics, ground motion amplification, and potential tsunamigenic effects of offshore seismicity might vary greatly from those of onshore locations and necessitate extensive site-specific investigations. To properly evaluate the seismic loads operating on the wind turbines and their foundations, these considerations must be incorporated into the design process. Soil-structure interaction (SSI) impacts are another factor to think about [25]. The interaction between the seafloor and the bases of offshore wind

turbines can have a major impact on how they react to earthquakes. Soil liquefaction potential, lateral spreading, and soil-pile interaction are all dynamic behaviors of the foundation-soil system that must be taken into account in the design to keep the building standing [26; 27]

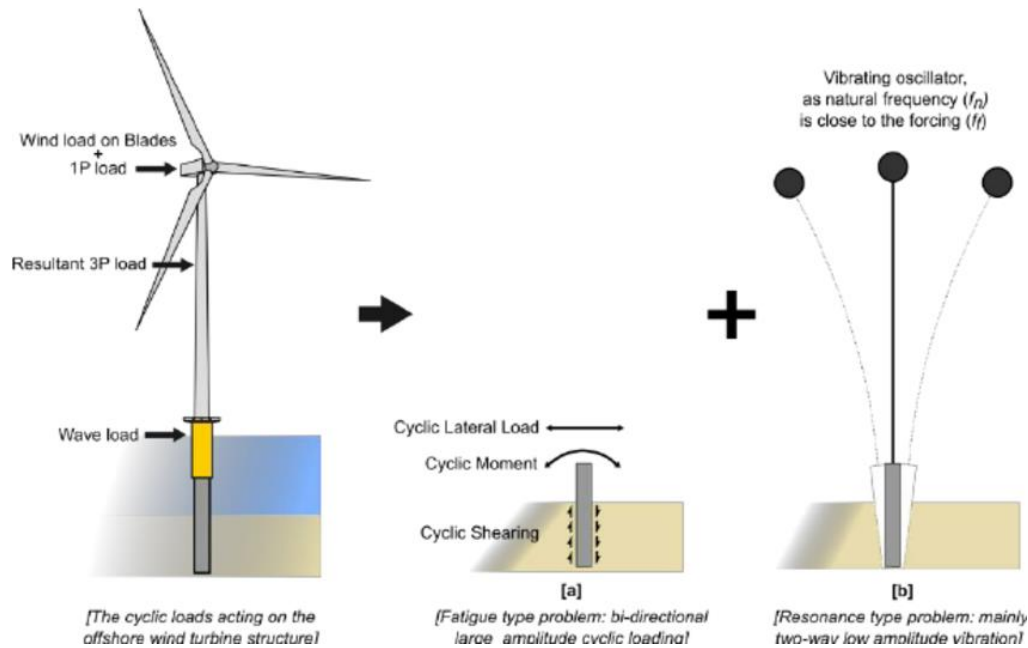


Figure 2: SSI Impacts the Response of Offshore Wind Turbines to Earthquakes, Including Soil Liquefaction

Source: https://www.researchgate.net/figure/Breakdown-of-Soil-Structure-Interaction-of-Offshore-Wind-Turbines-into-two-types-of_fig3_289585642

Assessment of dynamic response and fatigue life under seismic stress is further complicated by the dynamic character of offshore wind turbines. Accurately predicting the structural response and identifying potential failure modes from the interaction of the turbine blades, rotor-nacelle assembly, tower, and base needs sophisticated modelling approaches. For reliable seismic design, it is essential to take into account the dynamic behavior of the entire system, including the aerodynamic loads and the hydrodynamic impacts [28]. Offshore wind farm installation and upkeep are additionally complicated in seismically active areas [29].

Earthquakes can have a significant effect on installation vessels, worker safety, and the stability of equipment, all of which must be taken into account during the building and installation processes. In addition, regular inspections of the wind turbines and their bases are necessary to identify any deterioration or damage caused by earthquakes [\[30\]](#).

Seismic design difficulties in offshore wind farms need for an in-depth familiarity with seismic hazards, a precise characterization of SSI impacts, and an awareness of the system's dynamic behavior. To guarantee the structural integrity, safety, and dependable operation of offshore wind turbines in seismically active locations, it is essential to address these problems by advanced modelling, site-specific research, and robust design solutions [\[31\]](#).

2.3.1 Direct Impact of Soil Modeling Techniques on the Performance of OWTs During Seismic Activities

The effectiveness of OWTs (Offshore Wind Turbines) during seismic activity can be evaluated with the help of soil modelling tools [\[32\]](#). The reliability of forecasts about the OWT system's structural response, stability, and safety is directly influenced by these methods. Engineers can better predict how a building will respond to seismic loads if they have access to precise soil models [\[33\]](#).

Table 3: Impact of Soil Modeling Techniques on Offshore Wind Turbine (OWT) Performance During Seismic Activities

Soil Modeling Technique	Impact on OWT Performance during Seismic Activities
Simplified Equivalent Method	Limited accuracy in capturing complex soil-structure interaction effects
Linear Elastic Analysis	Underestimates non-linear soil behavior and may lead to conservative results
Nonlinear Soil Models	Provides more realistic representation of soil behavior and interaction
Soil-Structure Interaction	Incorporates dynamic interaction between the foundation and surrounding soil
Advanced Numerical Modeling	Offers detailed analysis of soil-structure interaction and foundation response

Analysis of the OWT's dynamic behavior is improved by including appropriate soil constitutive models and taking into account aspects like soil stiffness, damping, and nonlinearity. OWT performance in seismic events is dependent on a number of variables, including as the structure's dynamic response, stresses, displacements, and accelerations [\[35\]](#).

Engineers can then use the precise estimates to create foundations and structural systems that can withstand the predicted seismic forces with the aid of soil modelling tools. Engineers can improve the OWT's seismic performance by optimizing the design, choosing the right foundation types, and enacting mitigation measures based on their knowledge of the soil-structure interaction. This involves checking the stability of the foundation system and taking into account the impacts of soil amplification [\[36\]](#).

Table 4: Soil Modeling Technique

Soil Modeling Technique	Model Details	Impact on Seismic Response of OWTs	References
Linear Elastic Model	The straight versatile model is a worked-on approach used to investigate the way of behaving of seaward wind turbine (OWT) establishments. It expects straight flexible material way of behaving, ignores non-direct impacts, and considers the establishment as an unbending body upheld by soil springs, empowering assessment of primary reactions under various stacking conditions.	During seismic events, the linear elastic model for offshore wind turbine (OWT) foundations approximates their behavior by considering the dynamic forces and displacements caused by the seismic waves.	[37]
Nonlinear Elastic Model	An advanced method for analyzing the behavior of structures, such as offshore wind turbine (OWT) foundations, is the nonlinear elastic model. To accurately simulate the response under varying loading conditions, it takes into account nonlinear material behavior, geometric nonlinearity, and advanced constitutive models.	Offshore wind turbine (OWT) foundation seismic response analysis is significantly influenced by the nonlinear elastic model. It provides a more realistic representation of the foundation's behavior during seismic events by taking into account nonlinear material behavior and geometric effects.	[38]
Elasto-Plastic Model	An advanced method for analyzing the behavior of structures, such as the foundations of offshore wind turbines (OWTs), is the elasto-plastic model. It considers both versatile and plastic material way of behaving, integrating yield measures and plastic stream rules to precisely mimic the primary reaction under stacking conditions that surpass as far as possible.	The elasto-plastic model for seaward wind turbine (OWT) establishments empowers a more practical portrayal of their way of behaving during seismic occasions. It takes into account the behavior of both elastic and plastic materials, making it possible to simulate plastic deformation and yielding under seismic loads.	[39]
Advanced Constitutive Models (e.g. Modified Cam-Clay, Drucker-Prager, etc.)	The high level model, for example, the elasto-plastic model, altogether upgrades the examination of seismic reaction in seaward wind turbine (OWT) establishments by considering material nonlinearity and catching post-yield conduct, giving more precise expectations of underlying reaction and likely harm.	High level models, for example, elasto-plastic models, give a definite comprehension of how seaward wind turbine (OWT) establishments act during seismic occasions. The ability to accurately predict the structural response, potential damage accumulation, and failure mechanisms during seismic loading is made possible by these models, which take into account material nonlinearity, yielding, plastic deformation, and energy dissipation.	[40]

2.3.2 Specific Challenges in Modeling the Soil-Structure Interaction (SSI) and Impact on Operation of OWTs

There are a number of obstacles that must be overcome in order to accurately estimate soil-structure interaction (SSI) for offshore wind turbines (OWTs) [\[41\]](#). The difficulty is compounded by the lack of data and location-specific details. The OWT's design and operation could be jeopardized by inaccurate SSI modelling, which could result in an under- or overestimation of the structural response. It can cause problems including weak foundations, improperly assessed loads, and unstable buildings [\[42\]](#). This can make the building more vulnerable to earthquakes and other natural disasters, and can shorten its fatigue life or possibly cause it to collapse. Extensive geotechnical studies, cutting-edge numerical modelling tools, and validation against field measurements are essential for overcoming these obstacles. Accurate design, optimization of foundation systems, and increased operational safety for OWTs can result from improved SSI modelling, which in turn can lead to a better knowledge of the soil-structure behavior [\[43\]](#).

Offshore wind turbines (OWTs) provide special problems for accurately modelling soil-structure interaction (SSI) for sandy and clayey soils. Concerns about settling and lateral movement may arise because sandy soils are less stiff and more permeable than other types of soil. Underestimating foundation loads and jeopardizing stability can be the outcome of inaccurate SSI modelling for sandy soils. The stability of a foundation can be compromised by the swelling and shrinking of clayey soils, notwithstanding their greater stiffness. To reduce the likelihood of settlement and differential movements, an accurate model of SSI for clayey soils is essential [\[44\]](#). Both incidents highlight the importance of thorough site inspections and sophisticated soil modelling techniques for assuring the robust and dependable design and operation of OWTs.

Table 5: Challenges in SSI Modeling

Challenges in SSI Modeling	Potential Solutions/Methodologies	Impact on OWT Operation	References
Soil Complexity Behavior	To address the test of perplexing conduct in seaward wind turbine (OWT) establishments, a high-level system includes using progressed constitutive models. The foundation's response to complex loading conditions can be predicted with greater precision	Complex conduct in seaward wind turbine (OWT) establishments presents difficulties in plan and examination, requiring progressed displaying methods to guarantee precise forecasts and dependable execution evaluation.	[45]
Variation in Soil Properties	To address the variety in soil properties in seaward wind turbine (OWT) establishments, an answer includes directing site-explicit geotechnical examinations. As a result of these investigations, in-depth data on soil characteristics can be incorporated into stochastic modeling strategies to better capture the probabilistic nature of soil properties and enhance OWT foundation design and analysis.	Offshore wind turbines (OWTs) are impacted by variations in soil properties through their stability, structural integrity, and dynamic response, requiring precise assessment and design considerations to guarantee safe and effective operation.	[46]
Accurate Representation of Dynamic Load	Increased use of advanced numerical modeling techniques. Incorporating real-time monitoring and control systems. Implementing robust design criteria and standards. Conducting comprehensive structural health monitoring. Utilizing advanced sensing technologies for load estimation	Through the use of cutting-edge approaches, precise dynamic load representation on offshore wind turbines (OWT) assures dependable operation, enhanced structural integrity, and optimized performance, increasing the overall effectiveness and safety of OWT operation.	[47]

Chapter 3: Foundation Types for OWTs

3.1 Overview

The foundation is crucial to the stability and structural integrity of offshore wind turbines (OWTs). Different types of foundations have been created and used for OWTs because to the specific problems presented by the marine environment. Water depth, soil conditions, project needs, and site-specific factors all play a role in determining the best type of foundation to use [\[49\]](#). The monopile foundation is a popular option for OWTs. It is a single steel pile with a big diameter that is driven into the seafloor to a certain depth or until it hits a stable layer. Monopiles work best in mild climates with consistent soil and water levels [\[50\]](#). They have a high weight bearing capability, are easy to set up, and require little in the way of upkeep. However, scour protection or grouted connections may be necessary in softer soils or scour-prone places to improve stability and assure long-term performance. The jacket foundation is another kind of substructure that rests on the seafloor via a lattice of legs [\[51\]](#).

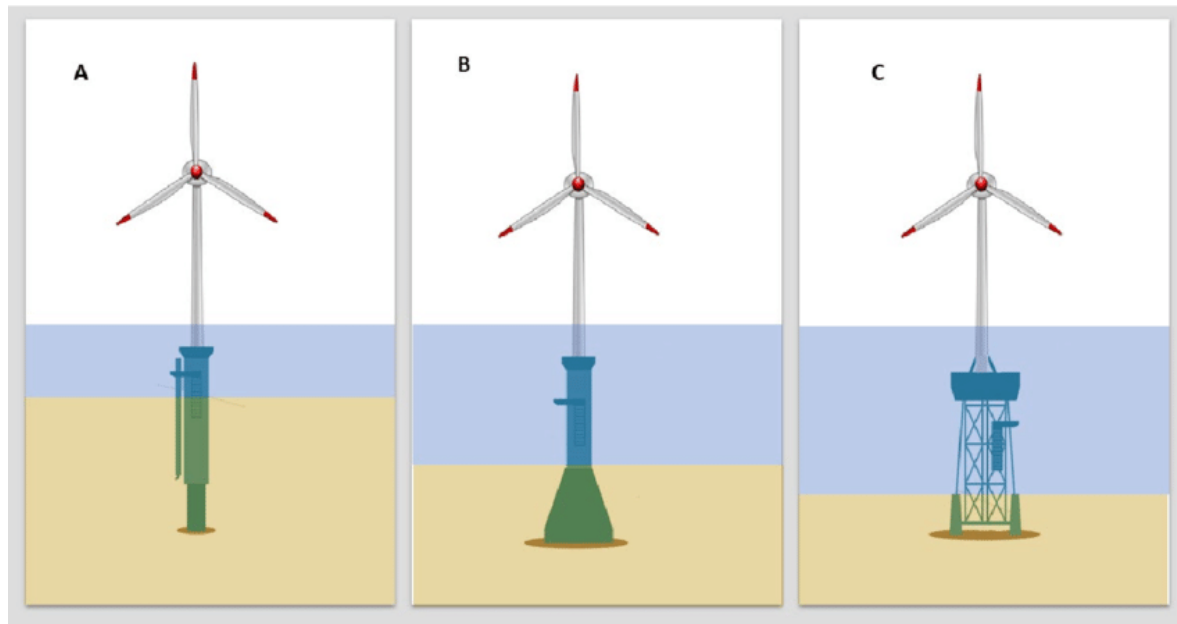


Figure 3: Different Types of Foundations for OWTs A. Monopile B. Gravity Based C. Jacket Foundation

When dealing with greater depths of water or more difficult soil, jacket foundations are the norm. They're sturdy, can hold a lot of weight, and won't buckle under side pressure. Jacket foundations are more difficult to design and fabricate than monopiles, necessitating sophisticated engineering analysis and unique building methods. Their modular design, however, simplifies both logistics and set up [\[52\]](#).

In places with soft or unstable soil, gravity-based foundations are another viable alternative for OWTs [\[53\]](#). Large concrete or steel constructions are designed to be self-weighted, with the added benefit of providing stability to the base. Installation of gravity-based foundations requires accurate alignment, and continued maintenance must take buoyancy and stability into account. Their load bearing capacity, scour resistance, and longevity are all impressive. Another interesting option for OWTs in deep-water settings are floating foundations [\[54\]](#). Tensioned cables or other anchoring devices are used to secure these bases to the ocean floor. Wind turbines may now be installed in regions that were previously

inaccessible thanks to floating foundations, which help alleviate some of the problems that arise from using traditional, ground-based installations. However, they add complexity to the design process in terms of dynamic response, mooring systems, and stability regulation [55; 56]. A thorough evaluation of site circumstances and project needs is necessary when deciding on a foundation type for OWTs [57]. Considerations for installation, upkeep, and cost-effectiveness, as well as environmental factors such water depth, soil type, wave height, and wind speed, must be made [58]. Foundation innovations, including as hybrid designs, innovative materials, and enhanced installation processes, are also the subject of continuing R&D to increase the performance and longevity of OWTs in different offshore settings [8].

3.2 Monopiles

Offshore wind turbines (OWTs) with monopile foundations have become the norm for a number of reasons. Because of its ease of use, low cost, and proven performance in the oil and gas industry, monopiles quickly rose to prominence. One tried and true method for supporting OWTs is to employ monopiles [18]. They have tried and true methods for design and implementation that allowed for quicker project development and rollout. When it came to supporting weight, monopiles were sturdy enough, lightweight enough, and simple enough to set up that they were the clear winner. Due to their proven reliability and other advantages, monopiles have become the standard for offshore wind turbines (OWTs) [11].

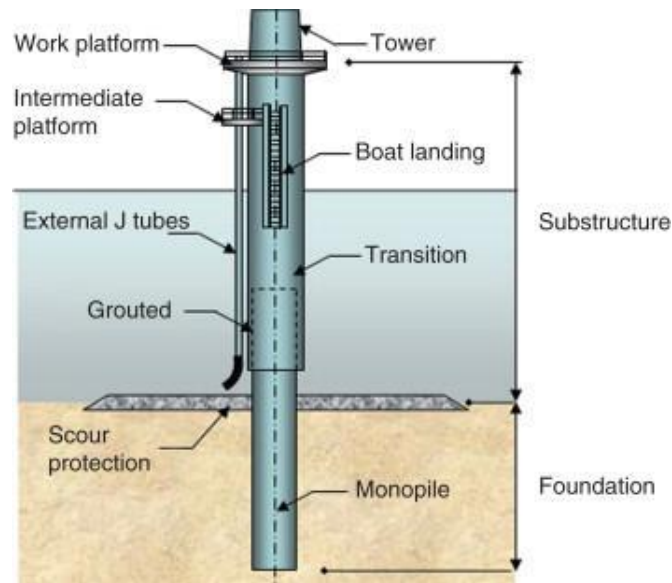


Figure 4: Detailed Diagram of Monopile

3.2.1 Advantages and Disadvantages

There are many advantages to using monopile foundations for offshore wind turbines (OWTs) [50] hence they are commonly used. One of its chief advantages is the simplicity with which monopiles can be installed. Pile driving installation methods have been used successfully for many years and are relatively inexpensive. Also, in addition to its outstanding load-bearing capability and stability, monopiles require only stable soil conditions [58]. Their massive diameter allows them to efficiently transmit the OWT's structural loads to the ocean floor. Offshore wind farms can benefit from monopiles since they are more cost-effective and require less maintenance [10]. However, there are disadvantages to monopiles that must be considered. Excessive settlement and lateral movement can occur when they are used on softer soils [58]. Additional measures, such as grouted connectors or scour protection, may be required to improve stability [8]. However, the usage of monopiles is constrained in deeper

water depths since the length and diameter of the piles increase substantially with depth, which could contribute to increased costs and logistical challenges during installation [18].

Although monopiles have seen extensive application in OWT installations, they are not without their drawbacks. They aren't ideal for use in deeper water, where the seafloor could be more difficult or unstable. In water depths more than 50 meters, for instance, the use of monopiles becomes impractical and expensive [22]. As OWTs get bigger and more powerful, bigger monopiles are needed to support them, and these structures are heavier and trickier to set up. In addition, monopiles may need further strengthening in seismically active regions to ensure their resilience. Due to these restrictions, alternate foundation options such jackets and gravity-based structures have been investigated for some OWT projects [25].

Table 6: Advantages and Disadvantages of Different Type of Foundation

Foundation Type	Advantages	Disadvantages
Monopile	Cost-effective and widely used	Limited to shallow water depths
Gravity Base	Suitable for a wide range of water depths	Large and heavy structures
Tripod/Jacket	Suitable for deeper water depths	Higher fabrication and installation costs
Floating	Flexibility in deployment locations	Complex design and mooring systems
Tension Leg Platform	Stable in deepwater conditions	Higher installation and maintenance costs
Suction Bucket	Rapid installation and removal	Limited to specific soil conditions
Hybrid/Combined	Combines advantages of different foundation types	Increased complexity and potential design challenges

3.2.2 Performance Under Seismic Loading

There are situations in which an offshore wind turbine (OWT) installation would benefit greatly from using monopiles. They thrive in shallow waters with a hard seafloor, including those with sand or clay [30]. The optimal water depth for these kinds of foundational structures is around 50 meters. Steel is the material of choice for most monopiles, and pile-driving methods are used to secure them to the seafloor. Their low price and ease of use make them ideal for massive undertakings [51]. Furthermore, monopiles provide dependable support in places with moderate to low seismic activity due to their high load-bearing capability and stability. Alternative foundation systems, such as jacket or gravity-based constructions, may be more appropriate in deeper waters or places with soft or unstable soil conditions.

Table 7: Performance of Different Type of Foundation Under Seismic Loading

Foundation Type	Performance under Seismic Loading
Monopile	- Generally robust performance due to simplicity and stiffness
	- Vulnerable to lateral loads and soil liquefaction in highly seismic regions
Gravity Base	- Good resistance to lateral loads and stable under seismic events
	- Requires significant mass, making it more challenging to transport and install
Tripod/Jacket	- Provides good resistance to seismic forces and lateral stability
	- Requires careful design to mitigate risks of pile buckling and fatigue
Floating	- Can reduce seismic loads due to hydrodynamic damping and flexibility
	- Requires advanced control systems and mooring to maintain stability during seismic events

Tension Leg Platform	- Exhibits high stiffness and resistance to lateral loads
	- Requires sophisticated mooring systems and dynamic analysis for seismic design
Suction Bucket	- Shows good performance under seismic loading due to increased soil-structure interaction
	- Requires specific soil conditions and careful installation to ensure stability
Hybrid/Combined	- Performance depends on the combination of foundation types and their individual strengths and risks
	- May offer improved overall performance by mitigating specific weaknesses of individual types

Offshore wind turbines (OWTs) in seismically active regions require careful evaluation of monopile performance under seismic stress. Due to their sturdy construction and rigidity, monopiles typically perform well in seismic environments. However, new difficulties and considerations may be brought about by seismic loading [56; 57]. Monopiles are built to withstand lateral stresses, while the horizontal forces generated by earthquakes pose little threat due to their enormous diameter and embedded length [1]. The pile-soil system's stiffness can also aid in dissipating seismic energy and lowering the OWT structure's dynamic response [58]. The monopile's own weight also helps to counteract uplift forces that can occur during earthquakes. Monopiles need thorough geotechnical and structural evaluations to function at their best when subjected to seismic loading [32]. By taking into account variables including soil liquefaction potential, lateral soil movements, and pile-soil interaction, these Analyzes determine how a monopile-soil system reacts to seismic ground motions [21]. The monopile's dynamic response and stability can be evaluated under seismic conditions using state-of-the-art numerical modelling techniques like finite element analysis [21].

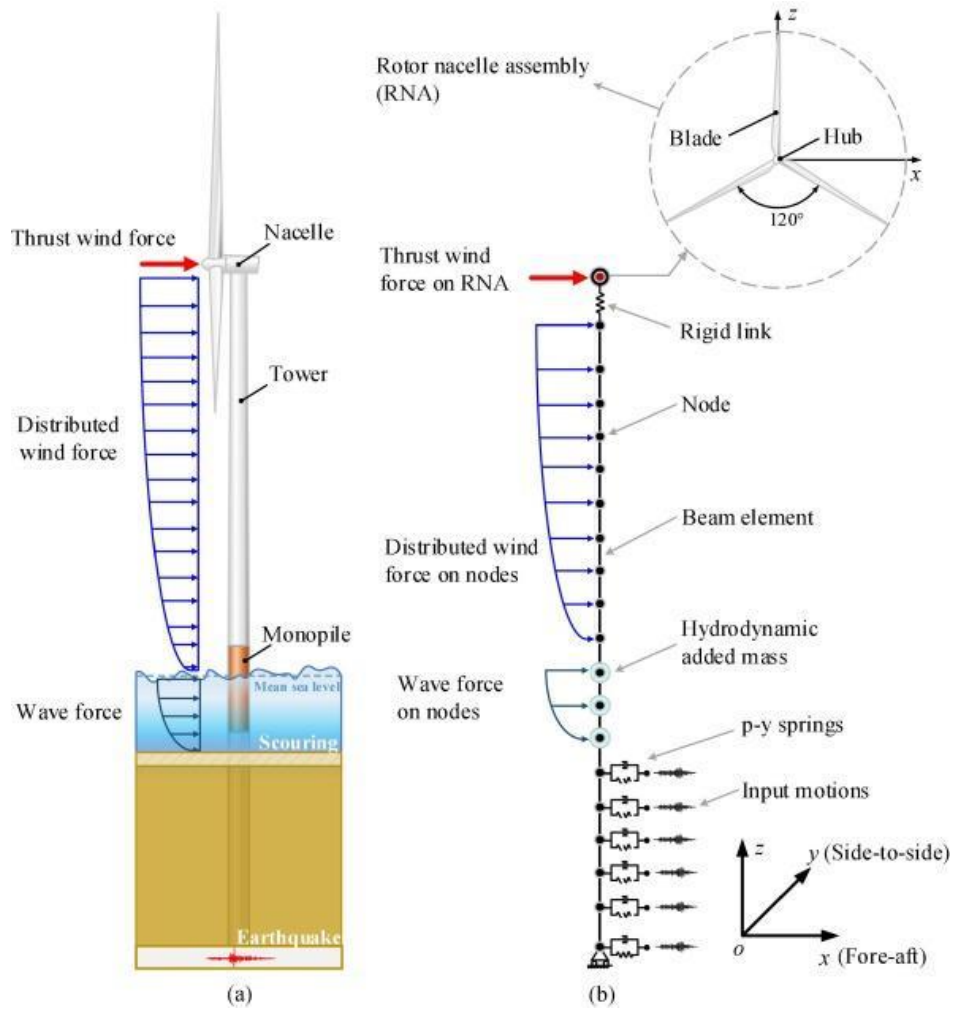


Figure 5: Seismic Response of Monopile

Source: <https://www.sciencedirect.com/science/article/pii/S0266352X2200009X>

Overall, monopiles function well under seismic loads because of their sturdy construction and design. However, in seismically active regions, it is crucial to take into account site-specific factors, conduct geotechnical investigations, and take appropriate design steps to maintain their stability and integrity [10].

3.3 Other Foundation Types

3.3.1 Comparison with Monopiles

Table 8: Comparison with Monopiles

Type	Key Features	Advantages	Disadvantages	Best for
Monopiles	Monopiles comprise of a solitary enormous width steel heap that is crashed into the seabed to offer help for the breeze turbine.	Cost-effective solution Versatile for various turbine sizes Simple design and installation process	Monopiles thrive in waters that range in depth from relatively shallow to moderate.	offshore wind turbines
Jacket Foundations	Sturdy, versatile, deep-water, multi-legged, steel structure for offshore wind turbines.	Stability, deep-water suitability, load-bearing capacity, modularity, and corrosion resistance.	Higher cost, complex fabrication, limited shallow-water suitability, and installation challenges.	Deep-water wind farms with complex soil conditions and larger turbines.
Gravity-Based Foundations	Large, concrete structures, self-weight for stability, no pile driving required.	Excellent stability, long lifespan, minimal maintenance, suitable for deep waters.	High construction cost, limited applicability to specific soil conditions, challenging transportation.	Deep-water sites with challenging soil conditions and seismic activity.

Other foundation types for offshore wind turbines (OWTs) provide options to monopiles for various site conditions and project necessities. Particularly in deeper water depths and challenging soil conditions, jacket foundations, for instance, provide increased stability and load-bearing capacity [\[17\]](#). They include a lattice structure with many legs,

providing increased resistance to lateral loads and the possibility of improved maintenance accessibility (Bush and Manuel, 2009). On the other hand, foundations that rely on gravity to give stability can be set even on more flimsy ground. Even while floating foundations make it possible to place OWTs in deepwater environments, they introduce new difficulties in the forms of dynamic response, mooring systems, and stability management [\[42\]](#).

Offshore wind turbines (OWTs) can be supported by a variety of other foundations in addition to monopiles, each of which has its own set of benefits and drawbacks [\[58\]](#). The greater stability and load-bearing capacity of jacket foundations is due to their lattice structure and many legs [\[40\]](#). They excel where monopiles may flounder, such as in deeper water or on more difficult soil. Strong in the face of lateral stresses and able to efficiently disperse seismic energy, jacket foundations are an excellent option in seismically active areas [\[40\]](#). In addition, their modular construction facilitates both travel and set up [\[47\]](#). There are a number of variables that make it harder to design and manufacture jacket foundations for offshore wind turbines than monopiles [\[15\]](#). To begin, the geometry of jacket foundations is more involved due to the presence of many tubular components, necessitating extensive engineering and analysis. Different types of loads, such as wind, wave, and current loads, as well as soil-structure interaction, must be taken into account during the design process [\[15\]](#). Since fabricating jacket foundations involves welding together various steel parts, accuracy and strict quality control are also essential. The size and weight of jacket foundations make them difficult to transport and set up [\[47\]](#). Jacket foundations for offshore wind turbines are more difficult and costly to design and produce than monopiles [\[47\]](#).

Areas with weaker or more unstable soil may also use foundations that rely on gravity and their own weight for stability [\[15\]](#). Both the mass and bearing area of their bases are substantial, making them earthquake-resistant. But they require careful installation, paying

special attention to weight distribution and buoyancy [47]. The load-bearing capacity and scour resistance of gravity-based foundations are superior to those of monopiles, but they are more complex to manufacture and install [15]. Since offshore wind turbines are so heavy, they can be supported by gravity-based foundations (GBFs) [. In order to set up GBFs properly, there are a few crucial steps that must be followed. To begin, water must be removed from the site, and a temporary caisson or cofferdam must be built. The GBF is towed to the construction site, where it is carefully set up inside the caisson and left there for the duration of the project. For the GBF to be properly installed, precise alignment is required at this stage. The GBF then sinks to the ocean floor under its own weight after water is pumped into the caisson. Alignment is critical to ensuring that the GBF's load-bearing structure remains in the most stable and secure orientation. Using tensioned cables or other anchoring methods, these bases allow wind turbines to be installed in areas with significant ocean depths. To account for the response of floating foundations to seismic loads, extensive dynamic analysis is necessary. The stability and integrity of these structures must be ensured during seismic occurrences by careful design and the deployment of an appropriate anchoring strategy (Geng et al., 2023).

Table 9: Properties for Different Foundation Type

Foundation Type	Suitable Soil Conditions	Suitable Water Depths
Monopiles	Dense sand, firm clay and Gravels	30-40 m
Jacket Foundations	Soft clay and stiff clay	20 to 40 m
Gravity-Based Foundations	Soft clay and Dense sand	Around 30 m

3.3.2 Performance Under Seismic Loading

Offshore wind turbines (OWTs) in seismically active regions require careful evaluation of the performance of foundation types other than monopiles under seismic loading. In terms of withstanding the lateral loads generated by earthquakes, jacket foundations excel due to their lattice structure and numerous legs. They're able to absorb and disperse seismic energy, making buildings safer (Wang et al., 2015). Because of their inherent stability against uplift forces brought on by earthquakes, gravity-based foundations are often used. Even though dynamic analysis and mooring system design for floating foundations are more involved, they can be made to withstand seismic loading (Kjorlaug et al., 2015). To guarantee the safety and dependability of OWT buildings, it is crucial to assess how various foundation types react to seismic loads (Liu et al., 2023).

For the design and assessment of offshore wind turbines (OWTs) in seismically active regions, understanding how alternative foundation types function under seismic loading is critical. Because of its lattice structure and numerous legs, jacket foundations perform well in seismic environments (Liu et al., 2023). The jacket design adds extra rigidity and redundancy, which helps increase resistance to lateral loads caused by earthquakes (Kjorlaug et al., 2015). These bases can diffuse seismic energy efficiently, lowering the OWT building's dynamic response (Geng et al., 2023).

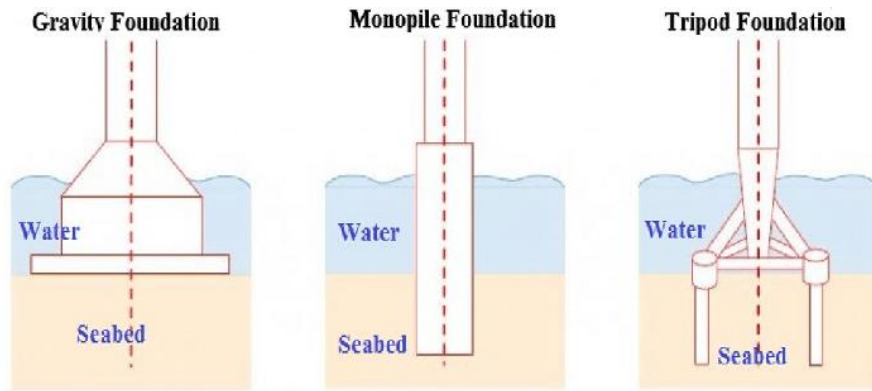


Figure 6: Interaction with Seafloor for Different Type of Foundation

The self-weight of gravity-based foundations provides intrinsic resistance to uplift pressures generated by earthquakes (Kjorlaug et al., 2015). Earthquakes cause dynamic forces, but the foundation's heavy bulk helps to counteract them (Liu et al., 2023).

Although floating foundations allow for deployment in deepwater regions, they must have their performance under seismic loads carefully considered (Mo et al., 2021). To evaluate the behavior of floating foundations during seismic occurrences, sophisticated dynamic analysis and mooring system design are required (Kjorlaug et al., 2015). Implementing floating foundation systems successfully requires careful attention to issues of stability, motion control, and reducing the impact of seismic forces (Arvan et al., 2023). Offshore wind turbines can be supported by gravity-based foundations (GBFs) due to the sheer weight of the turbines themselves. Several important actions must be taken in order to successfully install GBFs. The first step is to pump the water away from the site and build a temporary caisson or cofferdam to create a dry area for construction (Kjorlaug et al., 2015).

Table 10: Comparing the Seismic Performance of Monopiles, Jacket Foundations, and Gravity-Based Foundations.

Parameters	Monopiles	Jacket Foundations	Gravity-Based Foundations
Energy Absorption	Moderate	High	High
Resistance to Lateral Forces	Moderate	High	High
Resistance to Uplift Forces	Moderate	Moderate	High
Stability under Seismic Loading	Moderate	High	High

The GBF is then towed to the site and carefully placed within the caisson, where it will remain for the duration of the project. This step requires accurate alignment to ensure the GBF is installed in the intended spot. After that, water is pumped into the caisson, and the GBF sinks to the bottom of the ocean under its own weight. Correct alignment is essential for keeping the GBF's load-bearing structure in its strongest and safest possible position, free from tilting or misalignment (Kjorlaug et al., 2015).

It is critical to conduct in-depth Analyzes of how different types of foundations behave and react in seismic environments (Lopez et al., 2020). Safe, reliable, and resilient OWT structures in seismically active locations require the use of sophisticated numerical modelling techniques and site-specific studies (Mo et al., 2021).

Chapter 4: Seismic Analysis Methods for OWT Foundations

There are a variety of approaches that can be utilized when carrying out seismic analysis on the foundations of offshore wind turbines (OWTs) in order to evaluate the structural response and guarantee the system's safety and integrity. The following are a few of the most common approaches utilized in seismic analysis of OWT foundations

- **Analyzes of Equivalent Static:** Simplifying seismic event dynamic loads into equivalent static loads is the goal of this approach. It ignores the time-varying nature of the seismic excitation and assumes that maximum static loads control the structure's response (Sim et al., 2014).
- **Analyze of the Response Spectrum:** To determine the maximum structural response at various frequencies, this method makes use of the seismic ground motion's response spectrum. It takes into account the structure's dynamic characteristics as well as the resonance effects and frequency content of the seismic excitation (Schaumann et al., 2010).
- **Analyzes of Time and History:** This strategy includes involving recorded or manufactured time chronicles of seismic occasions as contribution to reproduce the powerful reaction of the OWT establishment. It provides a more realistic representation of the structural response and captures the entire temporal variation of the seismic excitation.
- **Non Dynamic:** The advantages of equivalent static and time-history analysis are combined in this approach. It takes into account the structure's dynamic characteristics and applies a series of static loads based on the response spectrum (Wang et al., 2015).

When time-history analysis requires a lot of computational power, pseudo-dynamic analysis comes in especially handy.

- **Analyzes on Pushovers:** This technique is regularly utilized for nonlinear investigation of OWT establishments. It involves placing a series of static loads in a predetermined order and gradually increasing their magnitude until the target displacement or collapse criteria are met. The foundation system's capacity and behavior under seismic loading can be evaluated using pushover analysis.
- **Analysis of Soil-Structure Interaction:** The relationship between the OWT foundation and the surrounding soil is taken into account by this approach. To capture the coupled response of the foundation and the soil during seismic events, it incorporates the soil's dynamic properties and behavior (Yang et al., 2019).
- **Analysis of seismic hazard:** The probability of various levels of seismic hazard at the OWT foundation site is quantified using this approach. To determine the likelihood of particular seismic events, it takes into account factors such as earthquake recurrence rates, fault activity, and ground motion variability (Kumar, 2020).
- **Analysis of the Numerical Finite Element:** The dynamic response of the OWT foundation system under seismic loading is modelled and analyzed with the help of this method, which makes use of cutting-edge numerical methods like finite element analysis (FEA). FEA can provide in-depth insights into the foundation response by capturing complex geometries, material behavior, and soil-structure interaction effects.

The seismic response and behavior of OWT foundations can be evaluated in a variety of ways using these methods. Project requirements, site-specific conditions, available data, computational resources, and the desired level of accuracy in the analysis all influence the

choice of method. In order to guarantee the safe and dependable design of OWT foundations in regions that are prone to earthquakes, it is essential to think about the best approach and carry out a thorough analysis. Generally, Seismic hazard analysis is preferred for the analysis which is detailed as follows.

4.1 Seismic Hazard Analysis

4.1.1 Deterministic and Probabilistic Approaches

A comprehensive examination of the seismic hazard is necessary to assess the likelihood of seismic damage to the bases of offshore wind turbines (OWTs). Part of this procedure involves making predictions about the occurrence and severity of earthquakes and other seismic events (Abdelaziz, 2022). Deterministic and probabilistic approaches are the two mainstays of seismic hazard analysis. A small number of hypothetical earthquakes of a certain magnitude occurring at a given distance from the location are considered by deterministic methods (Brouthen, 2022). Ground motion at the site can be reliably predicted in these hypothetical conditions using either historical records or current geological understanding. Designing for and assessing a building's response to various earthquake types can benefit from deterministic analysis. However, probabilistic approaches take into consideration the unpredictability of seismic events. Potential earthquakes are considered, and the likelihood of specific ground motion parameters being exceeded is estimated. Probabilistic analysis, which considers a larger range of events and their associated probabilities, allows for a more precise assessment of seismic risk.

4.2 Ground Motion Selection and Scaling

Offshore wind turbine (OWT) bases are Analyzed using seismic methods, which include selecting and scaling ground motion. The process of selecting ground motions

comprises picking earthquake data that are representative of the types of seismic activity that could influence the site (Deviprasad et al., 2022). The magnitude, location, and similarity to the site circumstances are usual criteria for selecting these records. Scaling is applied to the selected ground motion records to bring them into line with the design level ground motions by adjusting the records' amplitude and frequency content (Fu et al., 2023). This procedure verifies that the seismic analysis faithfully represents the OWT foundations' predicted response to earthquake shaking (Zhuang and Pang, 2022).

4.3 Analysis Methods Comparison

Linear and nonlinear approaches exist for seismic analysis of offshore wind turbine (OWT) bases. When using a linear approach, it is assumed that the structure's and soil's response is linearly elastic (Zhuang and Pang, 2022). Primitive design and analysis can benefit from the computational efficiency of these methods. However, they might not properly represent the soil and structure's nonlinear behavior when subjected to massive deformations and intense stress (Fu et al., 2023). The nonlinear behavior of the soil and the structure is taken into account using nonlinear methods. Nonlinear material properties, plastic deformations, and deterioration in soil stiffness are all taken into account (Broujerdian et al., 2023). The performance of OWT foundations under extreme loading circumstances must be evaluated, and nonlinear approaches offer more precise forecasts for such complex seismic events (Fu et al., 2023).

4.3.1 Linear and Nonlinear Methods

Linear and nonlinear approaches exist for seismic analysis of offshore wind turbine (OWT) bases. When using a linear approach, it is assumed that the structure's and soil's response is linearly elastic (He and Ye, 2023). Primitive design and analysis can benefit from the

computational efficiency of these methods. However, they might not properly represent the soil and structure's nonlinear behavior when subjected to massive deformations and intense stress (Basack et al., 2022). The nonlinear behavior of the soil and the structure is taken into account using nonlinear methods. Nonlinear material properties, plastic deformations, and deterioration in soil stiffness are all taken into account (Patra et al., 2022). The performance of OWT foundations under extreme loading circumstances must be evaluated, and nonlinear approaches offer more precise forecasts for such complex seismic events (He and Ye, 2023).

Following is the detailed comparative analysis:

Table 11: Linear and Nonlinear Approach

Point of Comparison	Linear Approach	Nonlinear Approach
Mathematical Model	Linear equations of motion	Nonlinear equations of motion
Soil-Structure Interaction	Modeled as linear springs or dampers	Nonlinear soil behavior considered
Response Prediction	Limited to linear response range	Captures both linear and nonlinear response behavior

Input Excitation	Typically uses simplified ground motion	Can incorporate recorded or synthetic time histories
Complexity	Relatively simpler calculations	More complex calculations and modeling
Computational Efficiency	Faster computations	Longer computational time

Damping Effect	Can only account for linear damping	Can include nonlinear damping effects
Realism of Response	Limited accuracy in capturing nonlinear behavior	Captures realistic response of structure and soil
Material Properties	Linear material behavior	Can account for nonlinear material properties
Nonlinear Pile-Soil Interaction	Not considered	Captures pile-soil interaction with nonlinear models
Accuracy	Suitable for simpler structures and low seismicity	Provides more accurate response prediction
Design Code Compliance	Follows linear design code provisions	May require specific nonlinear design guidelines
Safety Margin	Conservative design approach	Can optimize design for more accurate response
Computational Resources	Requires fewer computational resources	Requires more computational resources
Validity of Results	Limited to linear response region	Valid for both linear and nonlinear response regions

Following are the mathematical equations:

Linear Equation of Motion: $m * u'' + c * u' + k * u = F(t)$

Nonlinear Equation of Motion: $m * u'' + c * u' + k * u + g(u) = F(t)$

Hysteretic Material Behavior: $F(t) = k * u + \alpha * u' + \beta * u''$

Pile-Soil Interaction Model: $k * u = m * u'' + c * u' + P$

Soil Nonlinearity: $F(t) = k * u + g(u)$

These expressions highlight the mathematical formulations used in both linear and nonlinear approaches for seismic analysis, including the equations of motion, material behavior, and soil-structure interaction.

4.3.2 Static and Dynamic Analysis

Static and dynamic seismic analysis techniques can be further subdivided for OWT foundations. To do a static analysis, a single static force is used to stand in for the seismic loading (Alsultani and Khassaf, 2022). By making the assumption that the building has no dynamic response to the ground motion, this method streamlines the study. Static analysis is typically employed for low-risk, straightforward projects or in the early stages of design (Karasozen and West, 2022). However, ground motion is Analyzed dynamically, taking into account how it changes over time. It accounts for the inertia and damping effects of the structure and soil, capturing their dynamic response (Demartino et al., 2022). Predictions of the structure reaction to seismic forces can be made with greater accuracy and detail using dynamic analysis techniques like time-history analysis and response spectrum analysis (Tang et al., 2023).

4.3.3 Time-History and Response Spectrum Analysis

Seismic analysis for OWT foundations frequently makes use of time-history analysis and response spectrum analysis (Xie et al., 2023).

In time-history analysis, a ground motion time history, either recorded or simulated, is applied directly to the model of the building (Tang et al., 2023). The time-domain dynamic reaction of the structure and soil is taken into account in the analysis. Deformations,

accelerations, and stresses in the structure, as well as their time histories, can be studied in great depth by time-history analysis (Demartino et al., 2022). The effectiveness of OWT foundations during targeted seismic events can be evaluated with this method (Karasozen and West, 2022).

4.4 Case Studies of Seismic Analysis in OWT Foundation Systems

To guarantee the safety and efficiency of offshore wind turbine (OWT) installations, seismic analysis of their base systems is essential (Patra et al., 2022). The response and behavior of OWT foundations under seismic loads has been the subject of several case studies. Two such examples are as follows.

4.4.1 Case Study: Monopile Foundation System

Offshore wind farms in seismically active regions have been the focus of a case study that Analyzes the seismic performance of a monopile foundation system (Arvan et al., 2023). Nonlinear soil-structure interaction (SSI) analysis and time-history analysis were used in the investigation (Bakhti et al., 2023). For the SSI study, a nonlinear constitutive model was used to represent the soil, taking into account degradation in soil stiffness and nonlinear behavior. Beam elements were used to model the monopile's base and tower (Erdogan and Swain, 2022). Next, a set of ground motion records that were chosen to be typical of the seismic risk in the area were used to assess the system's dynamic reaction (Demirci et al., 2022). The research revealed significant nonlinear behavior on the part of the monopile foundation system, particularly with respect to the degradation of soil stiffness (Amani et al., 2022). The significance of accounting for SSI impacts in reflecting the system's response was further underscored by the analysis. The results of this case study helped to improve the monopile foundation system's design and make it more resistant to seismic forces (Li et al., 2022).

4.4.2 Case Study: Jacket Foundation System

Seismic analysis of an OWT jacket foundation system in a seismically active offshore zone was the focus of another case study. Response spectrum analysis and time-history analysis were just two of the dynamic analysis techniques that were used in this investigation (Zhang et al., 2022). Maximum structural reaction over time was initially determined by a response spectrum study (Li et al., 2022). The spectrum of the design response was created with the local seismic risk in mind. The research helped identify critical response modes and inform choices about design parameters (Shabakhty and Tabatabaei, 2022). Time-history analysis was then used to probe the jacket foundation system's dynamic reaction to typical ground motion data in greater depth (Liu et al., 2022). Soil-structure interaction effects were considered alongside Analyzes of accelerations, displacements, and member forces resulting from the structure's reaction (Antoniou et al., 2022). This case study showed how the dynamic properties of the soil and how it interacts with the structure have a significant impact on the response of jacket foundations (Antoniou et al., 2022). The results were essential in refining the design and boosting the jacket foundation's seismic resilience, providing crucial information on the system's performance and robustness under seismic stress (Liu et al., 2022).

Chapter 5: Seismic Design Standards for OWT Foundations

5.1 Overview of Relevant Codes and Guidelines

- Standards set by the International Electrotechnical Commission (IEC) Guidelines for the design of OWTs are provided by the IEC 61400-3 standard. This includes the evaluation of geotechnical conditions and the taking into account of seismic loads (Amani et al., 2022). It specifies what must be done and suggests how the base systems should be designed and Analyzed (Li et al., 2022)
- DNV GL, or Det Norske Veritas Germanischer Lloyd, offers standards for the construction and approval of OWTs. DNV-OS-J101 is one of their standards that takes into account seismic design factors such geotechnical investigations, soil-structure interaction assessments, and seismic loading Analyzes (Tang et al., 2023).
- Offshore structures, such as OWT foundations, are covered by the API RP 2A-WSD, which is a set of standards established by the American Petroleum Institute. Seismic design considerations like as hazard analysis, design ground motion determination, and response spectrum analysis are all accounted for (Arvan et al., 2023).
- Guidelines for the seismic design of European structures, especially offshore structures, are provided by Eurocode 8 (EN 1998-1). Geotechnical studies, seismic hazard evaluation, and foundation design criteria are only some of the topics discussed (Alsultani and Khassaf, 2022).
- Considerations such as geotechnical investigations, site-specific seismic hazard, soil-structure interaction, and structural analysis are outlined in these rules and standards, along with the requirements and methods for seismic design of OWT foundations

(Karasozen and West, 2022). Their goal is to make OWTs as secure and effective as possible when subjected to seismic loads (Demartino et al., 2022).

Engineers and designers should follow these rules and regulations to make sure their work is up to par with current standards in the field and any applicable laws (Chen et al., 2014). The geography, project details, and applicable rules all play a role in determining the precise code or guideline to be followed (Tang et al., 2023). When deciding which standards to use for an OWT foundation, it can be helpful to consult with local authorities and seismic design professionals (Xie et al., 2023).

5.2 International Standards Comparison

The IEC, DNV GL, API, and Eurocode standards, among others, have been developed to ensure the safety and reliability of OWT structures through the seismic design of OWT foundations. In general, these standards cover topics including geotechnical investigations, seismic hazard assessments, soil-structure interaction, and structural analysis, while there may be some differences in the specific requirements and methodology used (Demartino et al., 2022). To provide uniform principles for OWT foundation design throughout countries and regions while taking local seismic circumstances into account, the standards are produced based on regional considerations, regulatory frameworks, and industry practices (Tang et al., 2023).

Table 12: Evolution of Seismic Design Standards

Year	Standard/Guideline	Major Update
1931	First Uniform Building Code (UBC)	Incorporation of basic seismic provisions
1940	ASCE 7-40	Introduction of dynamic analysis and response spectra
1952	UBC-52	Inclusion of site-specific ground motion parameters
1978	UBC-78	Introduction of seismic zones based on peak ground acceleration
1988	UBC-88	Implementation of performance-based seismic design
1997	NEHRP Guidelines	Focus on performance objectives and site-specific design
2003	ASCE 7-02	Introduction of probabilistic seismic hazard analysis
2010	ASCE 7-10	Incorporation of site-specific ground motion and soil effects
2016	ASCE 7-16	Revision of seismic design criteria and risk assessment
2020	ASCE 7-20	Further refinement of seismic design provisions

- Offshore structures, such as OWT foundations, are governed by the guidelines established by the American Petroleum Institute (API). Recommendations for the evaluation and design of offshore platforms are provided in API RP 2A-WSD (Dongol et al., 2020). Provisions for seismic design are included, including topics like site-specific hazard assessments, establishing design ground motions, and analyzing responses across a wide frequency range (Dao and Ryan, 2022).

- Guidelines for the seismic design of European structures, especially offshore structures, are provided by Eurocode 8 (EN 1998-1). Geotechnical studies, seismic hazard evaluation, and foundation design criteria are only some of the topics discussed. Detailed processes for seismic analysis and design are provided by Eurocode standards, which place an emphasis on a performance-based approach (Velarde et al., 2019).
- While each location has its own set of requirements to follow, there are some universal principles that may be used to seismic design that cut across jurisdictions (Wang et al., 2015). Their goal is to guarantee that OWT foundations are prepared to perform adequately in the event of an earthquake (Wang et al., 2015).

Engineers working on designs need to be aware of the local laws and standards that may affect their work. The decision and implementation of the correct standard may be affected by things like local seismic hazard, soil conditions, and regulatory frameworks (Lopez et al., 2020). To ensure compliance with the appropriate international standards and to achieve the desired degree of safety and performance for OWT foundations, it is vital to confer with local authorities, experienced professionals, and specialists in seismic design (Liu et al., 2023).

5.3 Design Criteria and Requirements

The seismic design criteria and requirements are crucial to the safety and structural integrity of offshore wind turbines during seismic activity in the field of offshore wind energy. "AI-Enabled Dynamic Response Prediction of Offshore Wind Turbines Under Seismic Activity:" is the title of the study. "An Investigation into Soil-Model Parametric Dependencies" examines seismic design criteria and soil model parametric dependencies in predicting offshore wind turbine dynamic response (Geng et al., 2023).

The minimum level of seismic resistance that a building, like an offshore wind turbine, must have are known as seismic design criteria. The structure's location, the seismicity of the area, and any potential ground motions it might experience during an earthquake are all taken into account in the comprehensive seismic hazard assessments that underlie these criteria (Jahani et al., 2022).

The structural integrity and functionality of offshore wind turbines during and after an earthquake are typically the goals of the design requirements for seismically active offshore wind turbines. The selection of appropriate soil models, foundation design considerations, and structural analysis methods are all included in these requirements.

One of the critical difficulties in seismic plan for seaward wind turbines is precisely anticipating the powerful reaction of the turbines and their help structures under seismic burdens. The referenced review explores the parametric conditions of soil models, which assume a basic part in catching the way of behaving of the establishment soil framework during seismic occasions. Researchers want to improve the accuracy of dynamic response predictions and optimize the design and performance of offshore wind turbines in seismic-prone areas by comprehending these dependencies (Mittendorf and Sweetman, 2008).

The expected ground motions, the site-specific soil conditions, the natural frequencies of the structure, and the potential for liquefaction or effects of soil-structure interaction are all factors that must be taken into account when designing offshore wind turbines for seismic purposes. The turbines' ability to withstand seismic forces and maintain their operational functionality while minimizing the risk of structural damage or failure is the goal of these requirements (Otsmane and Bouzid, 2016).

Seismic design criteria and specifications are necessary for the secure and dependable operation of offshore wind turbines in regions prone to earthquakes. The research on how to

accurately predict the dynamic response of offshore wind turbines that are subjected to seismic activity using artificial intelligence advances our understanding of the parametric dependencies between soil models and models themselves. Offshore wind farms can be constructed and designed to withstand seismic events by adhering to stringent seismic design criteria (Pan and Cheng, 2016). This ensures the long-term viability and resilience of renewable energy generation in offshore environments.

5.4 Challenges in Applying Codes to Foundation Systems

There are a number of obstacles to overcome when applying codes and standards to foundation systems for offshore wind turbines, particularly in the context of seismic activity. "AI-Enabled Dynamic Response Prediction of Offshore Wind Turbines Under Seismic Activity:" is the title of the study. These difficulties are investigated in "An Investigation into Soil-Model Parametric Dependencies" with an emphasis on how the International Building Code (IBC) and American Petroleum Institute (API) standards are applied.

Offshore application adaptation: The building and structural design for onshore applications is the primary focus of the IBC and API codes. These codes must be carefully adapted to ensure that they are applicable to offshore foundation systems because of the unique characteristics of offshore wind turbines, including the harsh marine environment and dynamic loading conditions (Schaumann et al., 2010).

Insufficient instruction for particular situations: When compared to conventional structures and buildings, offshore wind turbines face distinct difficulties. For certain scenarios, such as the influence of wave and wind-induced vibrations, complex soil-structure interaction, and pile-soil-structure dynamics, the codes may not provide sufficient guidance. To address

these difficulties, designers must use engineering judgment and rely on additional guidelines and research (Sim et al., 2014).

Inadequate consideration of advanced methods of analysis: To accurately model the response of offshore wind turbine foundation systems to seismic activity, sophisticated analysis methods like nonlinear dynamic analysis and soil-structure interaction analysis are frequently required. However, these advanced methods may not be explicitly addressed in the codes, necessitating that designers either seek additional direction or apply them case-by-case.

Utilization of cutting-edge technologies: Enhancing foundation system design and dynamic response prediction is made possible by the rapid development of AI and machine learning. However, because the existing codes may not include provisions for incorporating these new technologies, researchers, industry professionals, and regulatory bodies will need to work together to create guidelines and standards that include these advancements (Yang et al., 2018). International standards are not consistent: Offshore wind projects are frequently carried out globally, and various nations may have their own regional codes and standards. Codes from various regions must be aligned and harmonised in order to guarantee design consistency and make international collaboration easier. Continuous research, teamwork, and an iterative approach to code development are necessary to address these issues (Velarede, 2019). The codes can be improved to provide comprehensive guidance for the design of foundation systems for offshore wind turbines under seismic activity by incorporating lessons learned from previous projects, embracing advancements in analysis techniques and technology, and engaging stakeholders from the industry (Yang et al., 2018).

Chapter 6: Advanced Simulation Techniques in Geotechnical Engineering

6.1 Finite Element Method

The limited component strategy (FEM) is a broadly involved mathematical method in geotechnical designing for examining complex primary and geotechnical issues. FEM can be used to simulate the behavior of foundation systems that are subjected to seismic loading in the context of the study on dynamic response prediction of offshore wind turbines under seismic activity. It divides the domain into smaller discrete elements, making it possible to calculate the response at each element and the system as a whole. FEM lets you look at things like the interaction between the structure and the soil, dynamic loading, and nonlinear behavior. This helps you learn how foundation systems perform during earthquakes (Kumar, 2020).

6.2 Boundary Element Method

Another numerical method utilized in geotechnical engineering is the boundary element method (BEM), particularly for soil-structure interaction-related issues. Instead of discretizing the domain as a whole, BEM models only its boundary (Ashkani, 2020). It reduces computational effort and better represents infinite domains, like the soil surrounding foundation systems, among other benefits. BEM can be used to break down the powerful reaction of seaward wind turbine establishments under seismic stacking, taking into account the associations between the design and the encompassing soil.

6.3 Mesh Generation and Model Simplifications

Simulation tools like FEM and BEM rely heavily on mesh generation. For reliable results, it is essential to create a mesh that accurately reflects the foundation system's geometry and material properties and the soil surrounding it. To make the analysis easier, the model can be simplified by using homogenized soil properties or making the geometry less complicated. However, accurate prediction of the dynamic response necessitates striking a balance between simplification and capturing the most important aspects of the problem (Grange and Salciarini, 2022).

6.4 Soil-Constitutive Models

Geotechnical engineering's advanced simulation methods rely heavily on soil-constitutive models. The behavior of the soil under various loading conditions, including seismic loading, is defined by these models. The complex behavior of soils during seismic events is captured by a variety of constitutive models, including linear elastic, nonlinear elastic, and plasticity models. For an accurate prediction of the response of offshore wind turbine foundations, the selection and calibration of the appropriate constitutive model are essential (Grange and Salciarini, 2022).

6.5 Model Calibration and Validation

Geotechnical engineering simulations cannot proceed without the necessary steps of calibrating and validating numerical models (Abdelaziz, 2022). By adjusting the parameters, the models must be calibrated to match the behavior that was observed during field or laboratory tests. To ensure the model's accuracy, validation involves comparing the predicted response to actual data or measurements. Procedures for calibration and validation are essential for increasing the precision of dynamic response predictions for offshore wind

turbine foundation systems under seismic activity and increasing confidence in the reliability of numerical simulations (Deviprasad et al., 2022).

Engineers can improve the accuracy of dynamic response predictions and gain a better understanding of the behavior of offshore wind turbine foundations under seismic loading conditions by utilizing advanced simulation techniques like FEM and BEM, taking into account the appropriate mesh generation and model simplifications, incorporating appropriate soil-constitutive models, and carrying out thorough model calibration and validation. These procedures add to the advancement of vigorous plan rules and methodologies for guaranteeing the primary trustworthiness and security of seaward wind turbines in seismic-inclined regions (Fu et al., 2023).

6.6 Case Studies of AI-enabled Analysis in OTW Foundation Systems

Case Studies of AI-enabled Analysis in Offshore Wind Turbine (OTW) Foundation Systems The use of Artificial Intelligence (AI) in the analysis of offshore wind turbine (OTW) foundation systems has demonstrated a lot of potential for improving the design and performance of these vital structures (Antoniou et al., 2022). Engineers can gain valuable insights into the behavior of foundation systems and optimize their design for improved stability, reliability, and cost-effectiveness by utilizing AI algorithms and methods. Here, we talk about two case studies that show how OTW foundation systems use AI-enabled analysis (Antoniou et al., 2022).

6.6.1 Prediction Pile Capacity

In OTW foundation systems, the bearing capacity of piles can be predicted using AI algorithms, particularly Machine Learning (ML) methods. Engineers can develop predictive models to estimate the pile capacity by training ML models on historical data that includes

pile installation parameters, soil properties, and corresponding load test results (Shabakhty and Tabatabaei, 2022). Pile length, diameter, soil conditions, and installation methods are all taken into account in these complex models. The data patterns can be used by the ML algorithms to accurately predict the capacity of the piles, assisting in the optimization of the foundation system's design and guaranteeing structural integrity (Shabakhty and Tabatabaei, 2022).

6.6.2 Optimization of Monopile Design

Additionally, the design of monopile foundations, which are frequently utilized in OTW installations, can be improved through the use of AI algorithms (Antoniou et al., 2022). Engineers can investigate a variety of design parameters, such as the dimensions of the pile, the wall thickness, and the geometry of the transition piece, by combining ML algorithms with genetic algorithms or other optimization methods. The AI-enabled analysis takes into account a lot of different things, like the state of the soil, the dynamic loads, and geotechnical constraints, to find the best design that meets the structural needs while using as little material as possible and saving money on construction (Antoniou et al., 2022).

These case studies show how AI has changed the way OTW foundation systems are designed and Analyzed (Shabakhty and Tabatabaei, 2022). Engineers can use AI algorithms to improve capacity predictions, optimize designs for better performance, and guarantee the stability and dependability of these crucial structures over time (Antoniou et al., 2022). In addition to improving operational efficiency and safety, the incorporation of AI into OTW foundation systems contributes to the creation of resilient and long-lasting offshore wind energy projects (Antoniou et al., 2022). It's important to note that these case studies only give a taste of how AI could be used to analyze OTW foundation systems. New possibilities for further optimizing the design, construction, and upkeep of these essential components in

offshore wind farms are being unlocked by ongoing AI research and technological advancements [\[45\]](#).

Chapter 7: Methodology

7.1 Overview of OWT Study

Engineering of Offshore Wind Turbine systems where the towering structure is anchored to the seabed is quite complex. More than assessing the static behavior, as the system faces constant dynamic loads, the dynamic response of the system is hard to accurately predict and monitor. The aim of this study is to evaluate the modal dynamics of the OWT system and assess the effects of increased loading and varying thickness of the foundation system on the dynamic behavior of OWT system.

The focus of this dissertation is on the dynamic analysis of an offshore wind turbine assembly comprising a turbine tower, monopile foundation and an embedded solid soil block. This study involves performing series of simulation on the Offshore Wind Turbine assembly. The geometry involves modeling the turbine tower, the monopile foundation and the solid block where the turbine tower-monopile foundation assembly will be embedded. The simulation focuses only on performing the dynamic study of the offshore wind turbine assemble structure. In order to perform the dynamic study, several seismic data are collected, cleaned and applied to the structure and the dynamic response is recorded. Frequency domain analysis is performed to assess the Eigen frequency values and the Eigen values of the assembled system.

7.2 Significance of Dynamic Analysis in Offshore Wind Turbines

The structural integrity and the operational safety of such complex systems is of prime importance considering the cost of construction and maintaining these systems. The engineering and the construction is already complex enough but when the dynamic factors are considered, it becomes quite relevant as failure of such systems sooner than the anticipated

design life results in significant losses. In order to address the dynamic performance issue, newer technologies such as floating wind turbines are being tried and tested. Regardless of the emerging technologies, the most reliable and tested form of offshore wind turbines involves towers anchored to the seabed. The monopile foundation system and the tower dynamics are rather intricate to model. This becomes more difficult when seismic interactions are considered. Assessing the true dynamic parameters of such systems is a task even difficult for a supercomputer as the number of interactions and the physics needed to accurately calculate this is far beyond the normal computational realm. The fundamental structural engineering principles are not directly valid during the design of the complete OWT-Monopile system.

There are many ways to tackle the creation of norms in the design of OWT systems. Usually, highly complex FEM routines are undertaken by independent engineering experts to design and validate every bit of material that will go into the creation of this system. The geotechnical engineering involves pure assessments of soil stresses and soil strains that will be induced during the design life of OWT's. The structural dynamics of the system is affected by ground and wave induced dynamic interactions. The most crucial engineering assessment during the design of such a system involves understanding the specific environmental traits of the planned location for the construction of OWTs and recognizing the dynamic behavior that the structure will endure during its life.

By scrutinizing the response of the entire assembly to seismic loading, this study aims to understand the most fundamental criteria of OWT structural dynamics and its response to seismicity.

7.3 Research Objectives and Goals

The primary objectives of this research are to:

1. **Conduct Seismic Dynamic Analysis:** Investigate the dynamic response of the offshore wind turbine assembly under seismic loading conditions.
2. **Assess Eigen Frequencies and Modes:** Perform frequency domain analysis to assess Eigen frequencies and modes of the assembled system.
3. **Explore Nacelle Load Effects:** Examine the impact of increasing nacelle loads on the dynamic behavior of the structure.
4. **Investigate Monopile Thickness Variation:** Analyze the influence of varying monopile thickness on the overall dynamic response.

7.4 Key Components of the Model

The offshore wind turbine assembly model encompasses three principal components: the turbine tower, the monopile foundation, and an embedded solid block. Each element plays a vital role in the structural integrity and dynamic response of the entire system.

Turbine Tower

The turbine tower is a fundamental structural element that supports the nacelle and rotor blades. It is characterized by a cylindrical shape, tapering towards the top. The tower is discretized into finite elements to accurately capture its geometric complexity.

Monopile Foundation

The monopile foundation serves as the structural anchor for the offshore wind turbine. Modeled as a cylindrical structure, the monopile extends beneath the seabed to provide stability. The geometric details, such as diameter and length, are carefully considered to reflect real-world monopile designs.

Embedded Solid Block

A solid block is incorporated into the model to represent the seabed and simulate the embedding of the monopile into the soil. The dimensions of the block are determined based on the expected seabed

conditions, ensuring a realistic representation of the interaction between the structure and the surrounding soil. Although, in order to save the computational cost, the soil block geometry is limited in terms of volume and only serves the purpose of embedding the monopile-tower assembly.

7.5 Rationale for Chosen Geometry

The selection of the model's geometry is underpinned by the aim to replicate a realistic offshore wind turbine assembly. The chosen dimensions, shapes, and proportions are informed by industry standards, empirical data, and engineering best practices. The rationale behind the chosen geometry is threefold:

Realism

The geometry aims to closely resemble the actual dimensions and shapes of offshore wind turbine components, ensuring that the simulation outcomes are applicable to real-world scenarios.

Feasibility

The selected geometry is computationally feasible for dynamic analysis, striking a balance between complexity and efficiency to facilitate accurate and timely simulations.

Representativeness

The geometry represents a typical offshore wind turbine assembly, allowing for generalizability of findings to a broader range of structures.

7.6 Simplifications and Assumptions

In order for the simulation to be computationally efficient and for simulation feasibility, certain simplifications and assumptions have been made in the geometry and model development:

Material Homogeneity

Homogeneous material properties are assumed for each component, neglecting material heterogeneity that may exist in real-world structures.

Soil Simplification

The soil is represented by a simplified embedded block, overlooking intricate soil-structure interaction complexities for the sake of modeling expediency.

Rigid Body Constraints

The nacelle assembly is simplified as a static load, and rigid body constraints are applied to streamline the analysis, avoiding the computational intricacies of modeling a detailed nacelle structure.

7.7 Procedure

7.7.1 Geometry

The simulation comprises of 3 parts.

1. Monopile:

This is modelled as a cylindrical shell. The dimensions of it are obtained by averaging the real monopiles that are currently deployed.

2. Turbine Tower

The OWT tower component is a tubular steel structure with a draft angle. The angle is chosen to represent the real design of the steel turbine towers. The dimensions including the curvature of the tower are aptly modelled.

3. Soil Block

The soil block even though a critical component during the OWT design, the soil domain is kept small as the computational cost rapidly exceed the computational limit of the available system.

7.7.2 Materials

Steel: The monopile and the turbine tower are made of steel and the generic steel parameters are input to the simulation. The non-linearity of the steel is not considered in this study due to computational limitations.

Soil: The soil domain is described with the basic dense clay parameters taken from the literature.

Table 13: Parameters

Mass Density of Soil	1.82 E-06 tonnes/mm ³
Young's Modulus of Soil	100 MPa
Poisson's Ratio for Soil	0.3
Mass Density of Steel	7.85 E-09
Young's Modulus of Steel	210000 MPa
Poisson's Ratio	0.3
Tower Shell Thickness	30 mm to 70 mm
Monopile Shell Thickness	30 mm to 70 mm
Nacelle Load	80 tonnes to 150 tonnes

7.8 Frequency Domain Analysis

Frequency domain analysis is required for the understanding of the natural frequencies and mode shapes of the offshore wind turbine assembly. The following steps outline the setup for this critical phase:

Eigen Frequency and Eigen Value Extraction

Eigen frequencies and mode shapes are extracted through rigorous frequency domain analysis. The model is subjected to modal analysis, where the system's response to harmonic loading is

explored. This process aids in identifying the natural frequencies at which the structure tends to vibrate. Eigen values are crucial indicators of the damping characteristics and stability of the system.

7.9 Modal Dynamics

The modal dynamic step introduces seismic loading to the offshore wind turbine assembly, simulating the dynamic response of the structure under realistic earthquake scenarios. The chosen seismic loads, representing significant historical events, include:

1. Chi Chi Earthquake
2. Kobe Earthquake
3. Northridge Earthquake
4. Loma Prieta Earthquake

Modal Dynamic Step

The modal dynamic step is designed to capture the dynamic behavior induced by seismic loading. This step involves applying the seismic loads in the time domain, considering the time-dependent response of the structure. The time history data for each selected earthquake is meticulously incorporated into the simulation to ensure an accurate representation of the seismic events.

Application of Seismic Loads

Each seismic load is sequentially applied to the model, mimicking the ground motion associated with the respective earthquake. The loads are strategically introduced to assess the system's response at various points in time, allowing for a comprehensive evaluation of the assembly's dynamic characteristics.

7.10 Post-Processing

Custom output data is requested in order to obtain relevant data to conduct the study. As the computational cost increases with every output request, and considering the large number of step increments, only the absolutely necessary outputs are requested from the simulation. With all the history outputs and the field outputs, the amount of data generated per run of the simulation is more than 65GB. It is not feasible to collect every output at all integration points, as the amount of compute required to conduct such a wide study is extremely high.

Attempts were made to optimize this process and finally only the outputs necessary for to conduct the Frequency Study and the Modal Dynamic Study were obtained from every run of the simulation. This procedure is relevant for the purposes of this dissertation.

The Eigen Values and Frequencies, Effective Mass in all 6 DOFs, Participatory Factors in all 6 DOFs, Base Motion Accelerations, Base Motion Velocities and Base Motion Displacements, for the entire system was collected in the 2nd step of the simulation for the Frequency Domain Analysis.

All the components of the Velocities, Accelerations and the Displacements were collected at the top of the Turbine Tower at every step increment of the 3rd step to plot a time history

Chapter 8: Results

8.1 Northridge Earthquake

8.1.1 Effective Masses

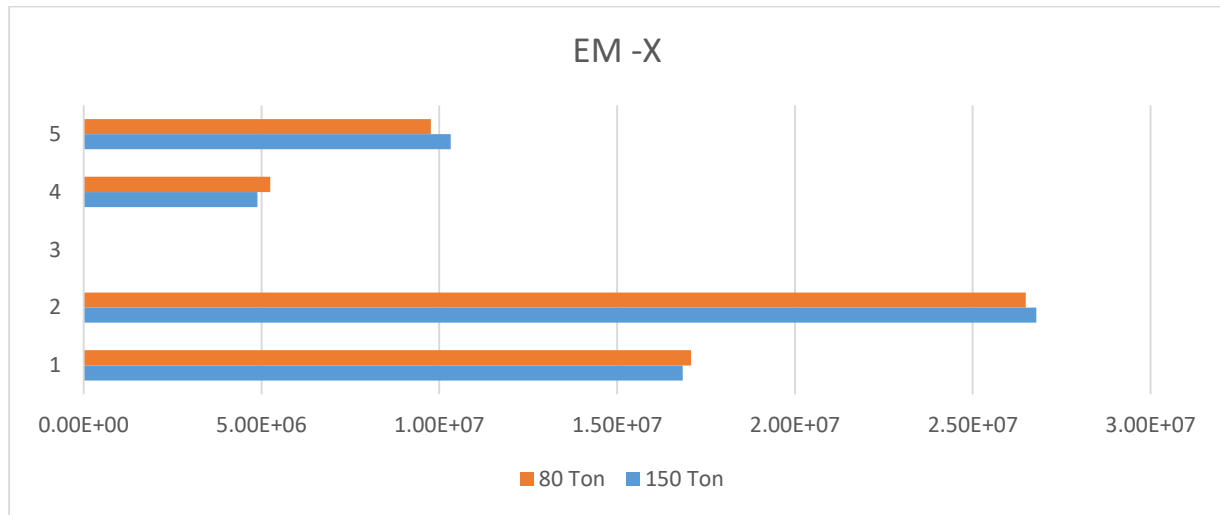


Figure 7: Northridge Effective Mass X

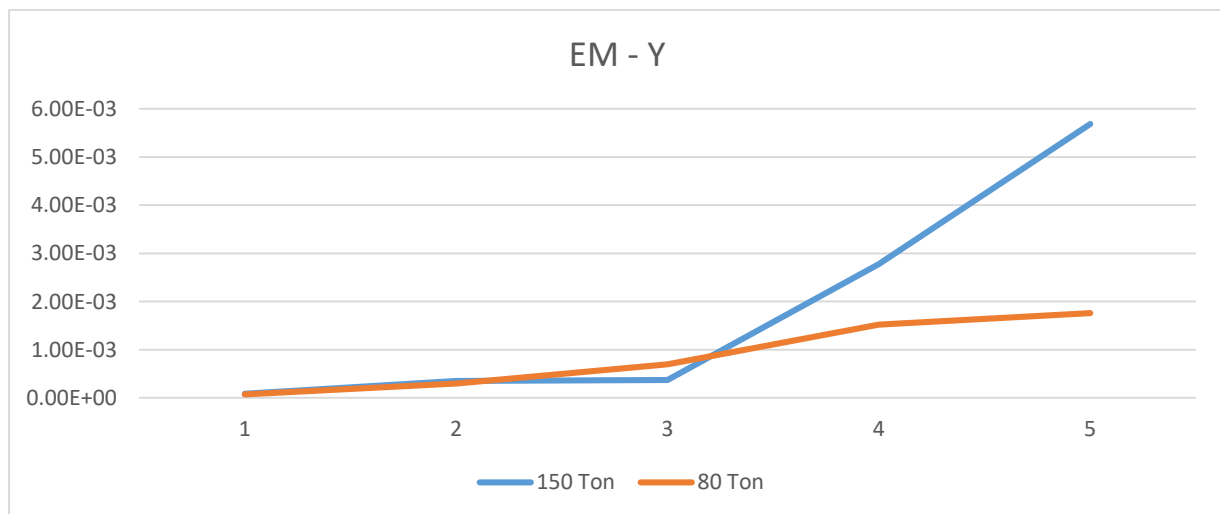


Figure 8: Northridge Effective Mass Y

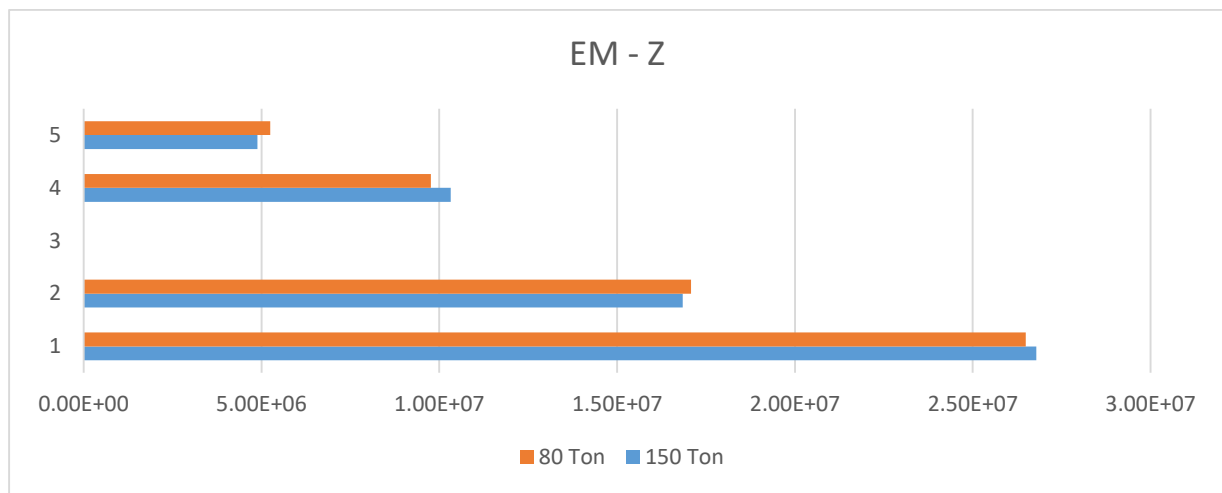


Figure 9: Northridge Effective Mass Z

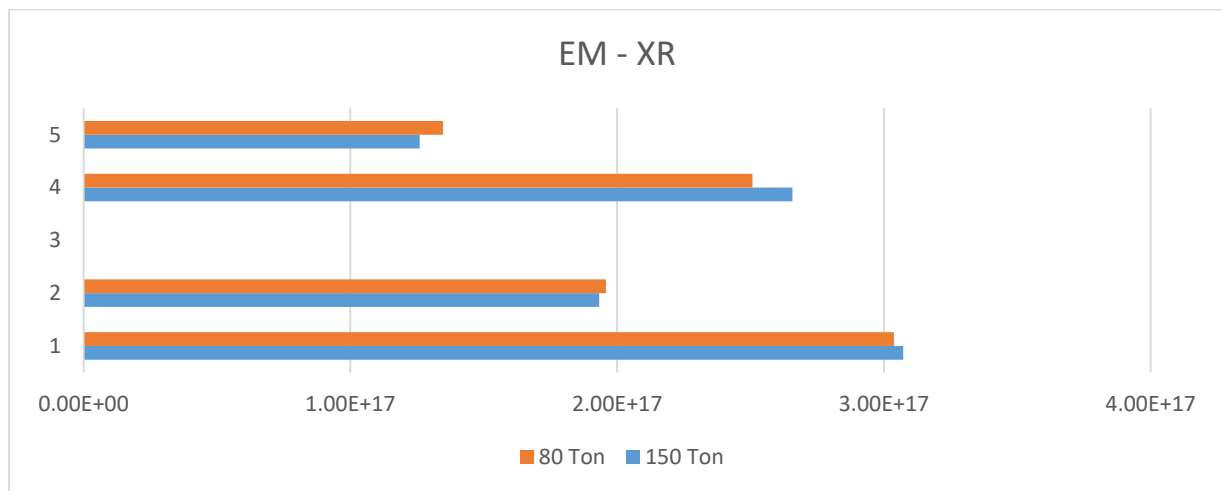


Figure 10: Northridge Effective Mass XR

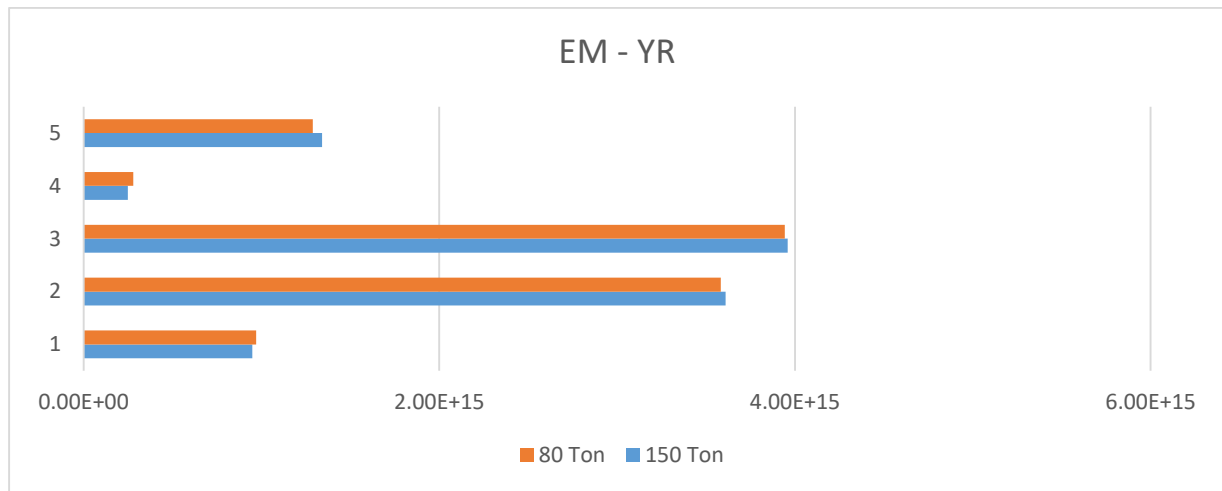


Figure 11: Northridge Effective Mass YR

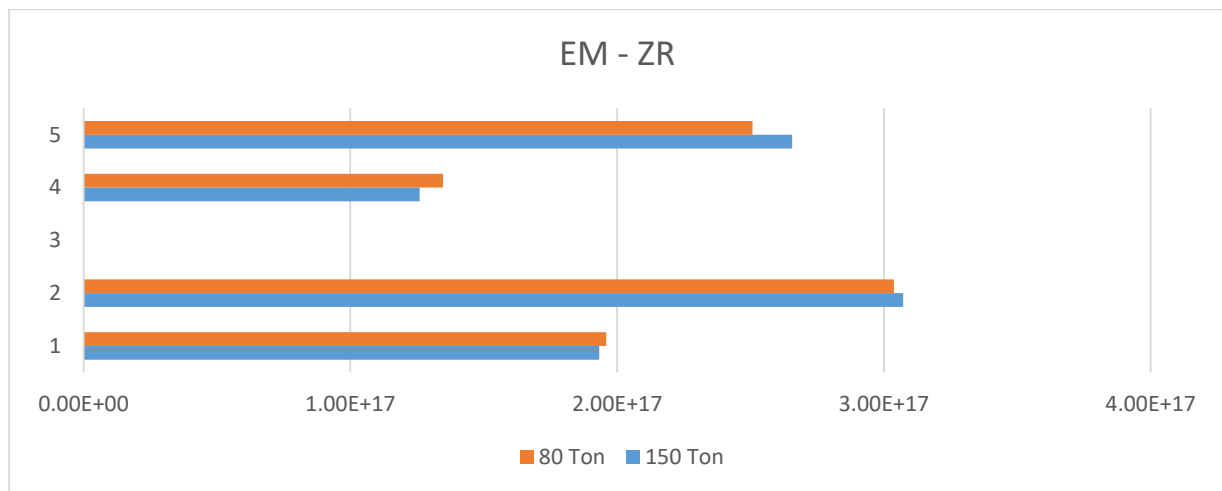


Figure 12: Northridge Effective Mass ZR

8.1.2 Participation Factors

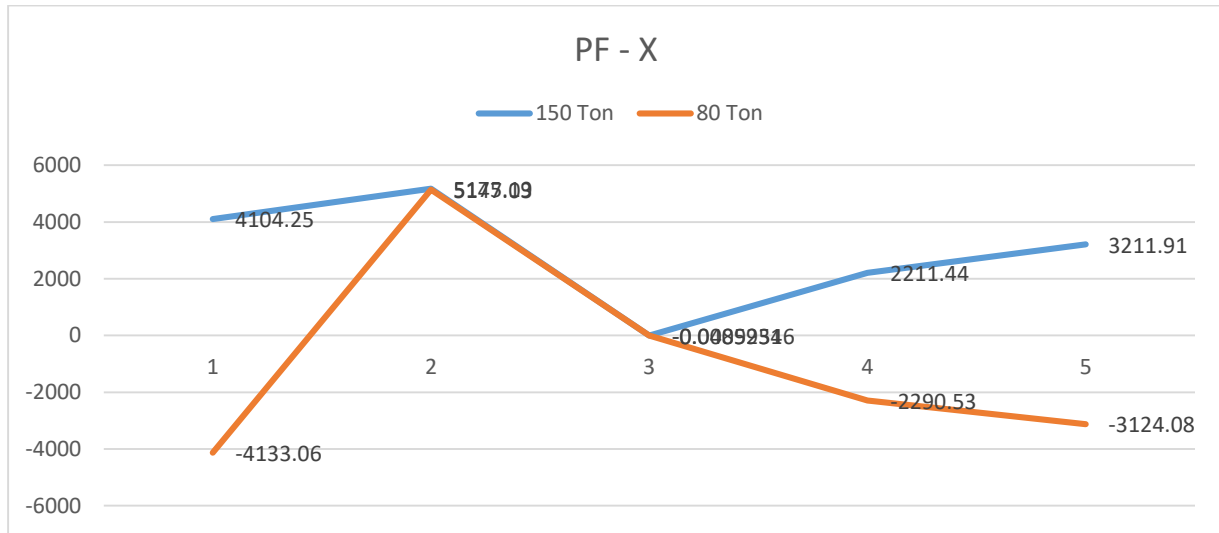


Figure 13: Northridge Participation Factor X

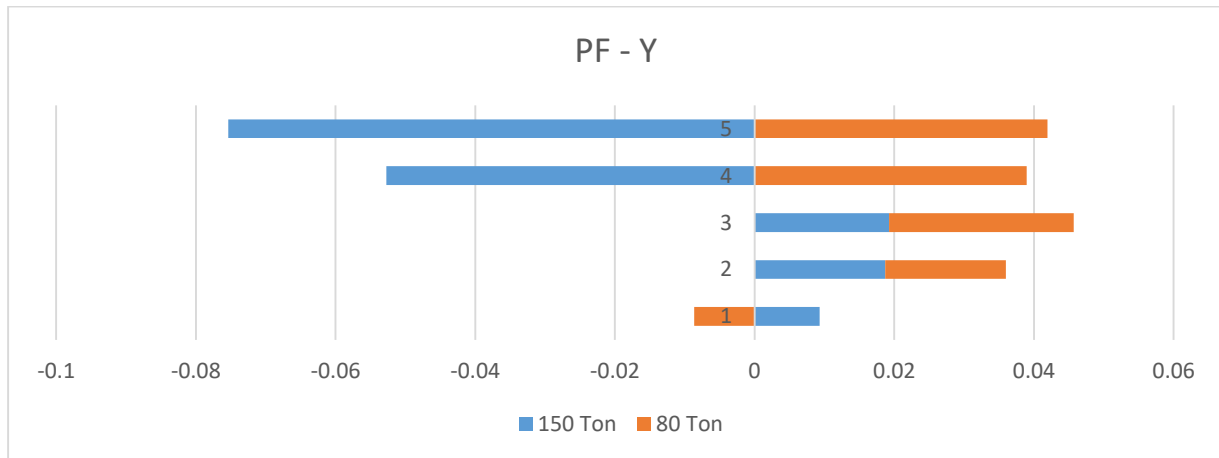


Figure 14: Northridge Participation Factor Y

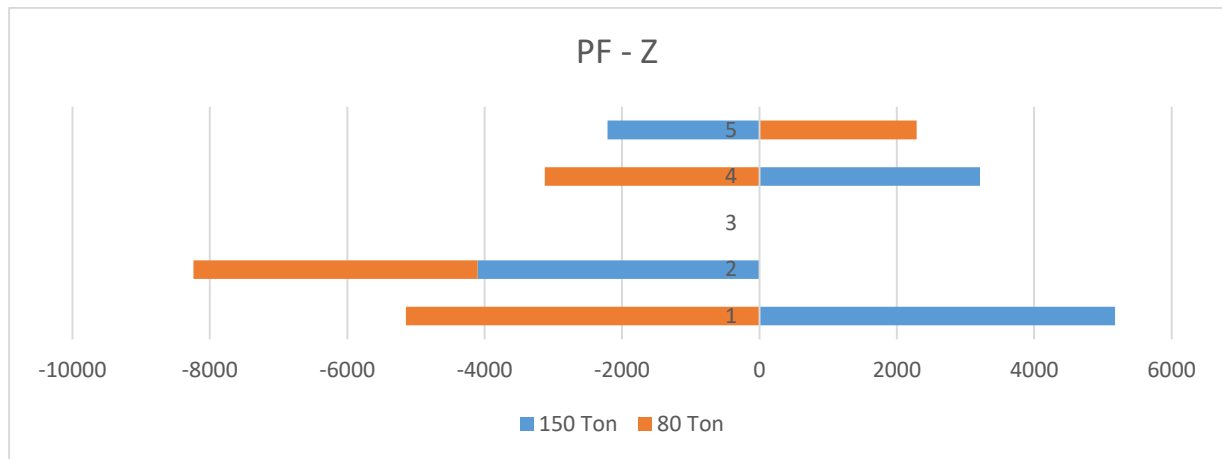


Figure 15: Northridge Participation Factor Z

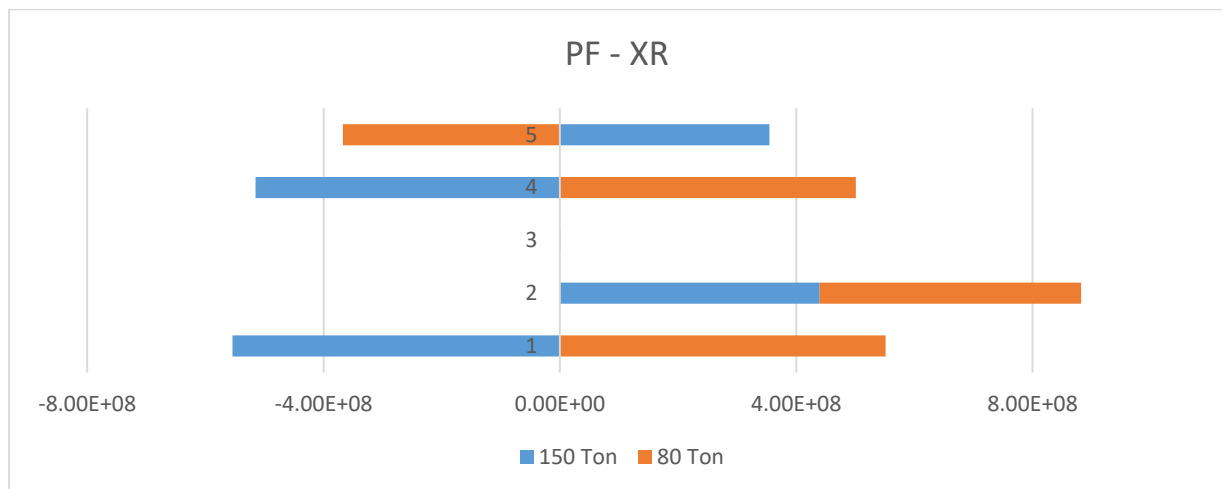


Figure 16: Northridge Participation Factor XR

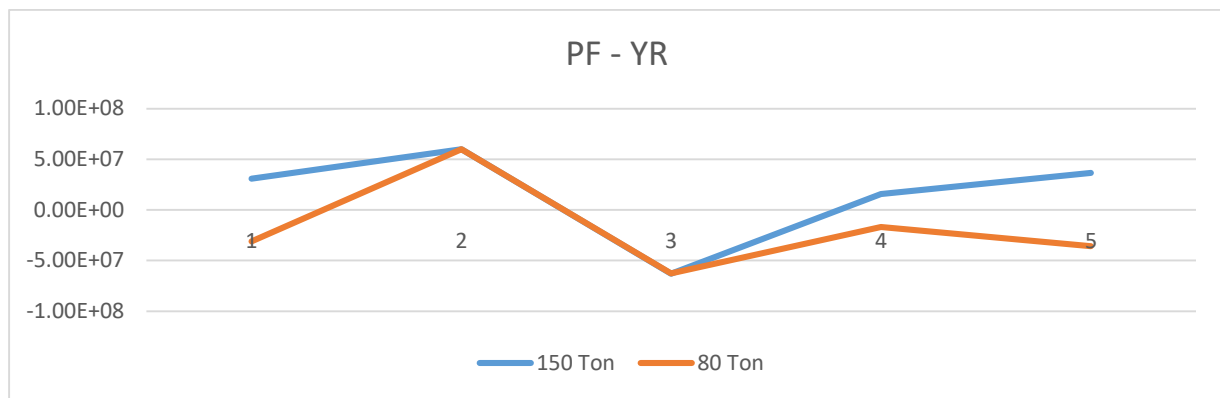


Figure 17: Northridge Participation Factor YR

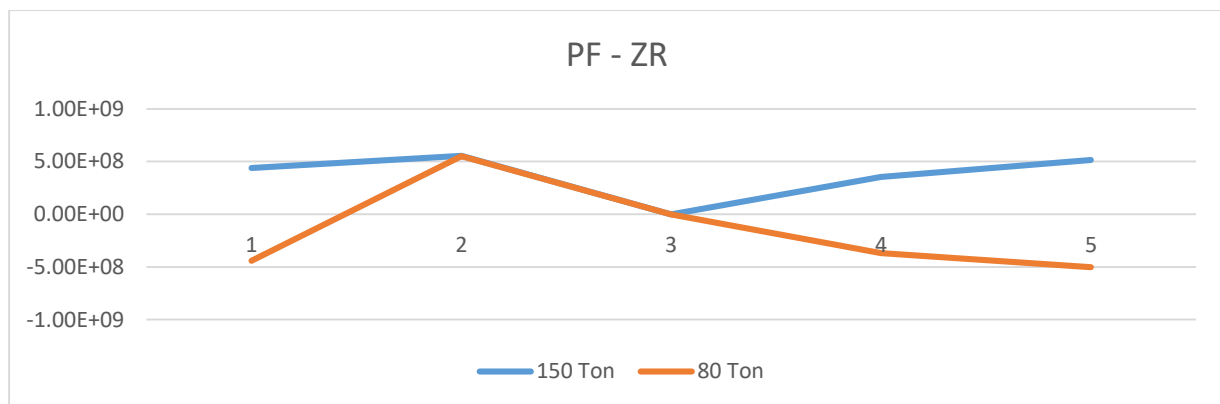


Figure 18: Northridge Participation Factor ZR

8.1.3 Eigen Values

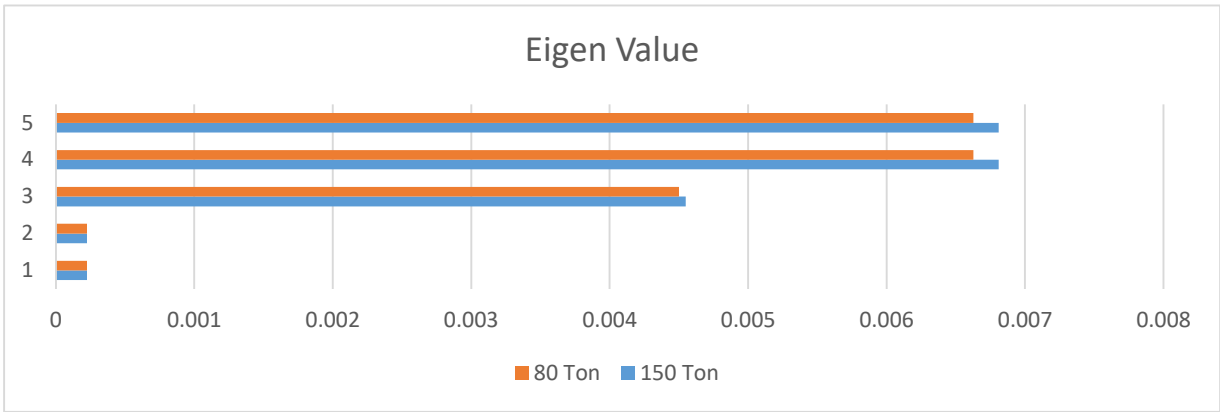


Figure 19: Eigen Value Comparison

8.1.4 Eigen Frequencies

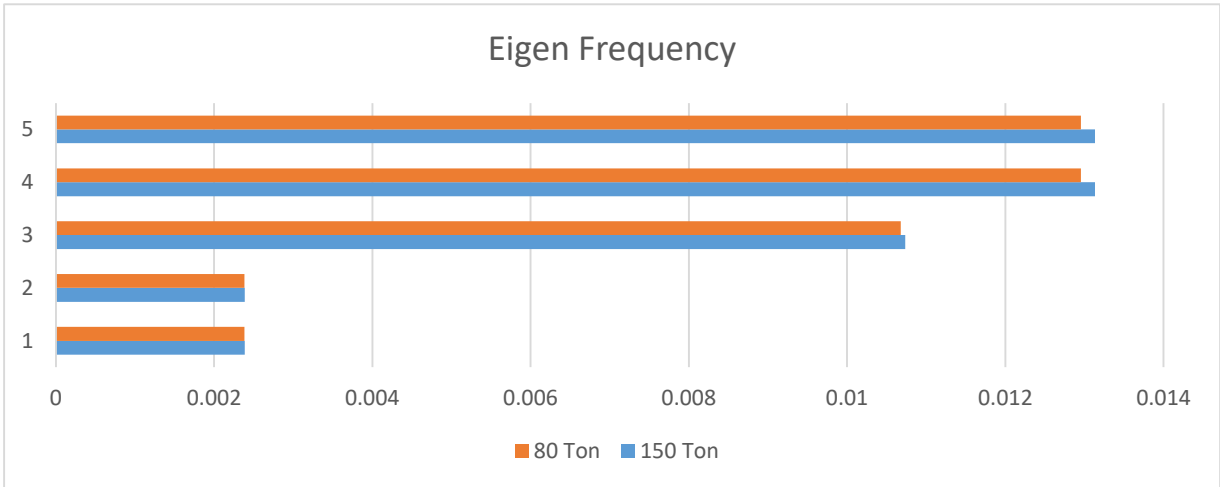


Figure 20: Eigen Frequency Comparison

8.1.5 Displacement, Velocity and Accelerations

Figure 21: Acceleration History Output

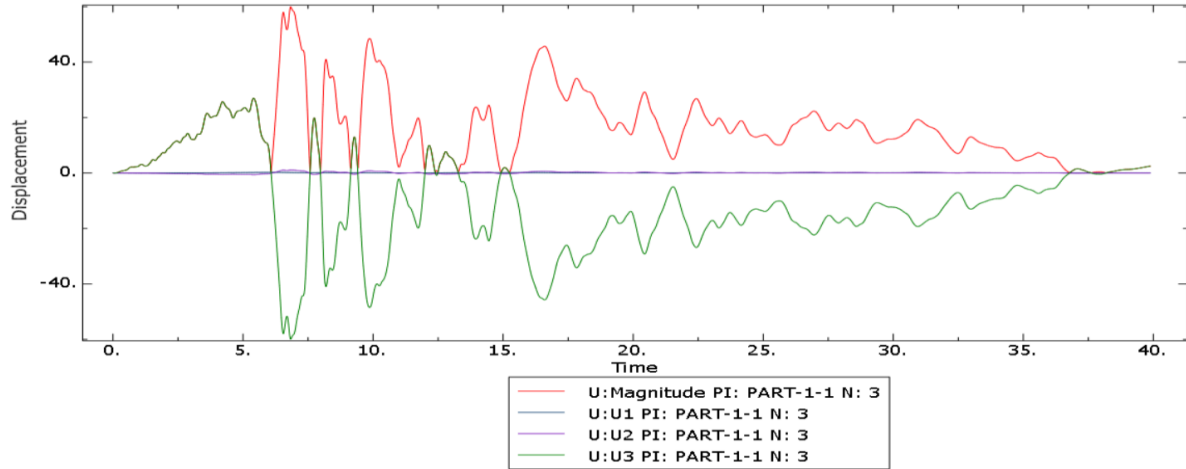


Figure 22: Displacement History Output

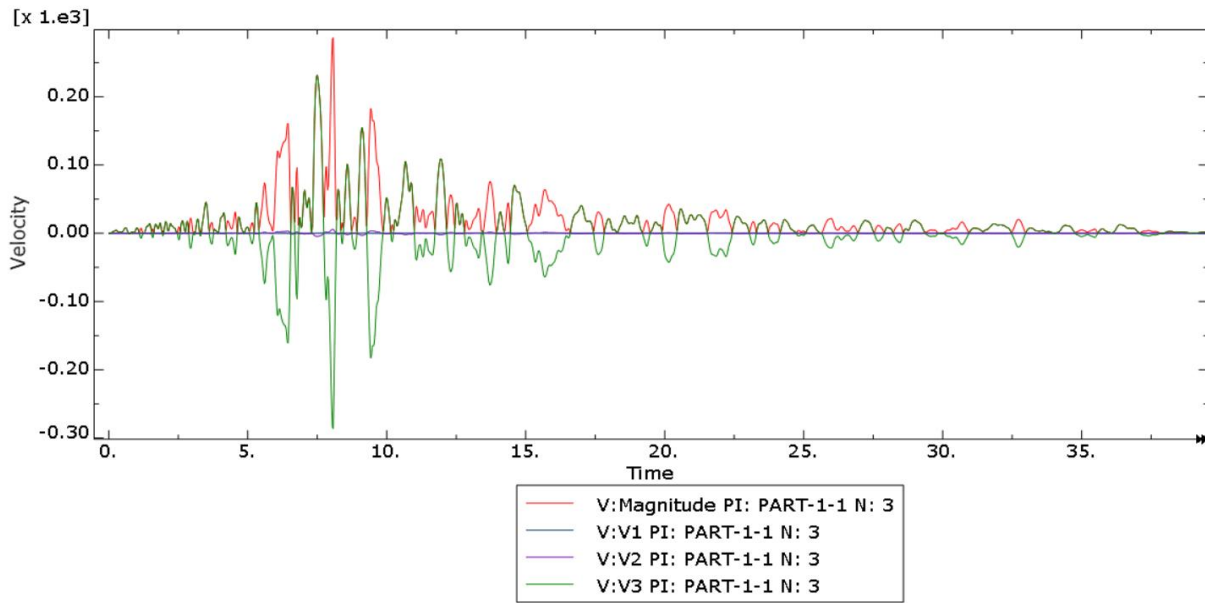


Figure 23: Velocity History Output

8.2 Loma Prieta Earthquake

8.2.1 Effective Masses

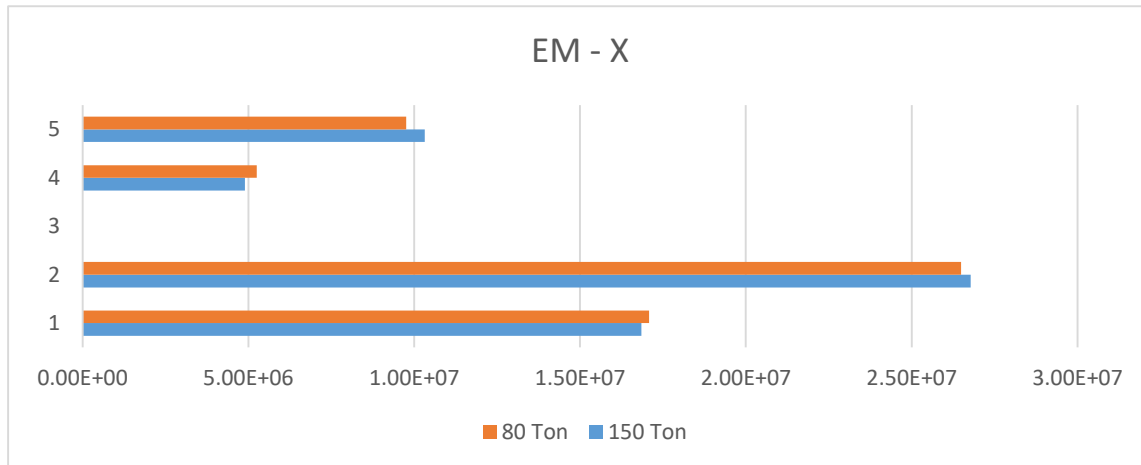


Figure 24: Loma Prieta Effective Mass- X Comparison

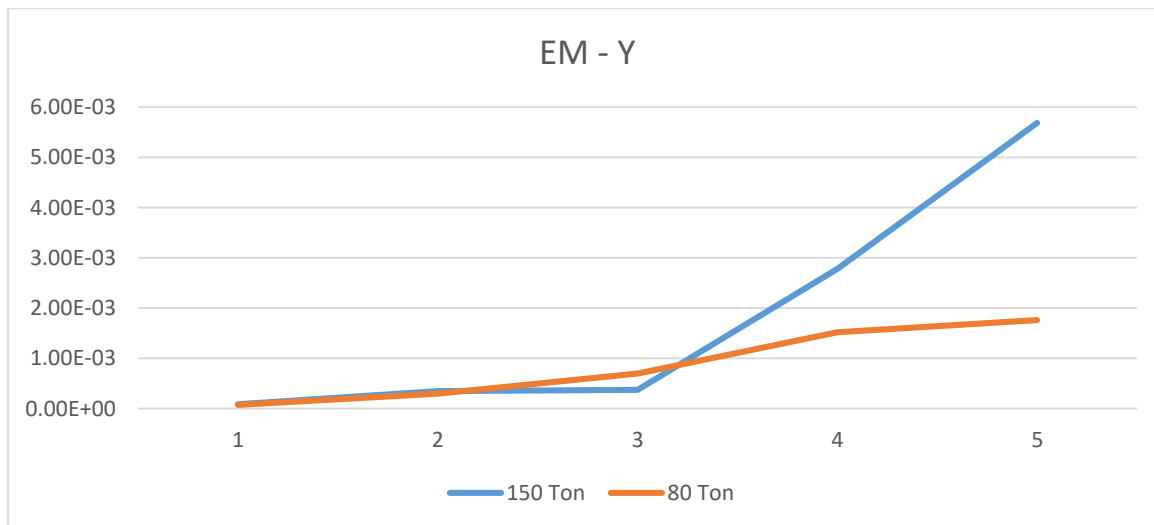


Figure 25: Loma Prieta Effective Mass- Y Comparison

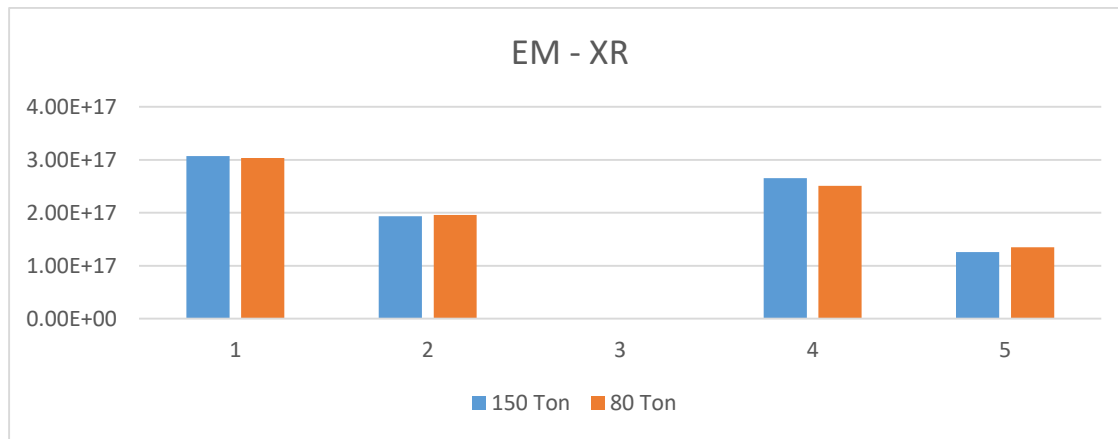


Figure 26: Loma Prieta Participation Factor - XR Comparison

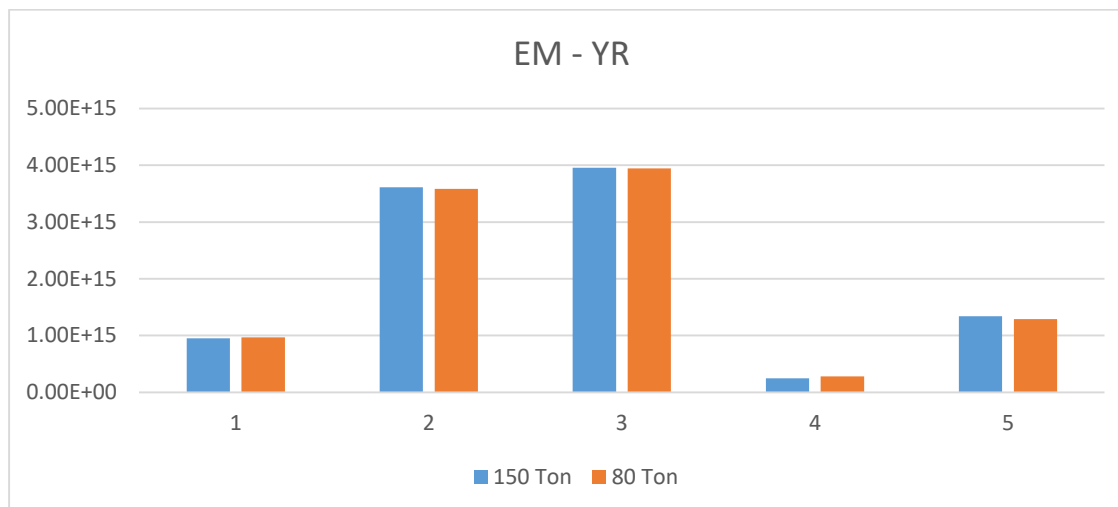


Figure 27: Loma Prieta Participation Factor - YR Comparison

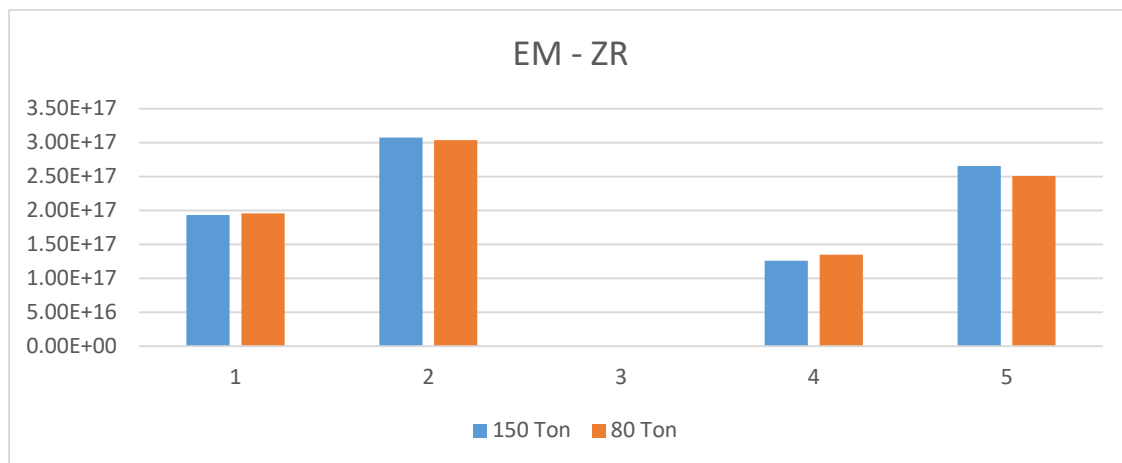


Figure 28: Loma Prieta Participation Factor - ZR Comparison

8.2.2 Participation Factors

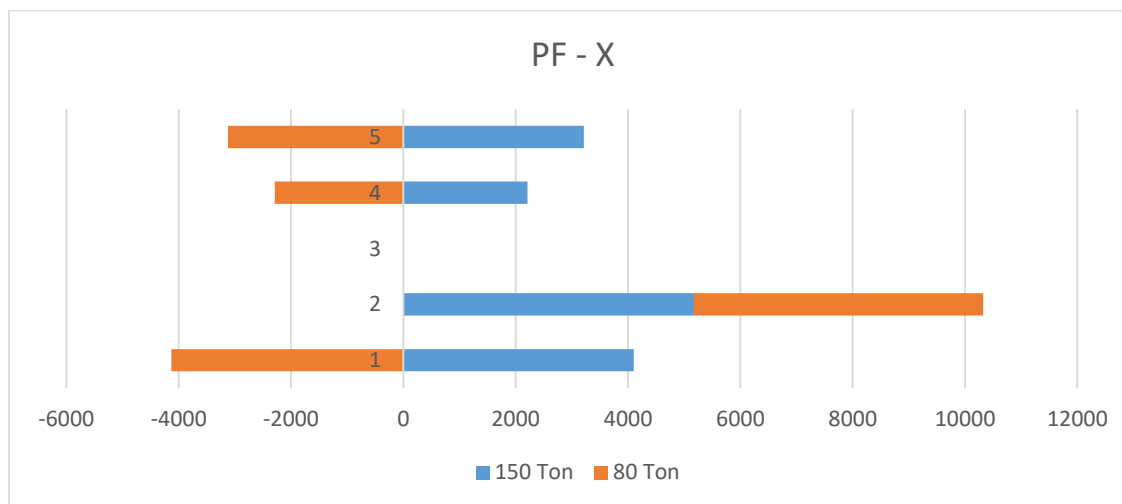


Figure 29: Loma Prieta Participation Factor - X Comparison

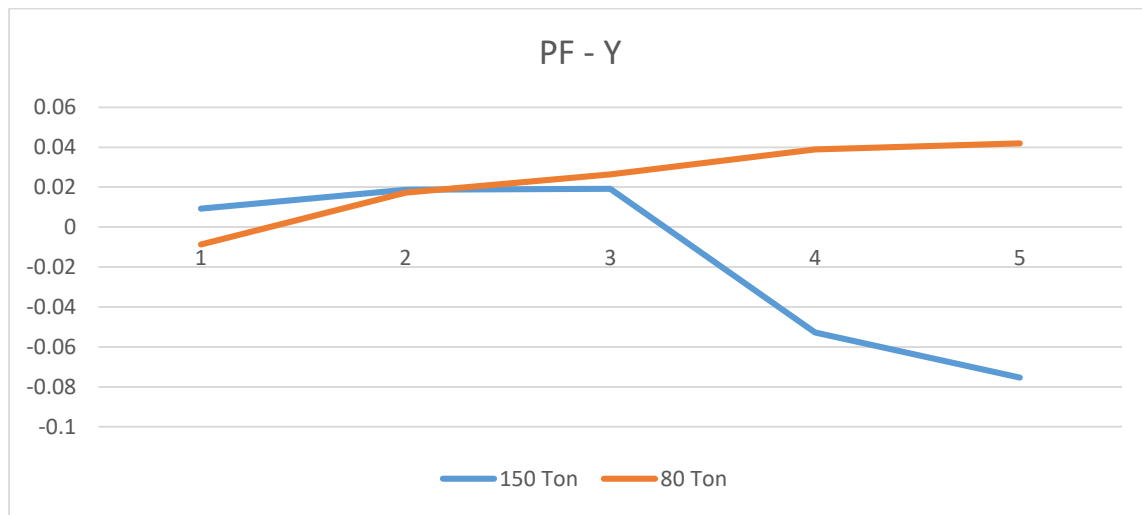


Figure 30: Loma Prieta Participation Factor - Y Comparison

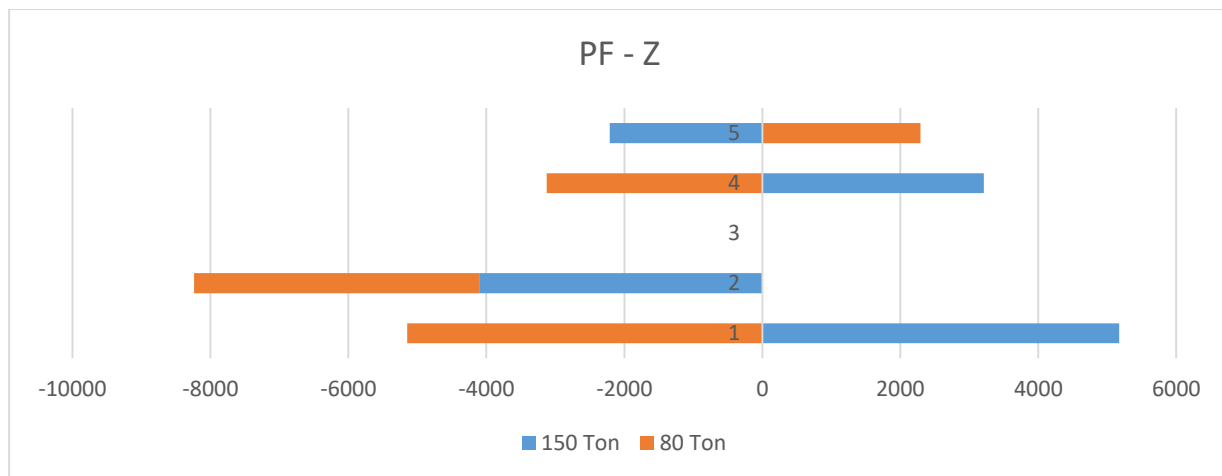


Figure 31: Loma Prieta Participation Factor - Z Comparison

8.2.3 Eigen Values

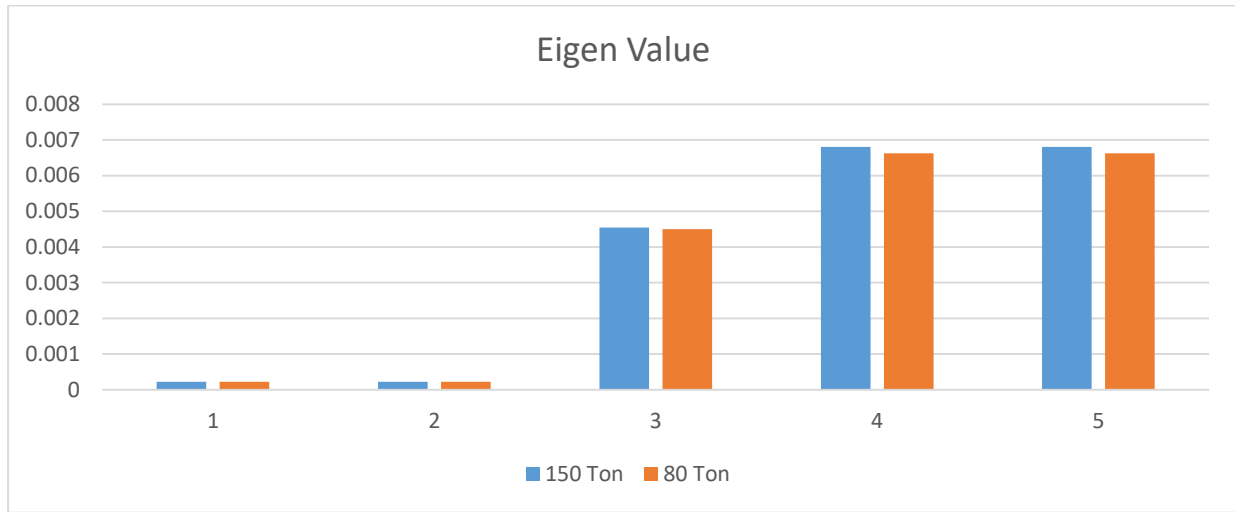


Figure 32: Loma Prieta Eigen Value Comparison

8.2.4 Eigen Frequencies

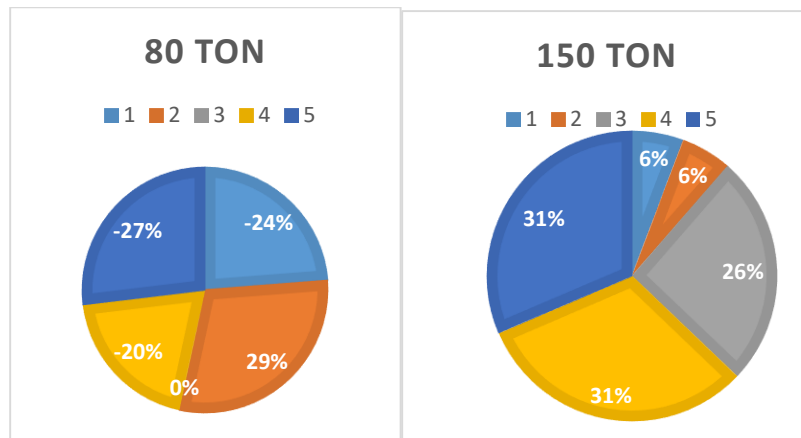


Figure 33: Eigen Frequencies @ Nacelle 80 T & 150T

8.2.5 Base Motion Displacement, Acceleration and Velocity

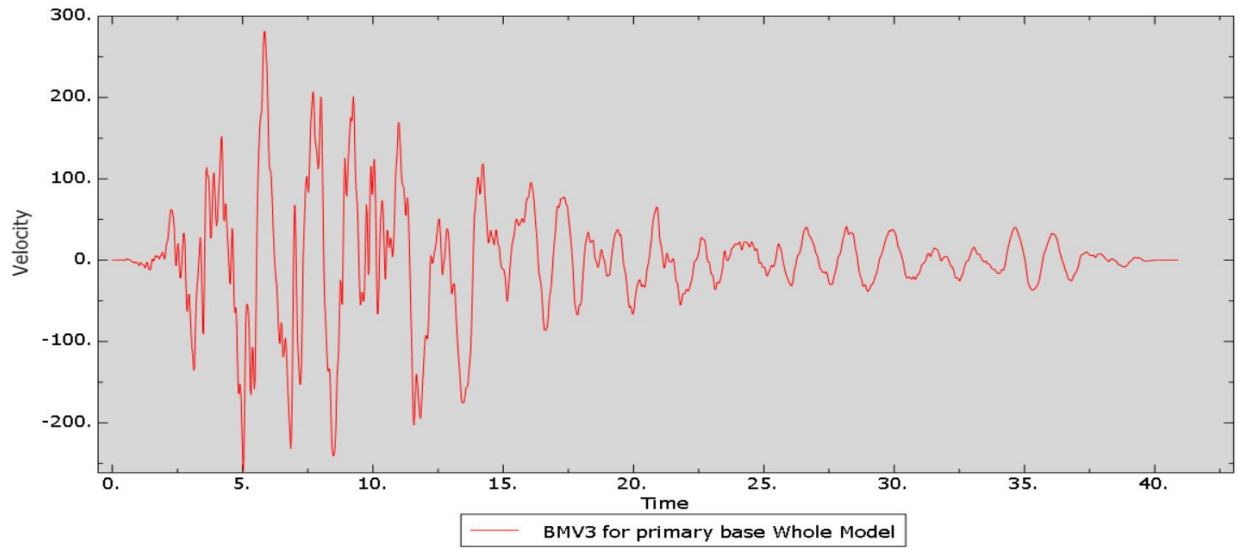


Figure 34: Loma Prieta - Base Motion Velocity

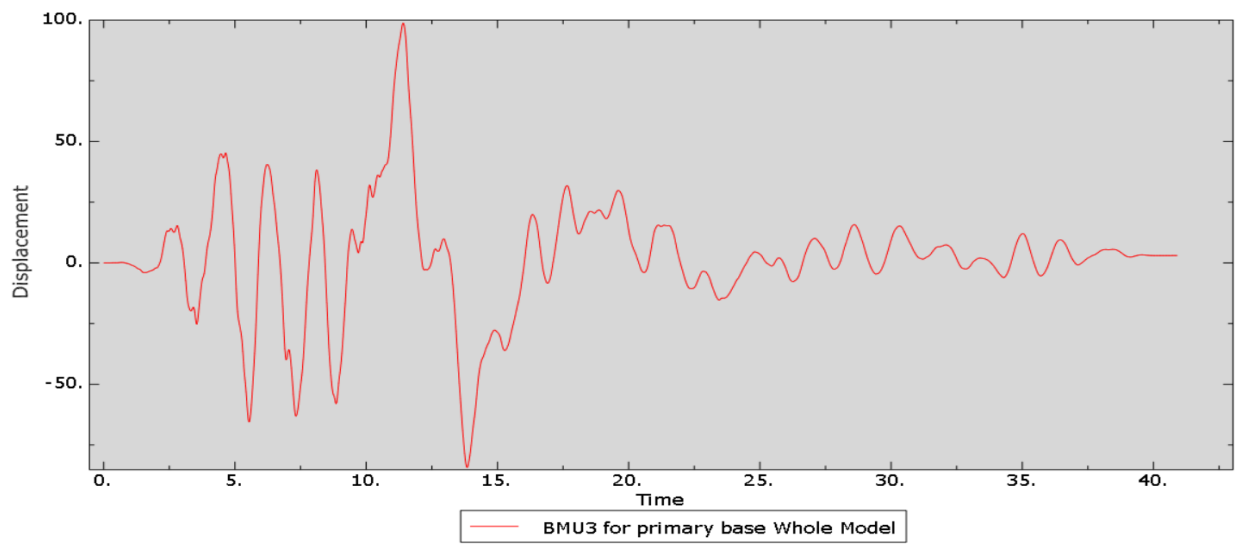


Figure 35: Loma Prieta - Base Motion Displacement

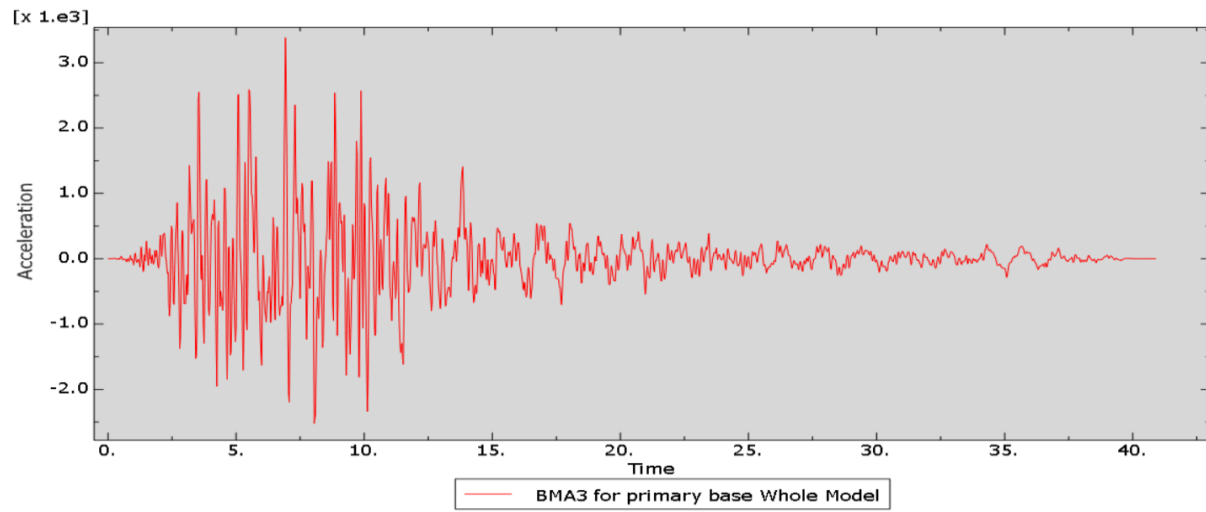


Figure 36: Loma Prieta - Base Motion Acceleration

8.2.6 Time-History Outputs

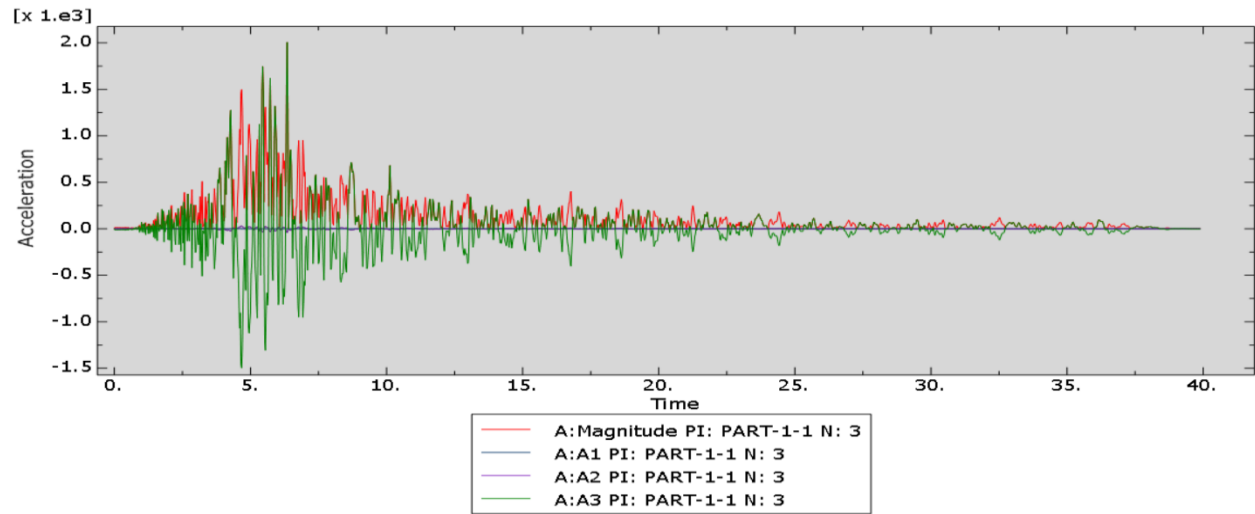


Figure 37: History Output Acceleration

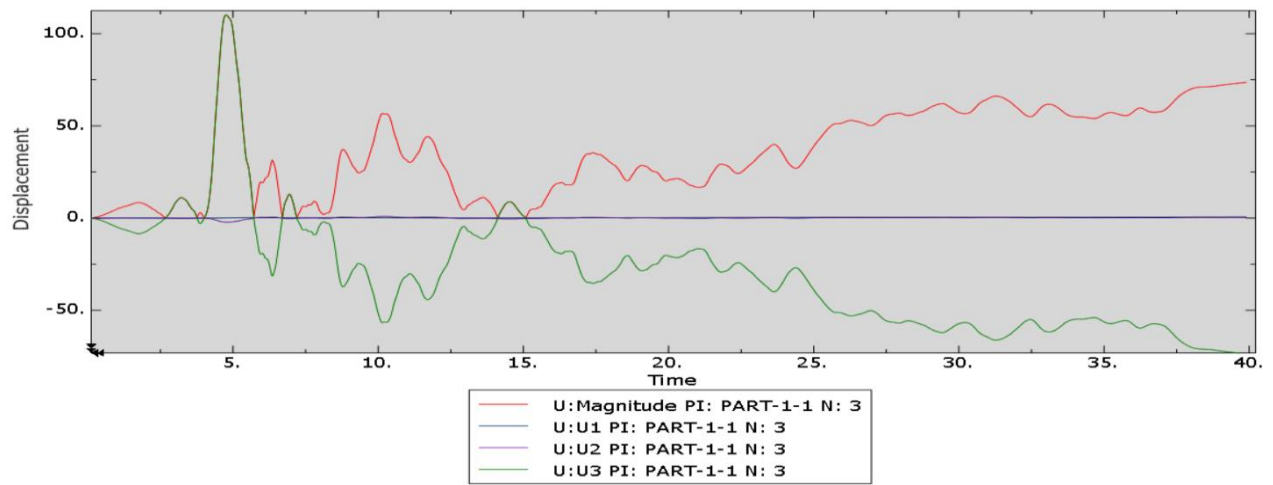


Figure 38: History Output Displacement

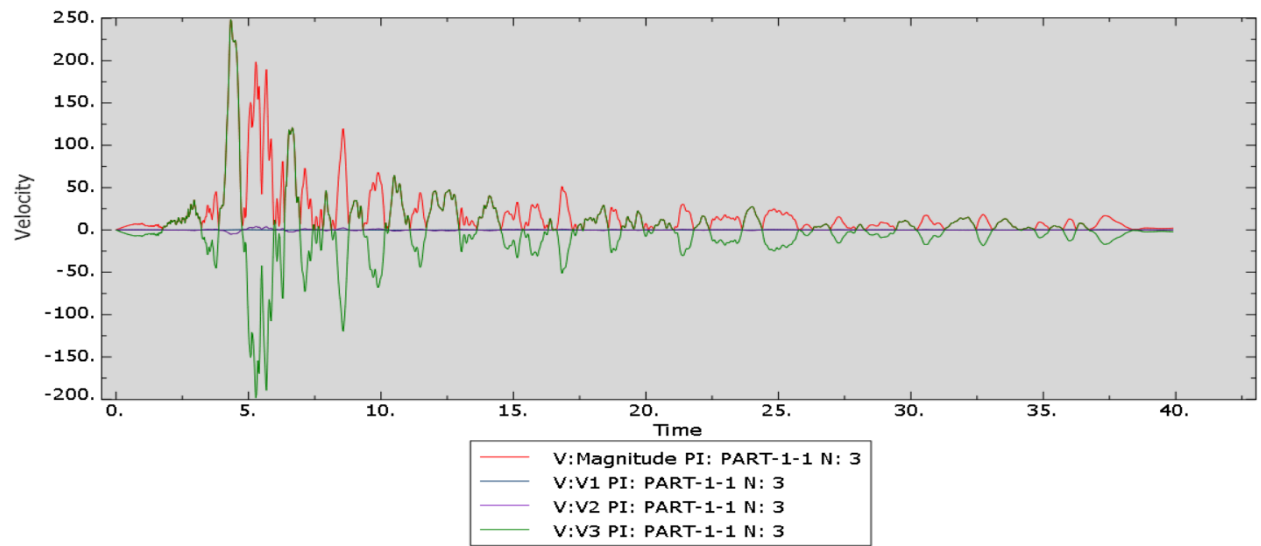


Figure 39: History Output Velocity

8.3 Kobe Earthquake

8.3.1 Effective Mass

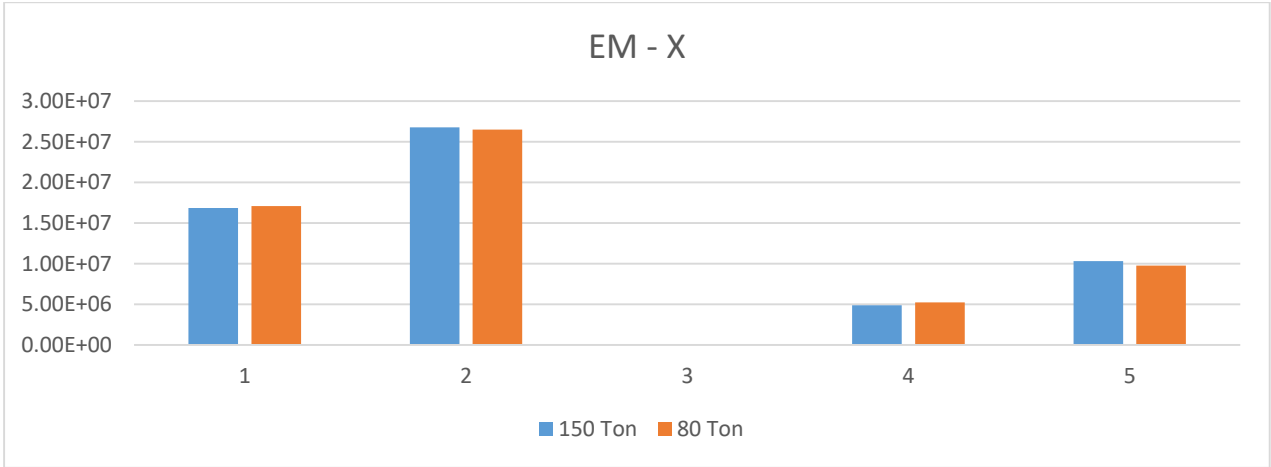


Figure 40: Kobe Effective Mass – X

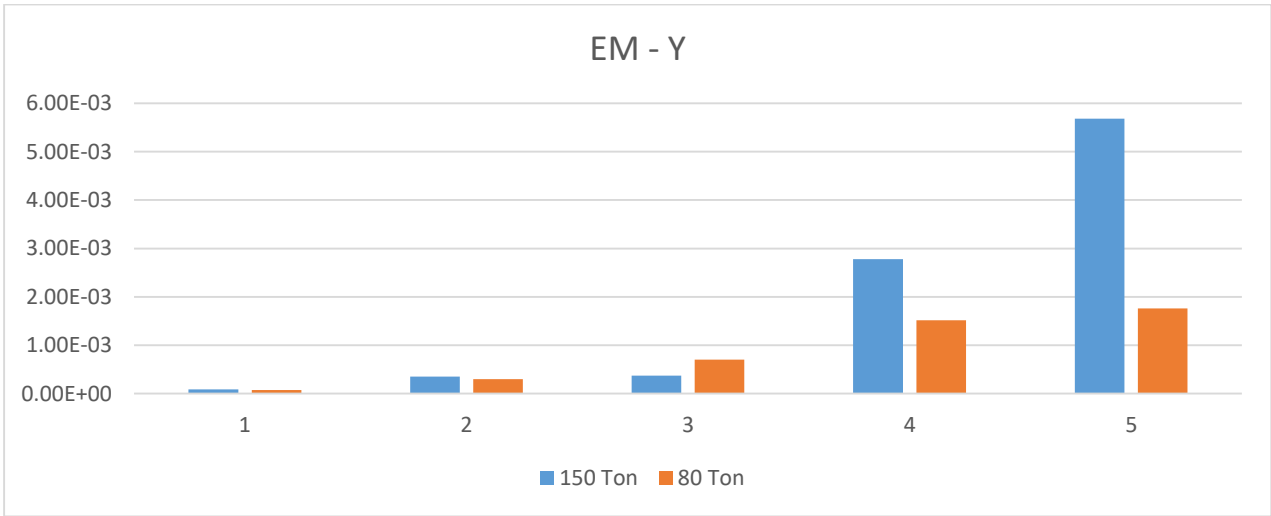


Figure 41: Kobe Effective Mass – Y

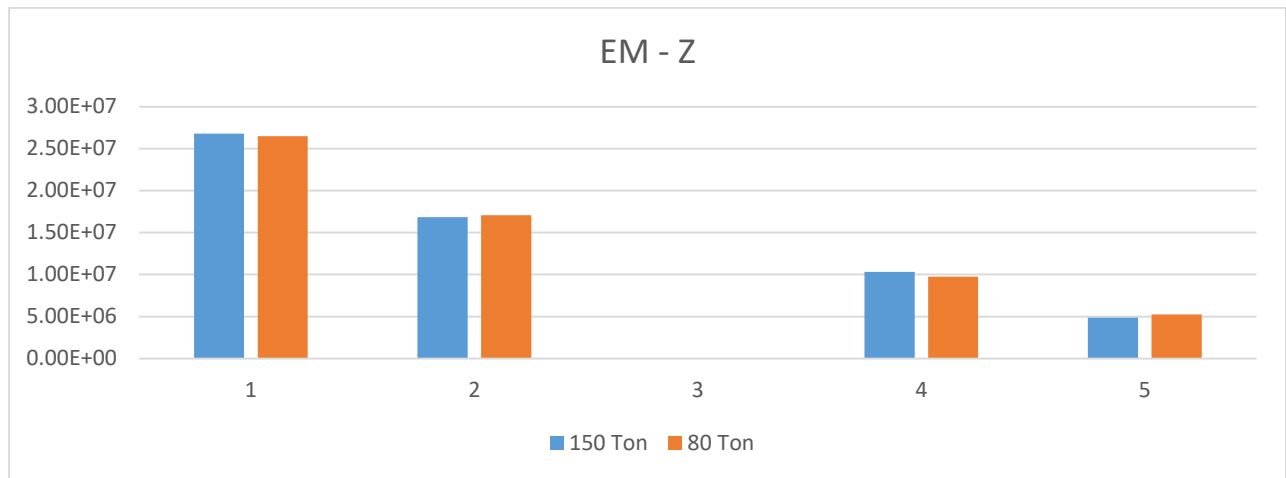


Figure 42: Kobe Effective Mass – Z

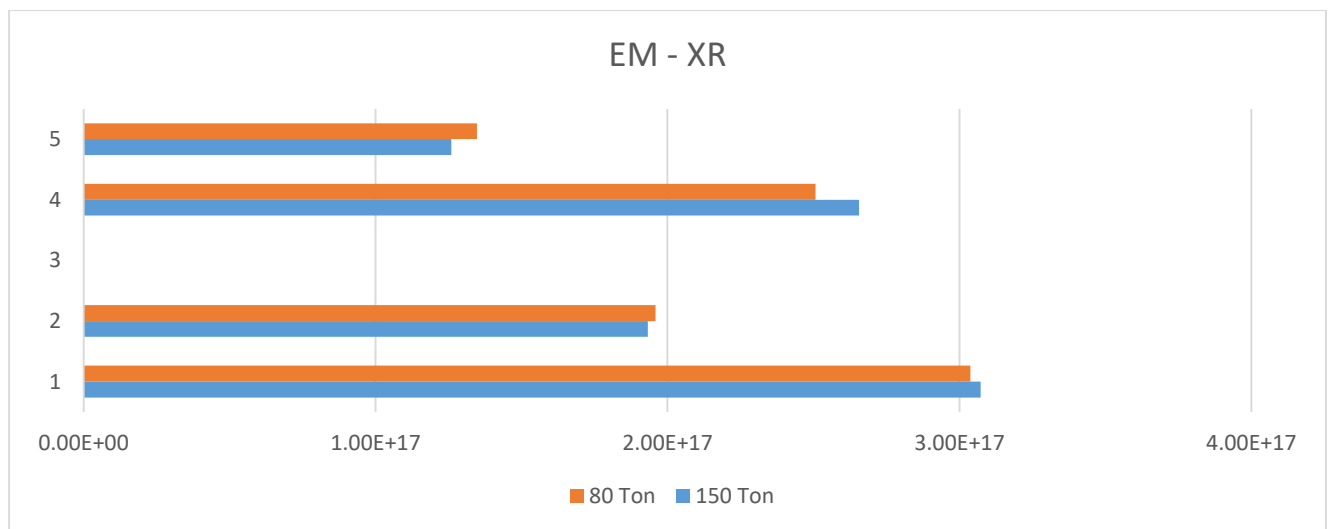


Figure 43: Kobe Effective Mass – X - Rotation

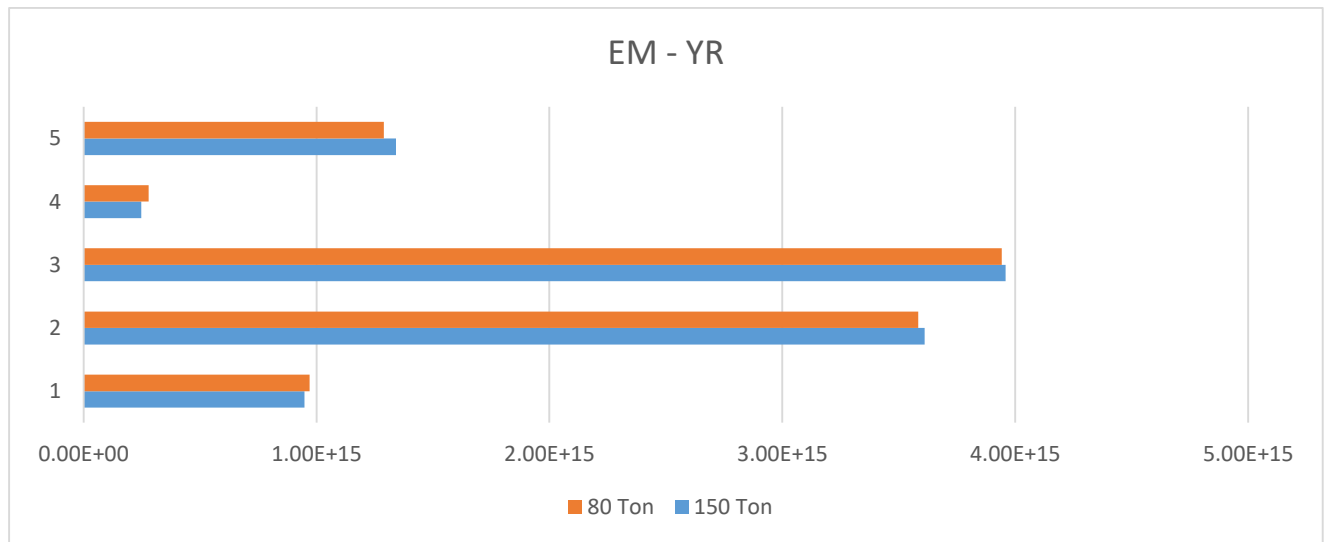


Figure 44 : Kobe Effective Mass – Y - Rotation

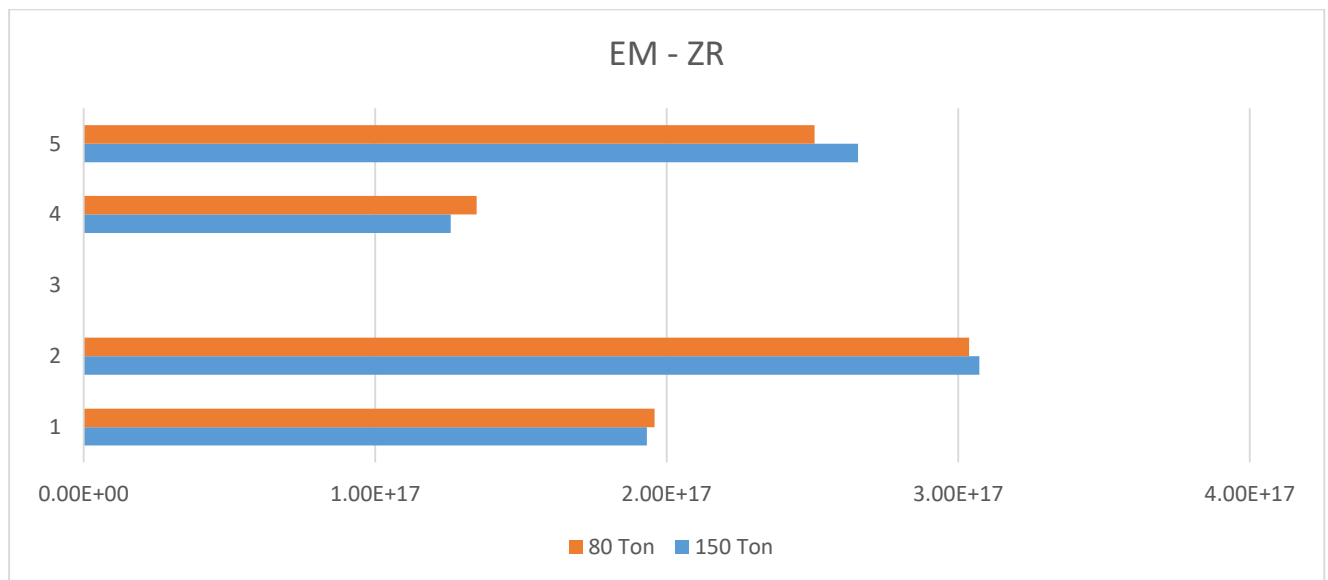


Figure 45: Kobe Effective Mass – Z - Rotation

8.3.2 Participation Factors

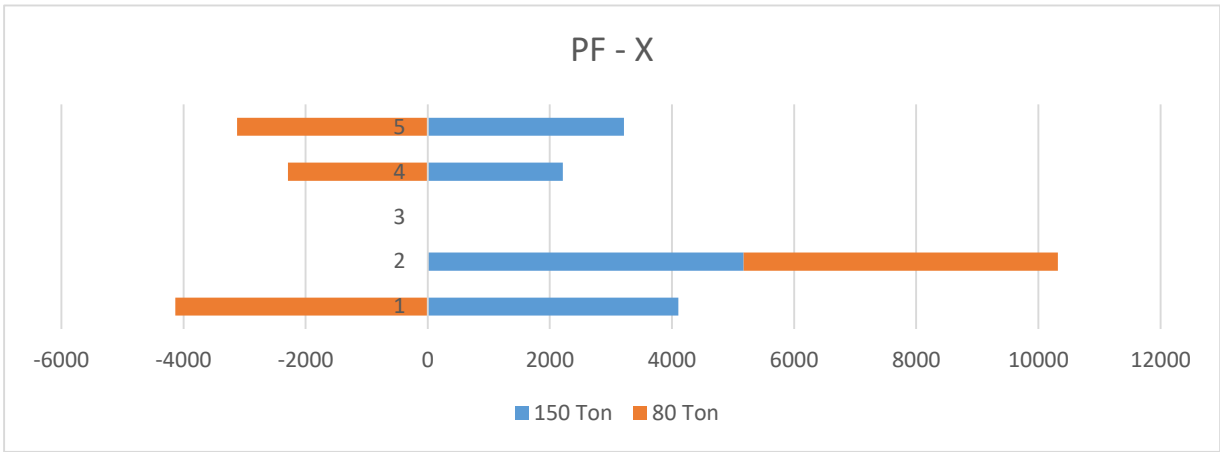


Figure 46: Participation Factor – X

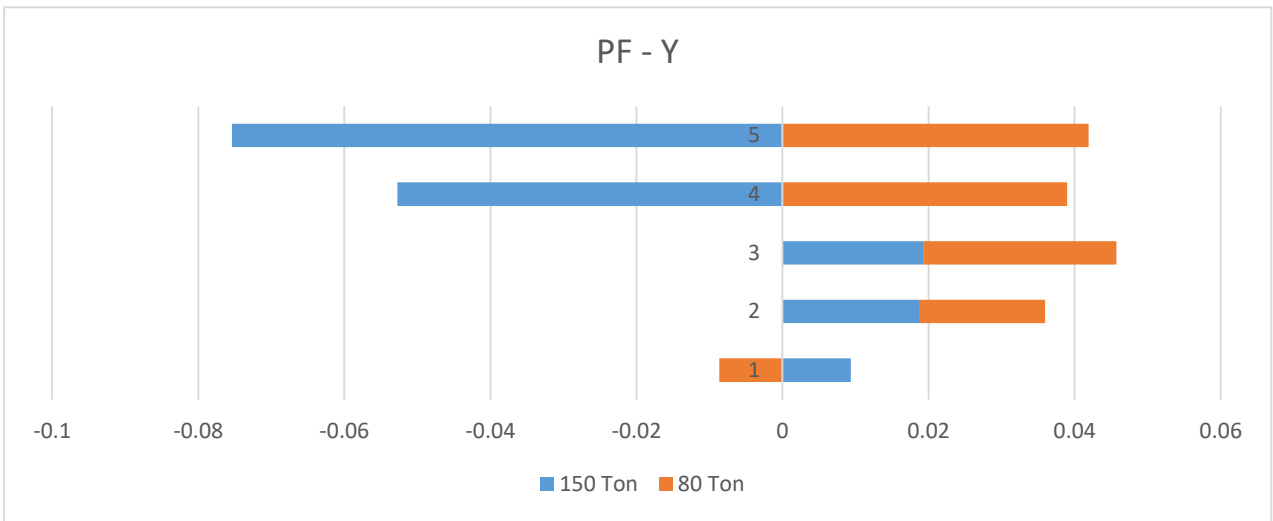


Figure 47: Participation Factor – Y

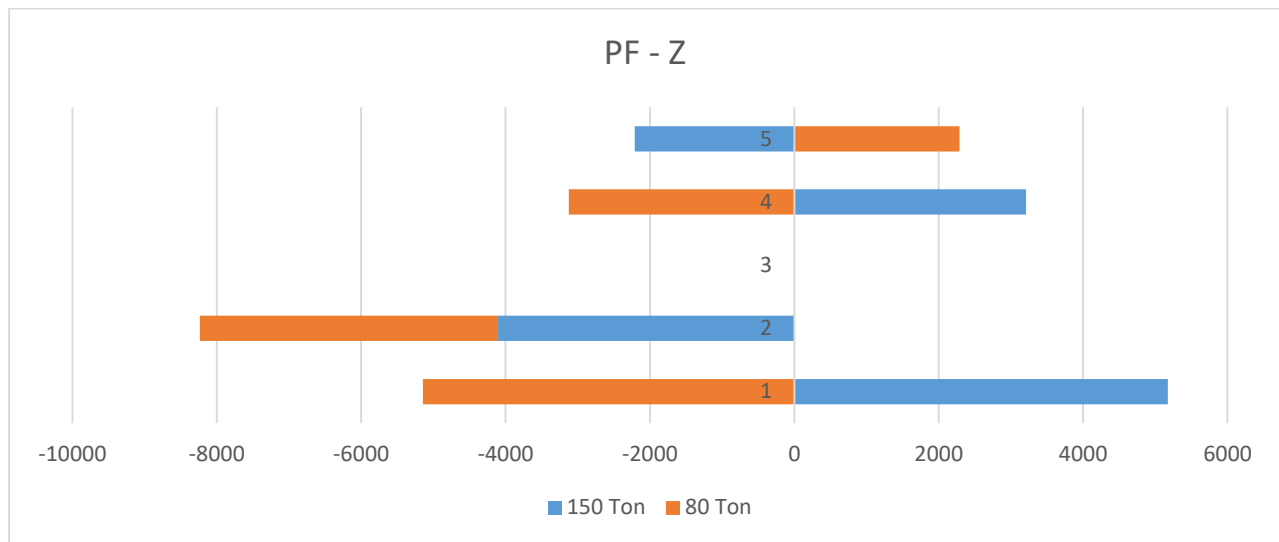


Figure 48: Participation Factor – Z

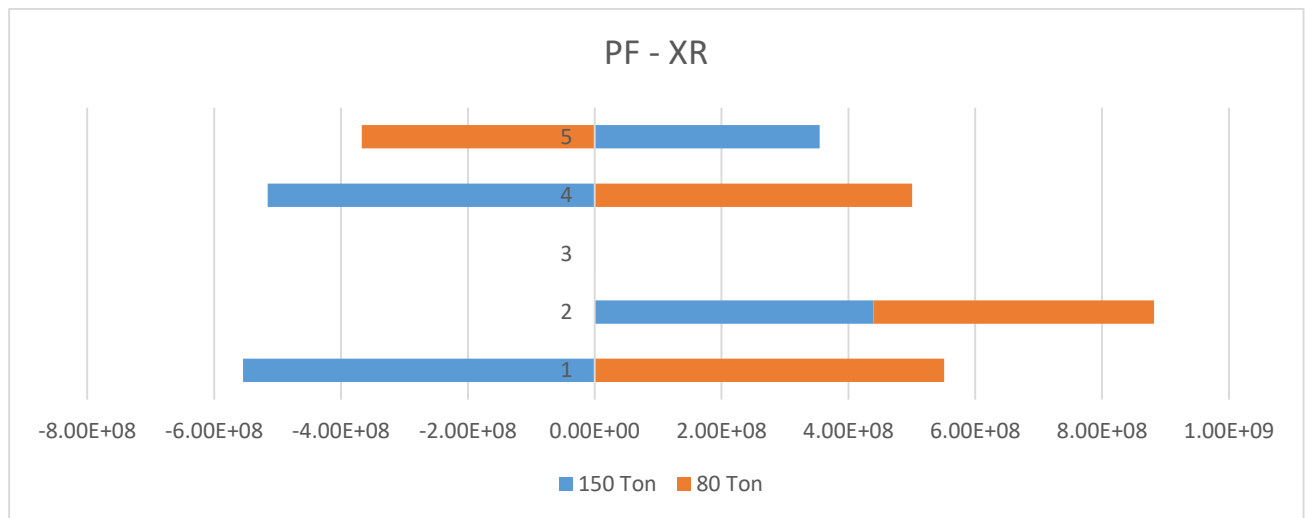


Figure 49: Participation Factor – X - Rotation

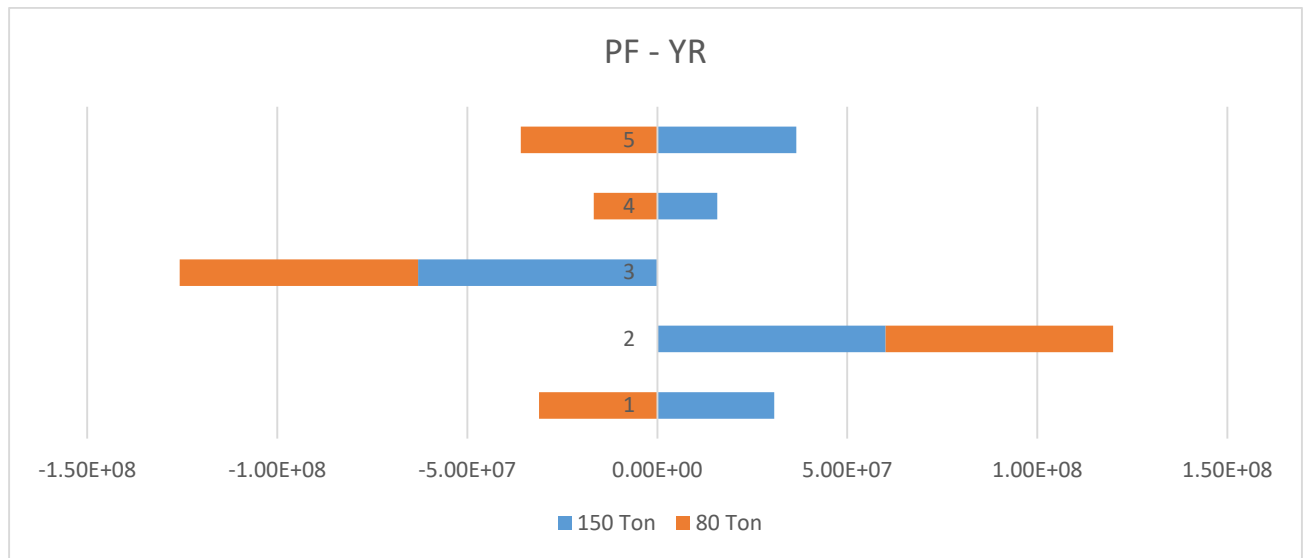


Figure 50: Participation Factor – Y - Rotation

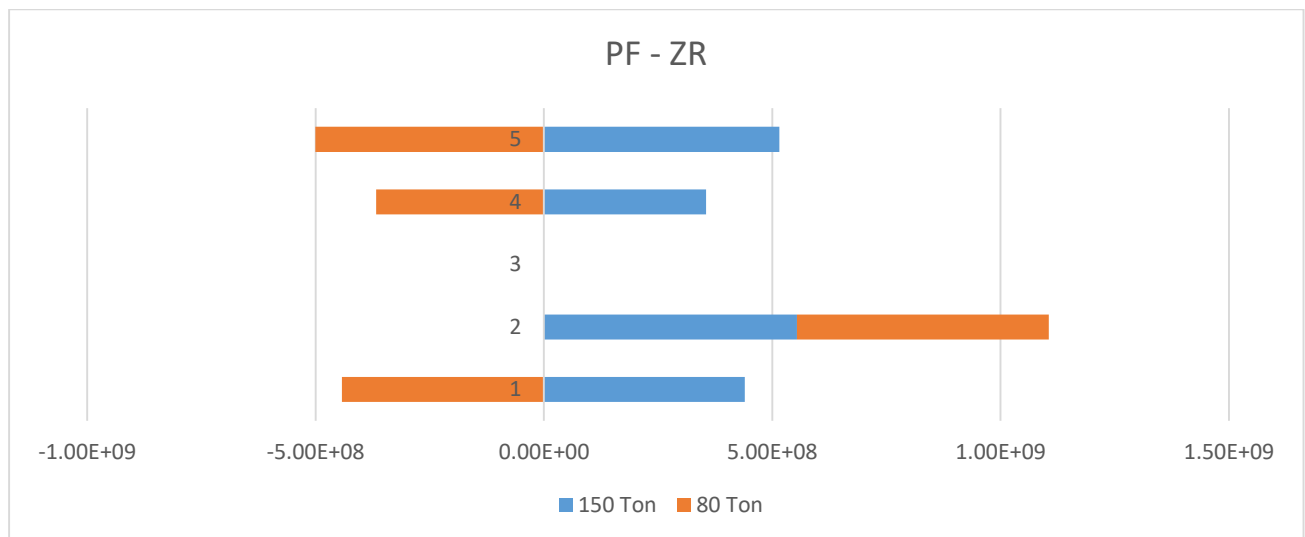


Figure 51: Participation Factor – Z - Rotation

8.4 Chi-Chi Earthquake

8.4.1 Eigen Values

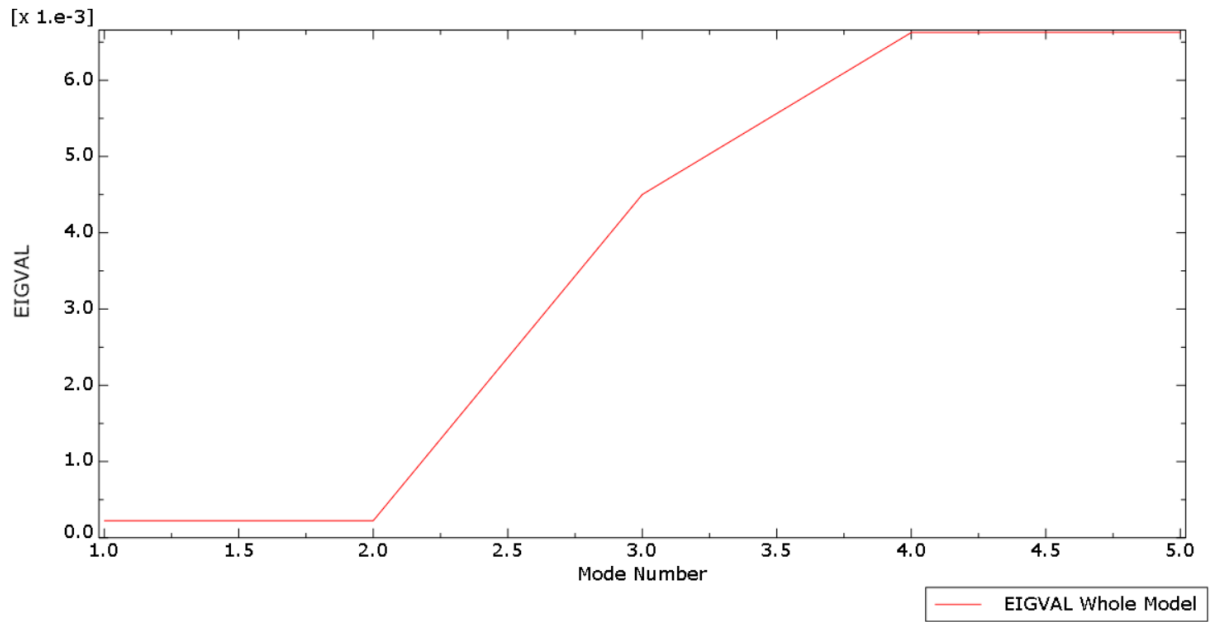


Figure 52: Eigen Value of Entire Model

8.4.2 Eigen Frequency

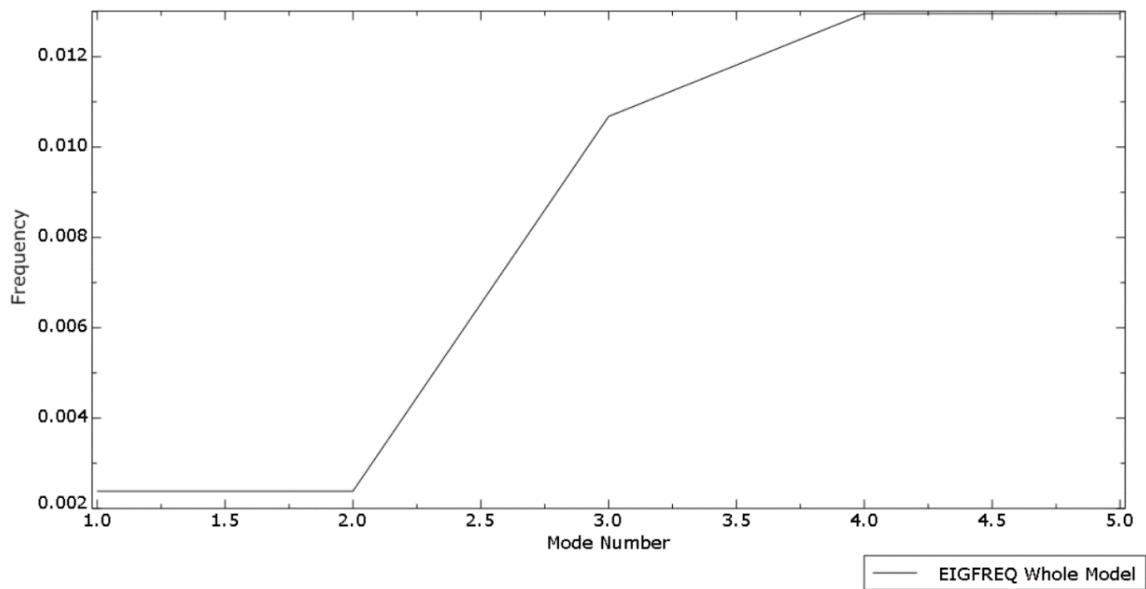


Figure 53: Eigen Frequency of Entire Model

8.4.3 Time-History Outputs

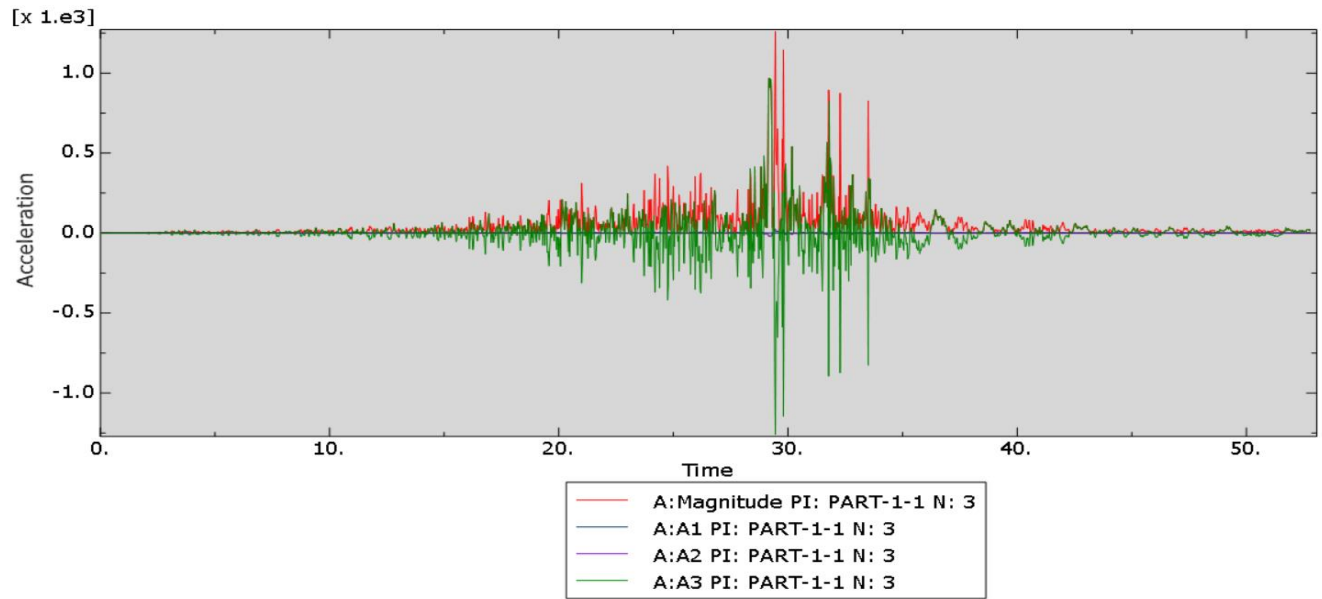


Figure 54: Acceleration History Output

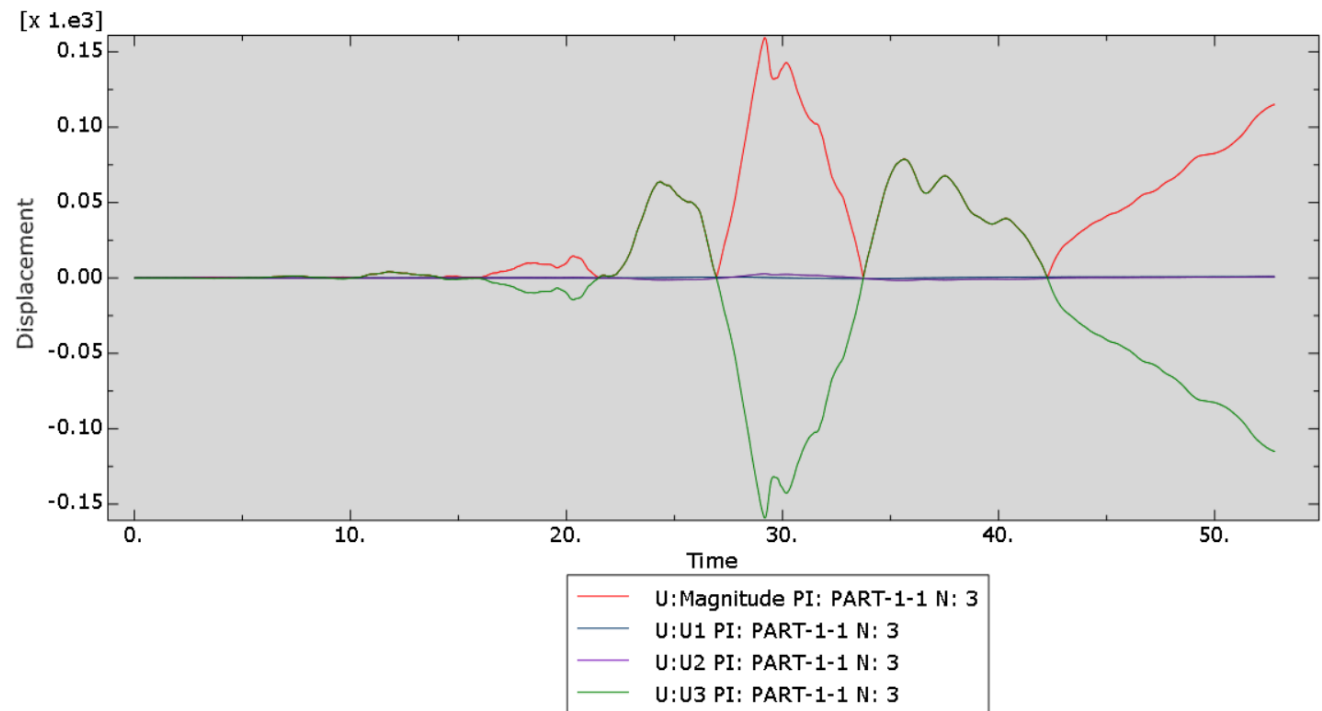


Figure 55: Displacement History Output

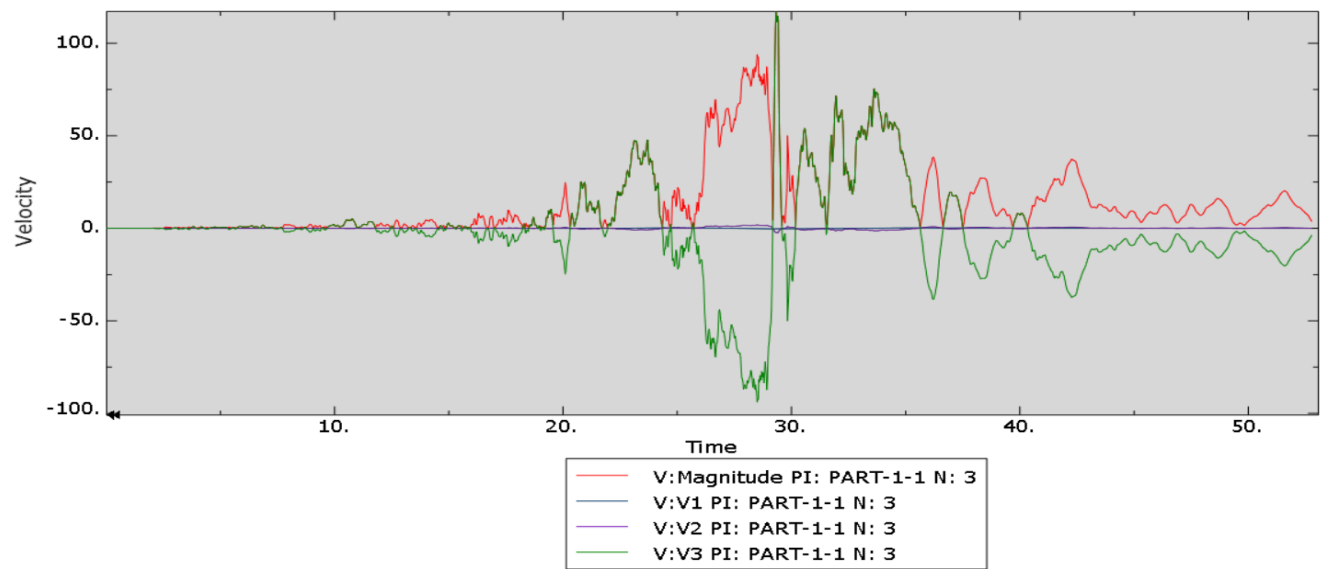


Figure 56: Velocity History Output

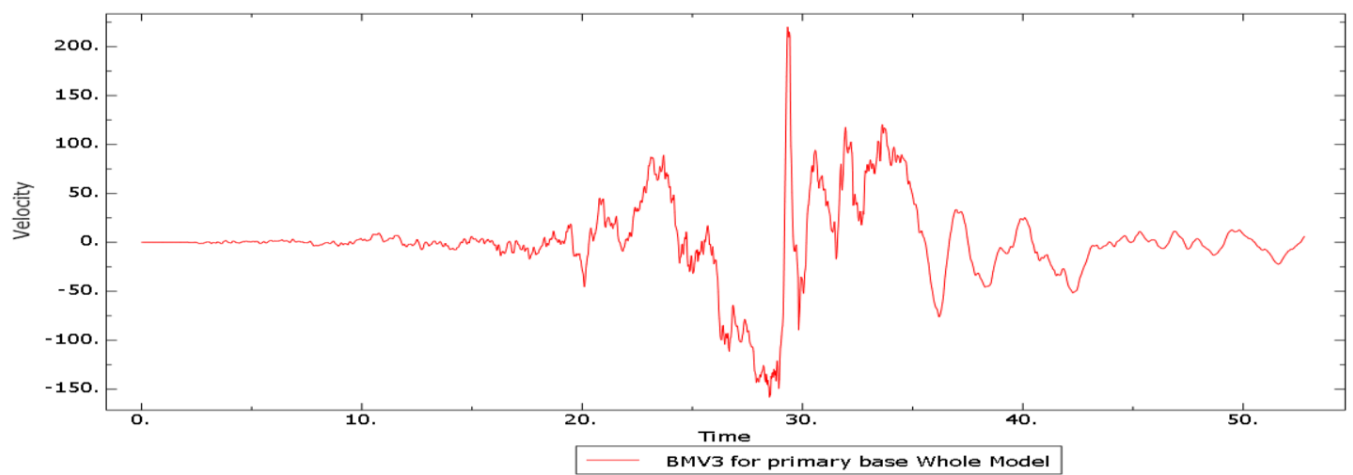
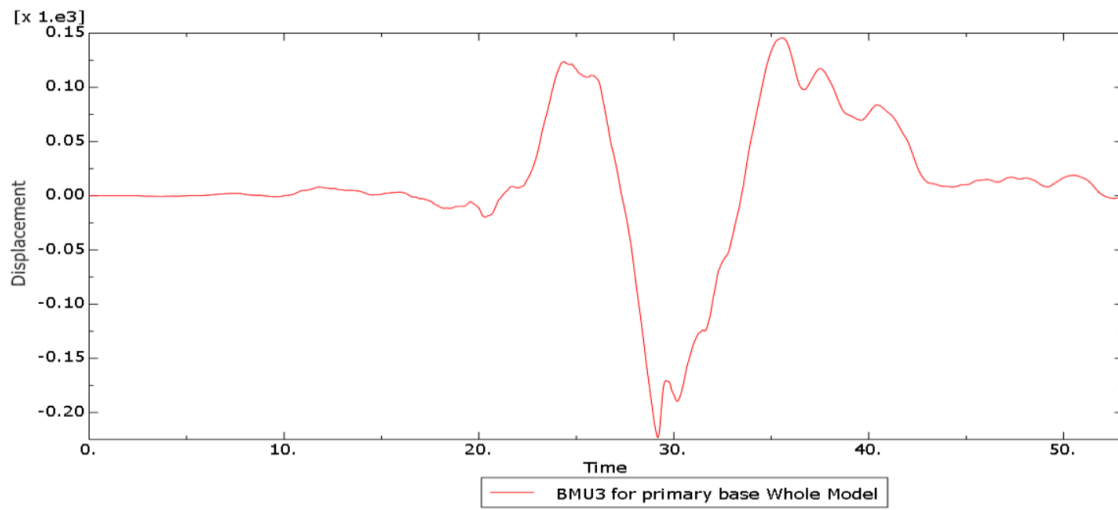


Figure 57: Base Motion Velocity (V3)

8.4.4 Base Motion (A, V, & U)



Base Motion Displacement (U3)

Figure 58: Base Motion Displacement (U3)

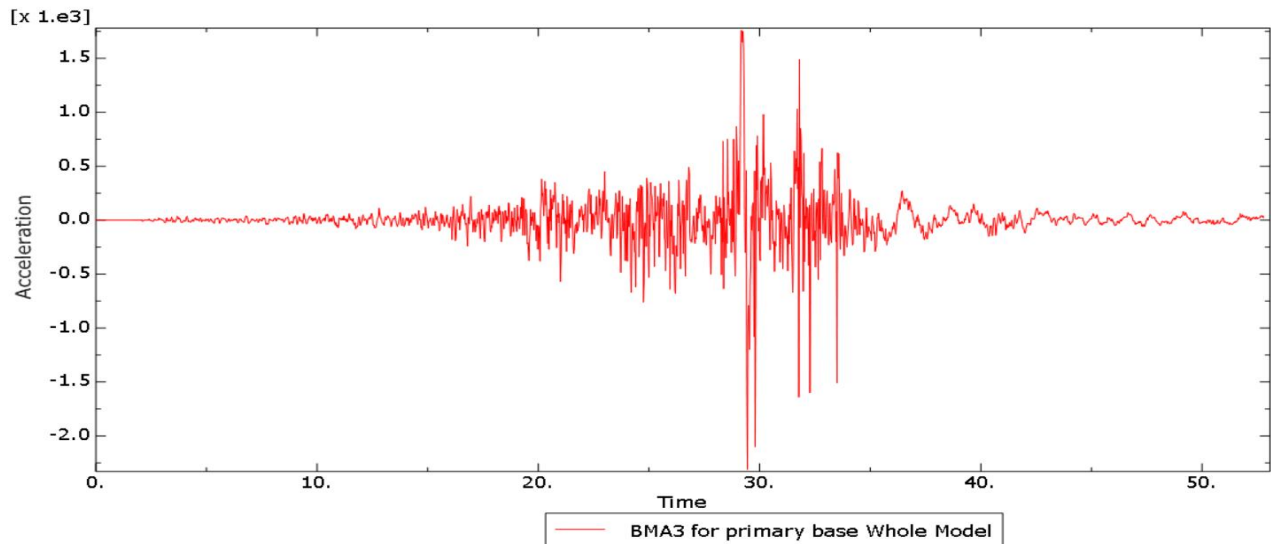


Figure 59: Base Motion Acceleration (A3)

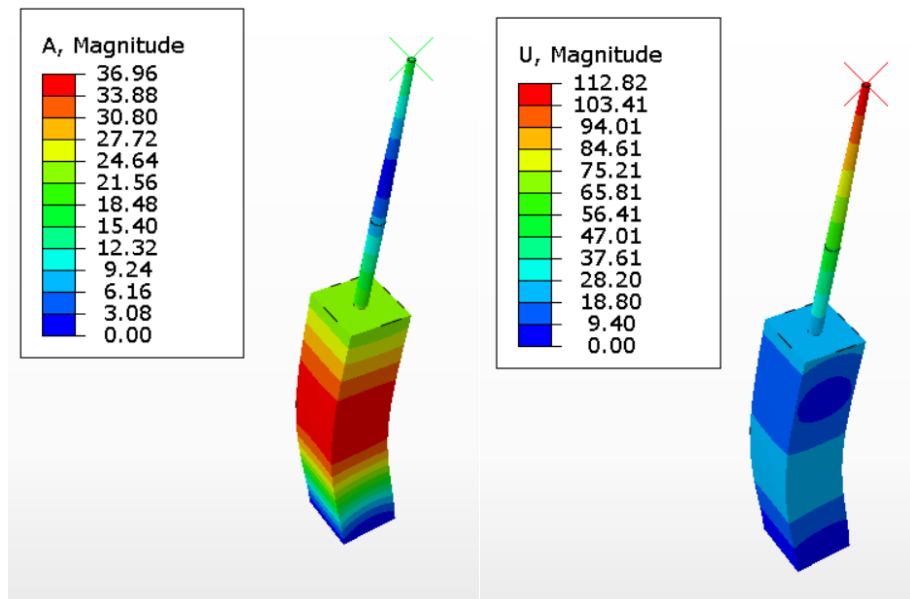


Figure 60: FEA Contours (A, U)

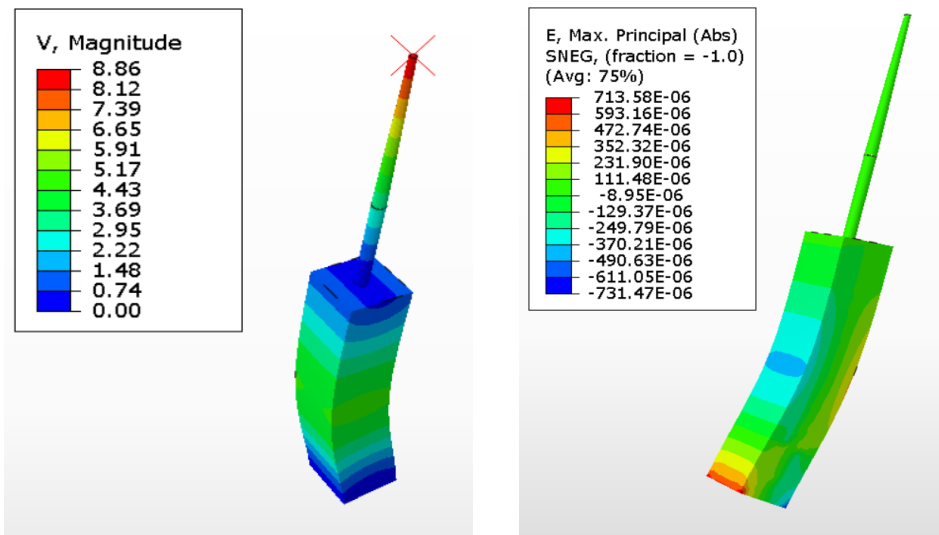


Figure 61: FEA Contours (V, E_max)

Chapter 9: Discussion

In this section we discuss the results that we have obtained.

In the following graphs, the 'N' in the labels refers to the Nacelle Load value in tons and the 'T' refers to the Thickness of steel elements in millimeters.

9.1 Eigen Values Variation

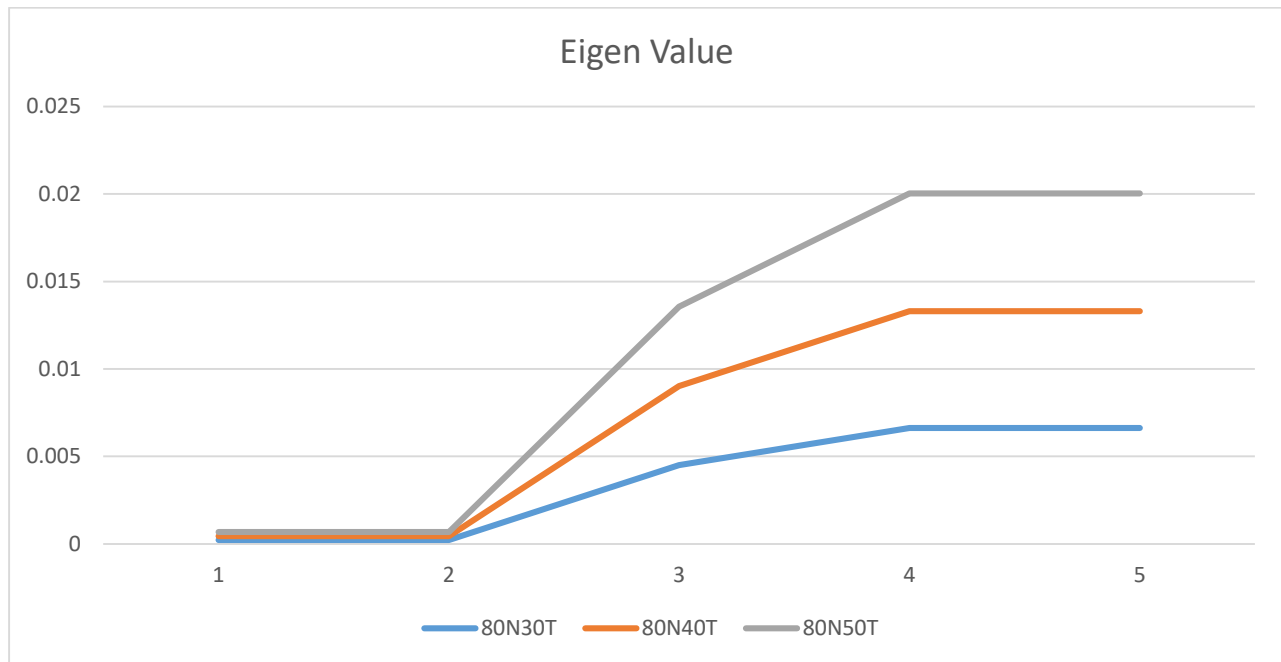


Figure 62: Multiplot Eigen Value Comparison Nacelle 80T

The changing Eigen Values for the changing thickness with the same Nacelle load can be observed in this chart.

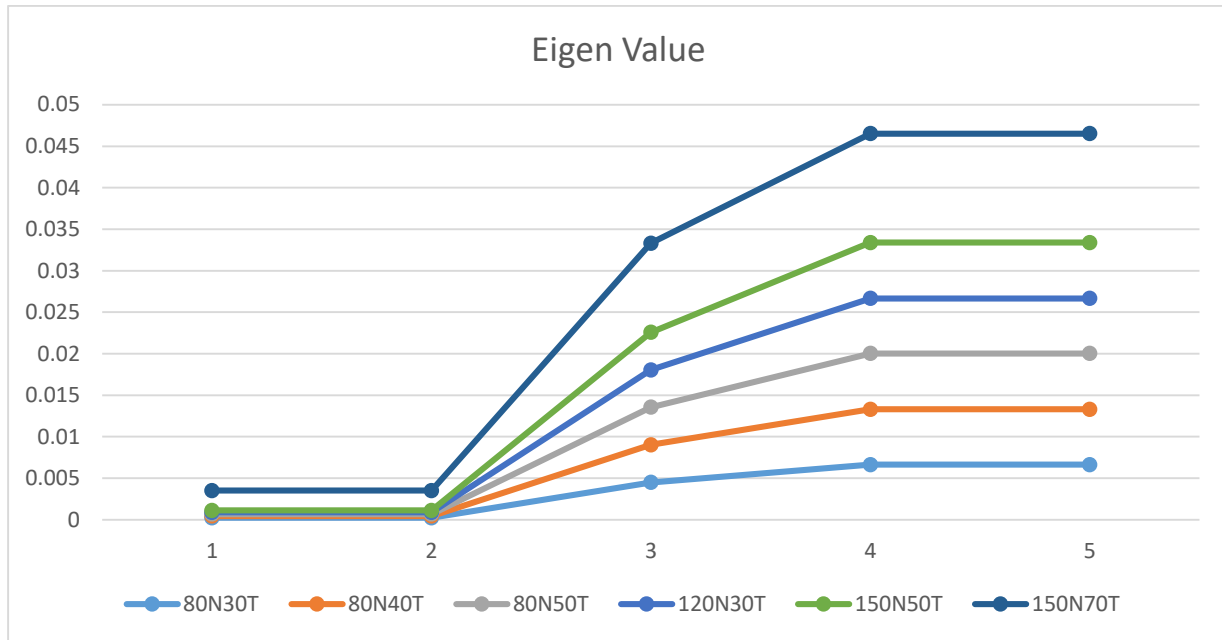


Figure 63: Multiplot Eigen Value Comparison

In this graph, the changing Eigen Values for different Nacelle loads as well as thicknesses can be observed.

In this subsection, we delve into the analysis of eigenvalues obtained from the dynamic response simulations, focusing on variations in eigenvalues concerning changes in nacelle loads and thicknesses of the steel elements, specifically the Monopile and the Tower.

9.1.1 Effect of Thickness Variation at Constant Nacelle Load (80 Ton)

The first three columns of eigenvalues correspond to simulations with a constant nacelle load of 80 tons, varying only the thickness of the steel elements. Observing these columns, we notice a consistent pattern:

As the thickness increases from 30T to 50T, there is a gradual progression in the eigenvalues for the first few modes. This indicates that the structural response becomes more

pronounced with thicker steel elements, likely resulting in changes in natural frequencies and mode shapes.

9.1.2 Impact of Increasing Nacelle Load

Transitioning to subsequent columns where nacelle loads are increased while maintaining a constant thickness (50T), we observe:

Higher nacelle loads lead to a noticeable upward trend in eigenvalues across all modes. This is indicative of increased stiffness and mass within the system, resulting in a shift in natural frequencies. The structure is responding more vigorously to dynamic loading, reflecting the influence of the added nacelle load.

9.1.3 Combined Influence of Nacelle Load and Thickness Variation

The last two columns represent simulations where both nacelle loads and thicknesses are increased. Noteworthy observations include:

Eigenvalues continue to exhibit an upward trend, emphasizing the cumulative effect of elevated nacelle loads and thicker steel elements on the dynamic behavior of the system.

9.1.4 Discussion on Eigenvalue Patterns

The observed patterns in eigenvalues portrays the sensitivity of the offshore wind turbine assembly to changes in both nacelle loads and structural dimensions. The increase in eigenvalues suggests an intricate interplay between mass, stiffness, and dynamic loading conditions, influencing the system's natural frequencies and modes.

It can be observed that the eigenvalues are directly linked to the dynamic characteristics of the structure. A comprehensive understanding of these variations is vital for designing offshore wind turbine components that can withstand varying operational conditions and loading scenarios.

The trends identified in the eigenvalue variations pave the way for further investigations into mode shapes, modal participation factors, and the overall dynamic response of the system. These insights are crucial for optimizing the design and ensuring the structural integrity and performance of offshore wind turbine assemblies under the unique environmental paradigm.

9.2 Eigen Frequency Variation

In this section we explore the variations in Eigen frequencies derived from the dynamic response simulations. The Eigen frequencies, representing the natural frequencies of the offshore wind turbine assembly, are analyzed concerning changes in nacelle loads and thicknesses of the steel elements.

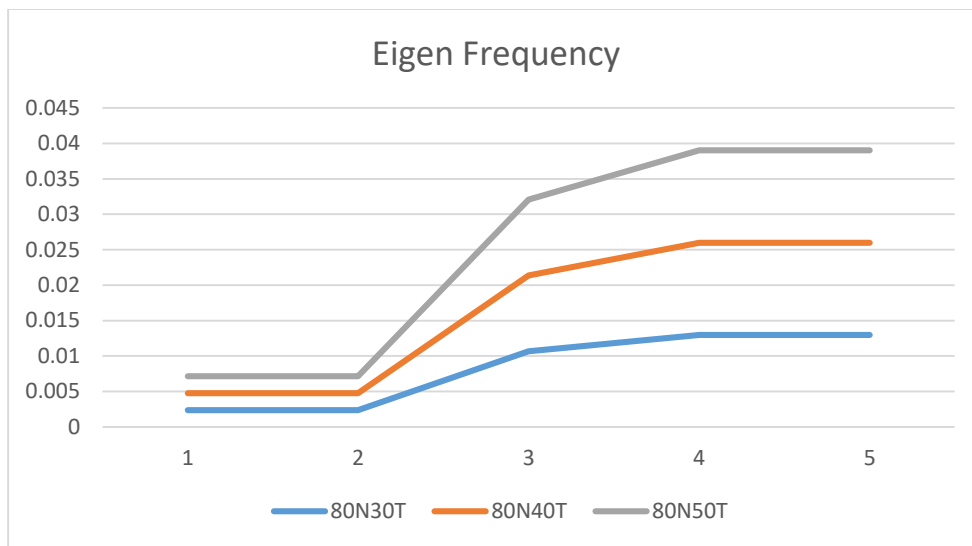


Figure 64: Multiplot Eigen Frequency Comparison Nacelle 80T

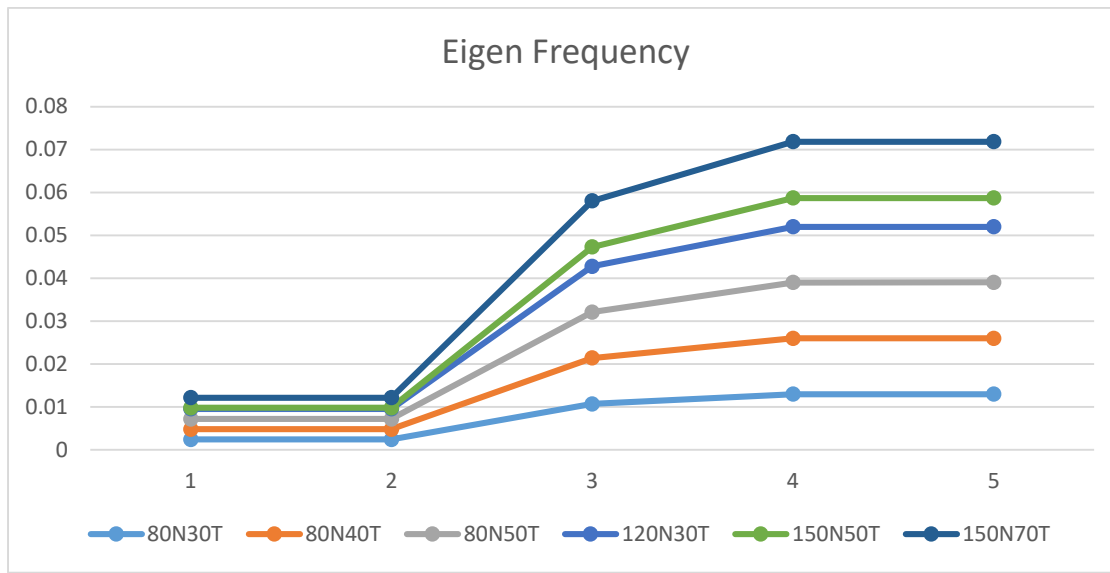


Figure 65: Multiplot Eigen Frequency Comparison

9.2.1 Impact of Thickness Variation at Constant Nacelle Load

Examining the first three columns corresponding to a constant nacelle load of 80 tons with varying thicknesses, we discern the following trends in Eigen frequencies:

Eigen frequencies exhibit a consistent rise as the thickness increases from 30T to 50T. This indicates a direct correlation between the thickness of the steel elements (Monopile and Tower) and the natural frequencies of the structure. The system's response becomes more pronounced with thicker elements, influencing the dynamic behavior.

9.2.2 Influence of Increasing Nacelle Load

Transitioning to subsequent columns where nacelle loads are increased while maintaining a constant thickness (50T), the impact on Eigen frequencies becomes apparent:

Higher nacelle loads lead to a discernible upward shift in Eigen frequencies across all modes. This suggests an increase in system stiffness and mass, causing a shift in natural

frequencies. The dynamic response of the structure becomes more pronounced with the addition of higher nacelle loads.

9.2.3 Combined Effect of Nacelle Load and Thickness Variation

The last two columns represent simulations where both nacelle loads and thicknesses are increased. Key observations include:

Eigen frequencies continue to exhibit an upward trend, indicating a cumulative effect of elevated nacelle loads and thicker steel elements on the natural frequencies of the system.

9.3 Participation Factor Assessment

This section delves into the analysis of participation factors, providing insights into the distribution of mass or displacement among the modes of vibration for the offshore wind turbine assembly. The data is presented for various simulations with varying nacelle loads and thicknesses of the steel elements

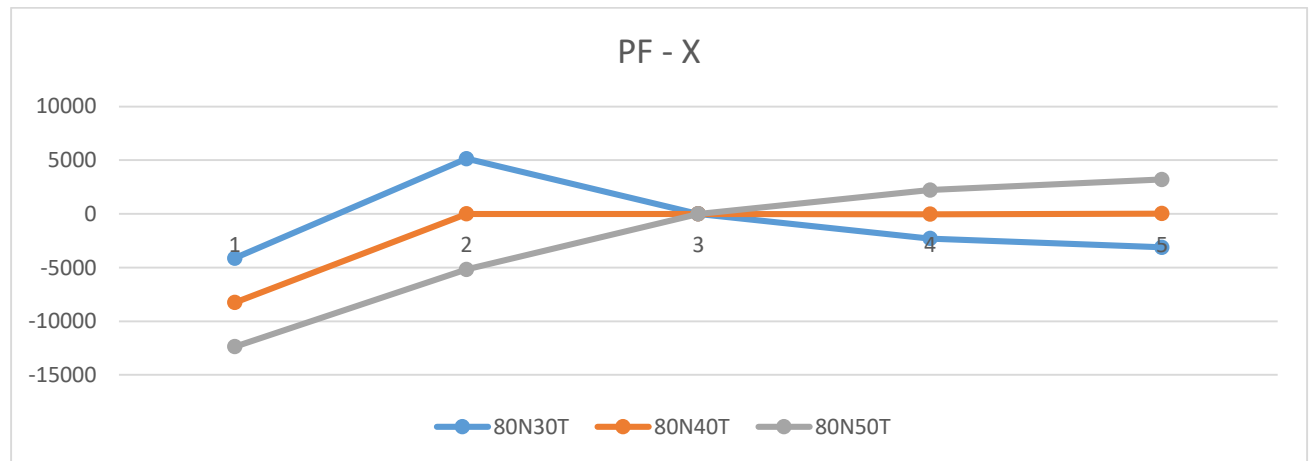


Figure 66: Multiplot Nacelle 80T Participation Factor Comparison X

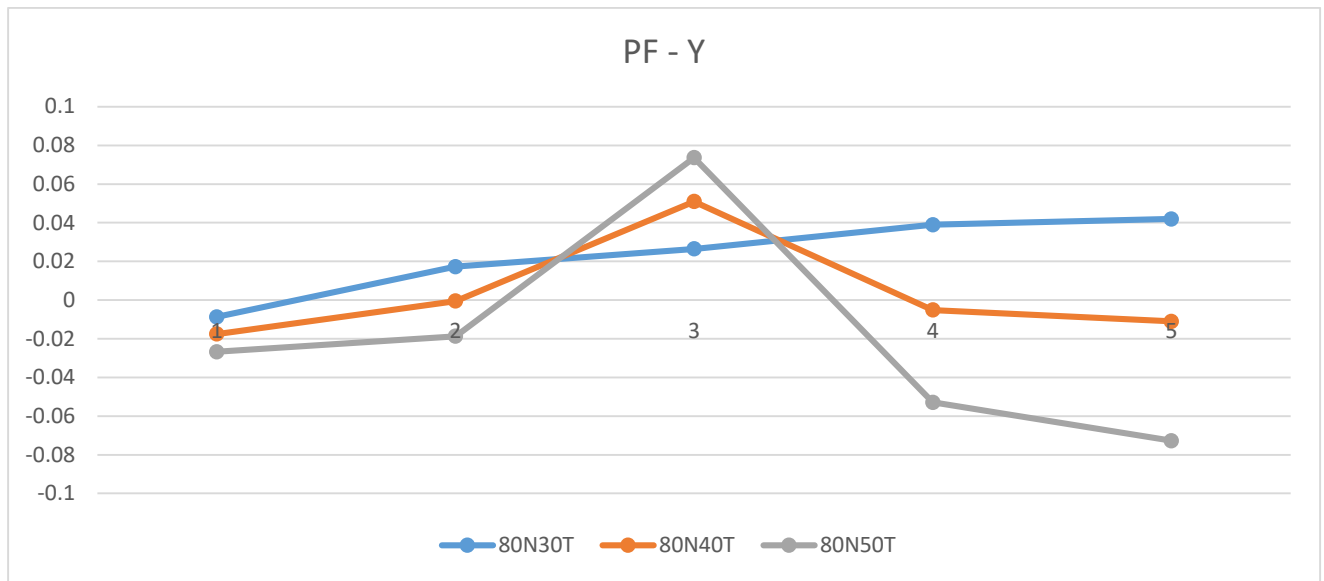


Figure 67: Multiplot Nacelle 80T Participation Factor Comparison Y

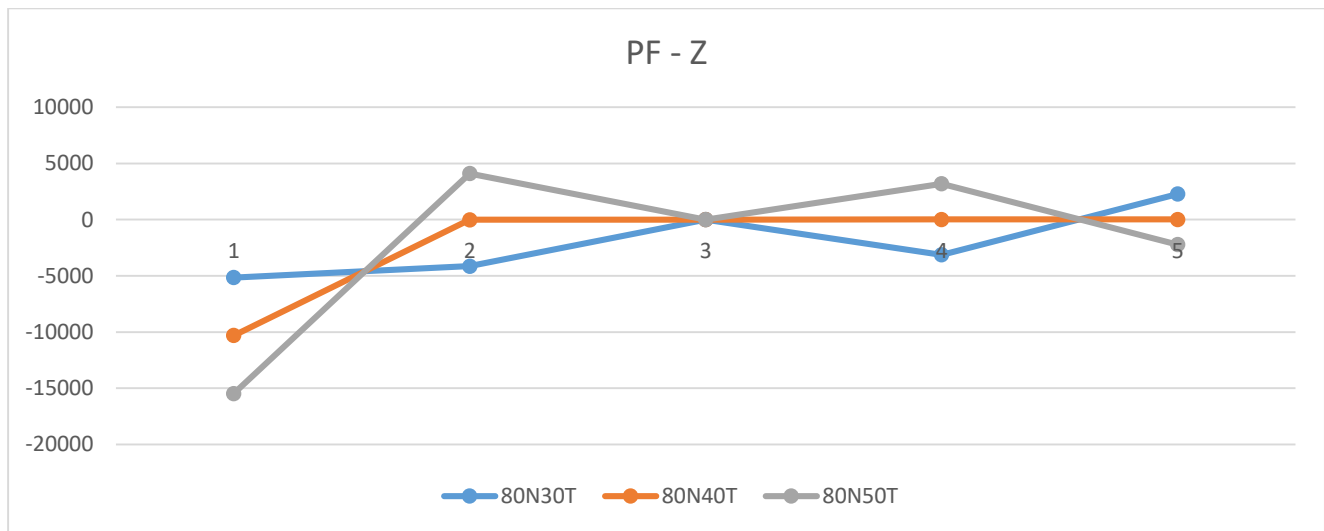


Figure 68: Multiplot Nacelle 80T Participation Factor Comparison Z

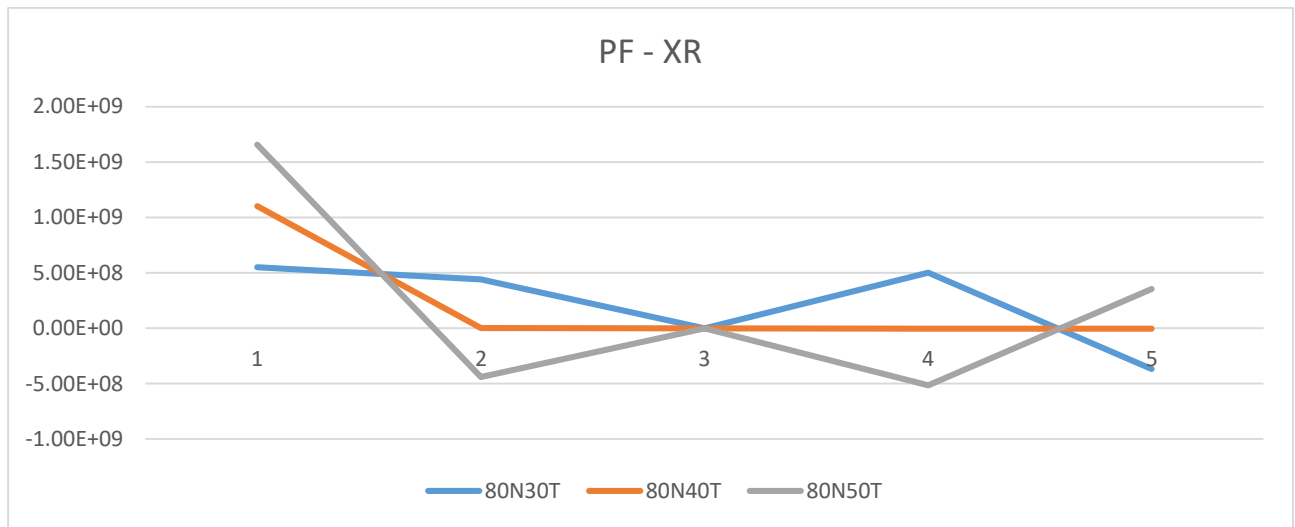


Figure 69: Multiplot Nacelle 80T Participation Factor Comparison XR

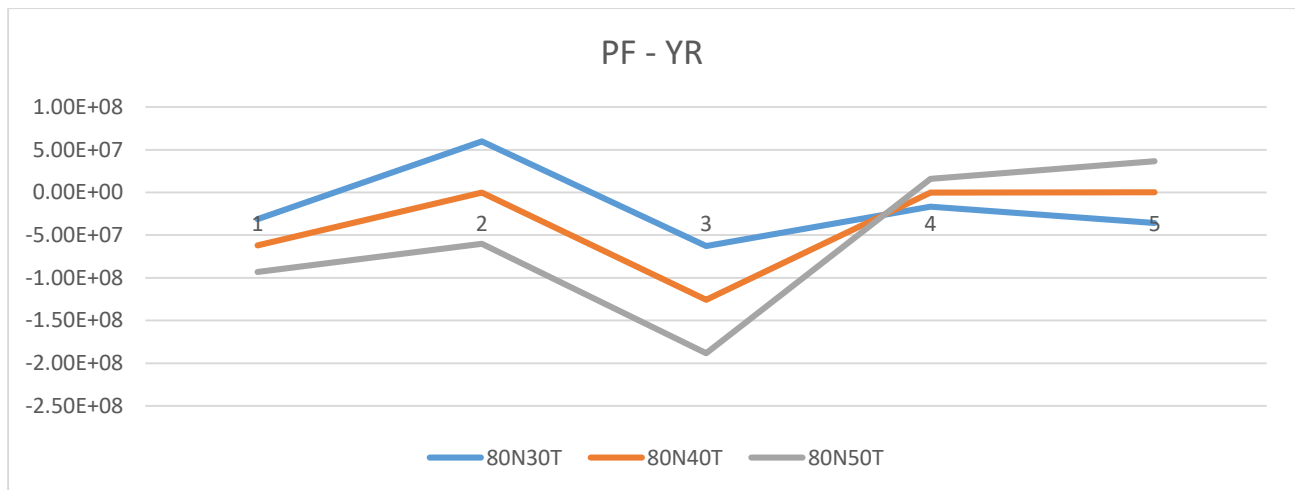


Figure 70: Multiplot Nacelle 80T Participation Factor Comparison YR

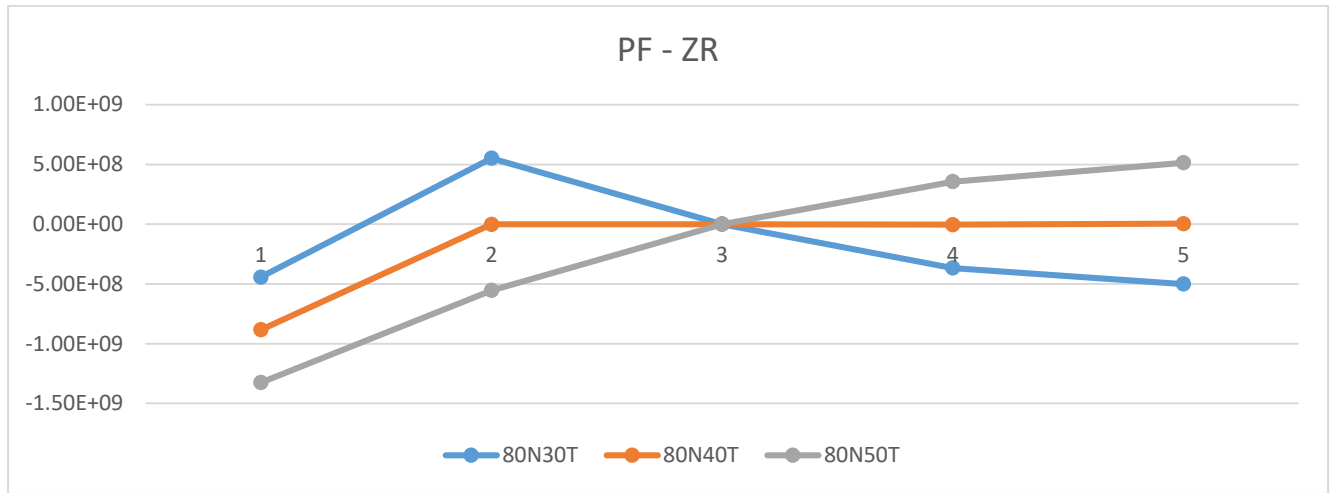


Figure 71: Multiplot Nacelle 80T Participation Factor Comparison ZR

9.3.1 Effect of Thickness Variation at Constant Nacelle Load (80 Tons)

For the first mode, participation factors demonstrate a significant negative value, indicating a dominant influence of this mode on the dynamic response. As the thickness increases from 30T to 50T, participation factors become less negative, suggesting a shift in the distribution of vibrational energy among different modes.

Similar observations are noted for the second mode, where participation factors transition from positive to negative values. This underscores the dynamic interplay between modes as structural dimensions' change.

Third and fourth modes exhibit smaller participation factors, implying a more distributed influence among multiple modes.

9.3.2 Influence of Increasing Nacelle Load

Shifting focus to simulations with increased nacelle loads while maintaining a constant thickness (50T), noteworthy trends in participation factors include:

Participation factors exhibit substantial changes with variations in nacelle load, emphasizing the pronounced impact of increased mass on specific modes.

For the first and second modes, participation factors become more extreme, indicating a heightened influence of these modes under higher nacelle loads.

9.3.3 Combined Effect of Nacelle Load And Thickness Variation

In simulations where both nacelle loads and thicknesses are increased, the cumulative effect on participation factors is evident:

Participation factors continue to evolve, reflecting the complex interaction between structural parameters and loading conditions.

Shifts in participation factors highlight the sensitivity of the system to changes in both nacelle load and thickness, with certain modes exerting greater influence as the system adapts to varying dynamic conditions.

9.3.4 Discussion on Participation Factor Patterns

The observed patterns in participation factors provide us with critical insights into the dynamic characteristics of the offshore wind turbine assembly. The negative and positive values signify the dominance and distribution of vibrational energy among different modes.

Understanding these participation factor variations is essential for optimizing the design of offshore wind turbine structures. Identifying the modes with significant participation factors is important for engineers, as this understanding enables the enhanced design and mitigation of specific vibrational responses under the unique setting in which OWTs operate.

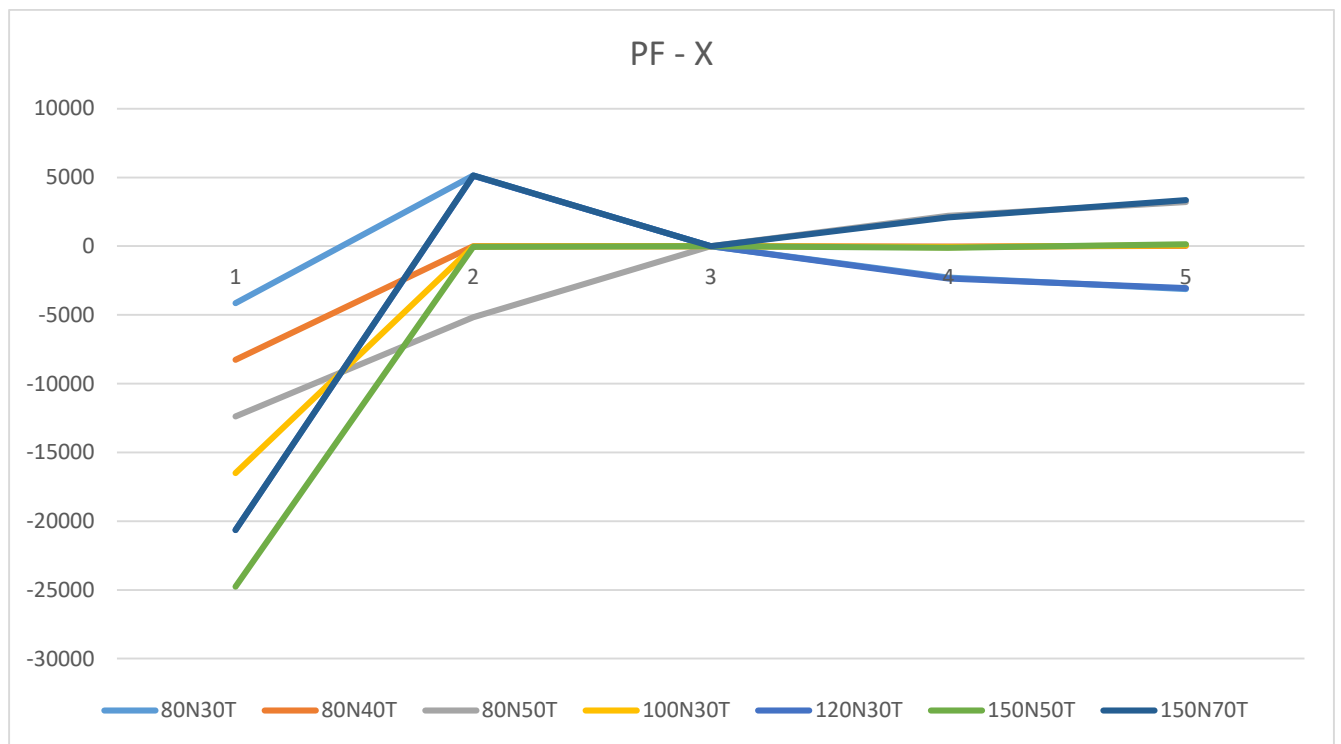


Figure 72: Multiplot Participation Factor Comparison X

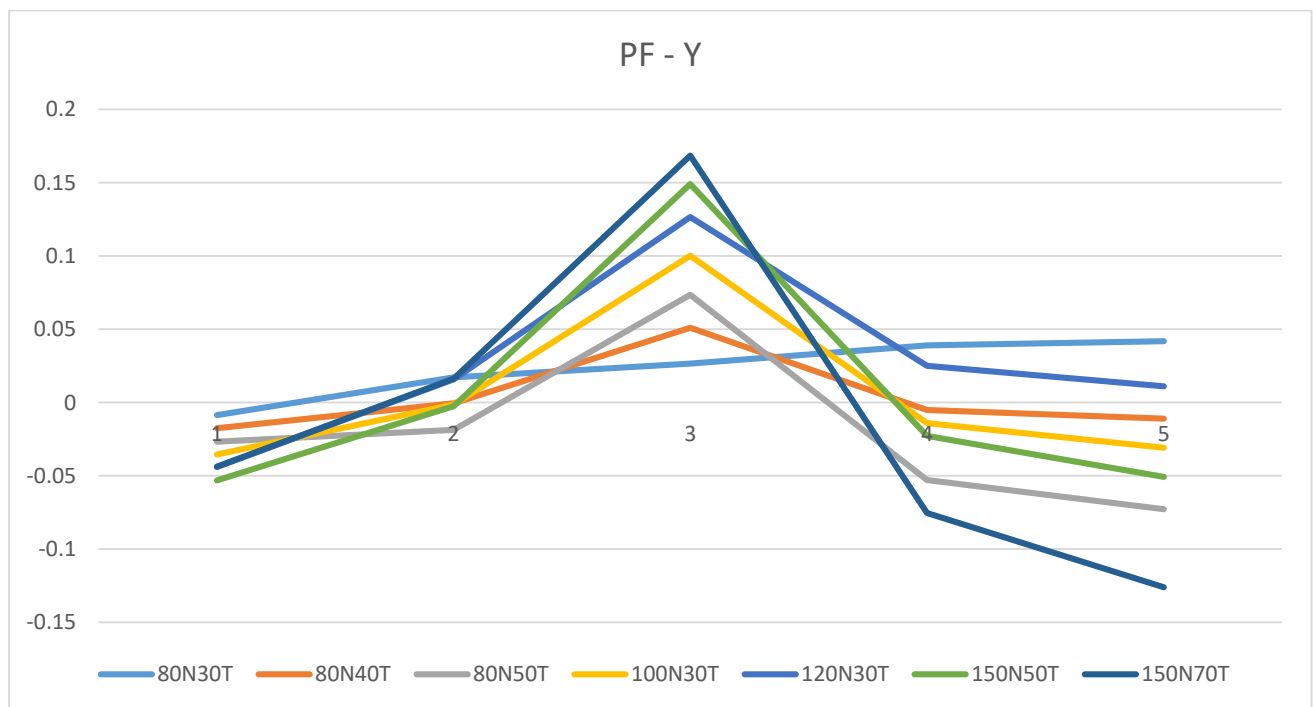


Figure 73: Multiplot Participation Factor Comparison Y

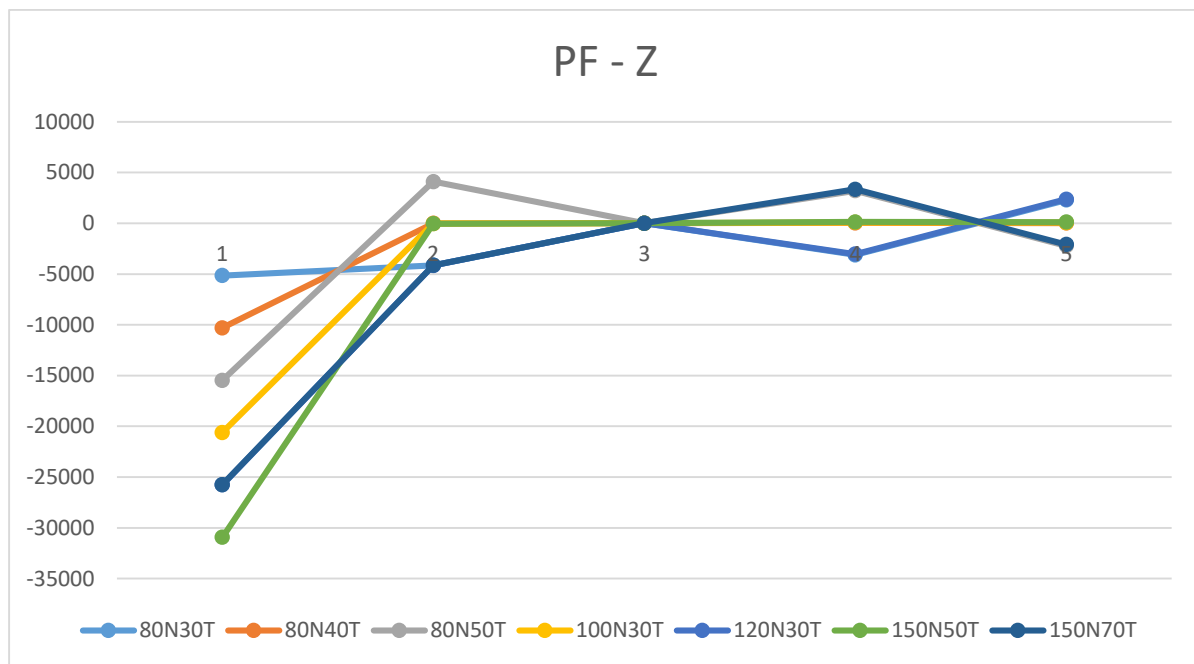


Figure 74: Multiplot Participation Factor Comparison Z

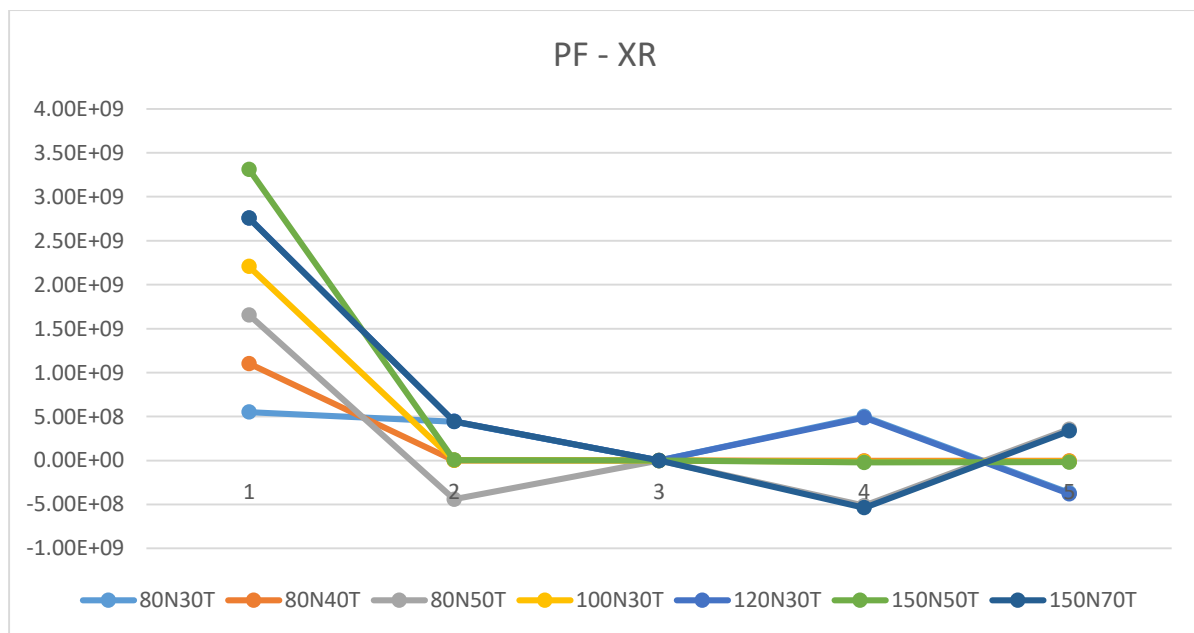


Figure 75: Multiplot Participation Factor Comparison XR

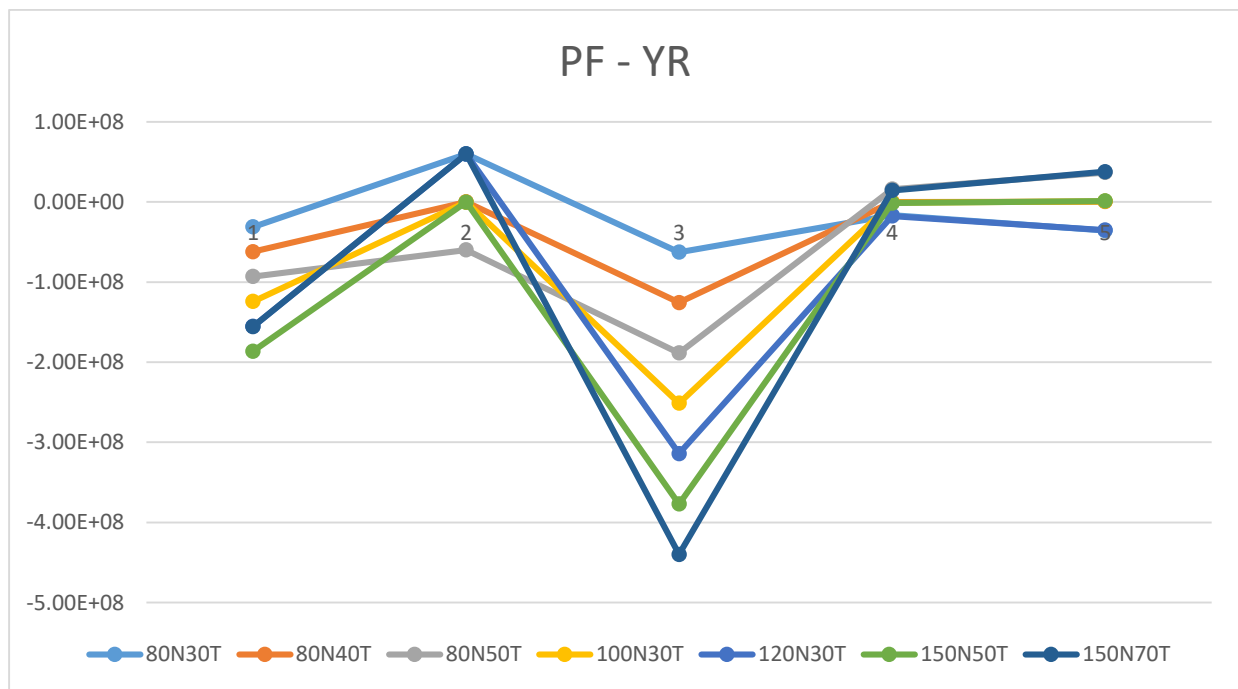


Figure 76: Multiplot Participation Factor Comparison YR

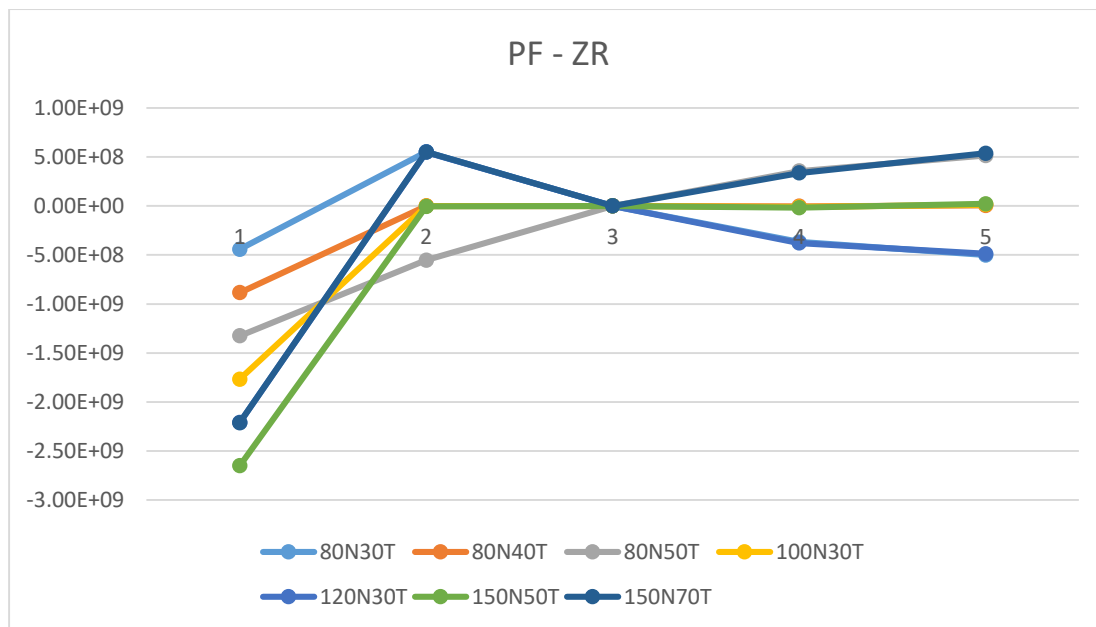


Figure 77: Multiplot Participation Factor Comparison ZR

9.4 Effective Mass Assessment

9.4.1 Effect of Thickness Variation at Constant Nacelle Load (80 Tons)

Analyzing the effective mass for simulations with a constant nacelle load of 80 tons and varying thicknesses reveals intriguing patterns:

The effective mass at each degree of freedom exhibits a gradual decrease as the thickness increases from 30T to 50T. This indicates that thicker structural elements contribute to a reduction in the effective mass, potentially enhancing the system's ability to resist dynamic loads.

The variation in effective mass is more pronounced for translational degrees of freedom (X, Y, Z) compared to rotational degrees of freedom (X-rotation, Y-rotation, Z-rotation)

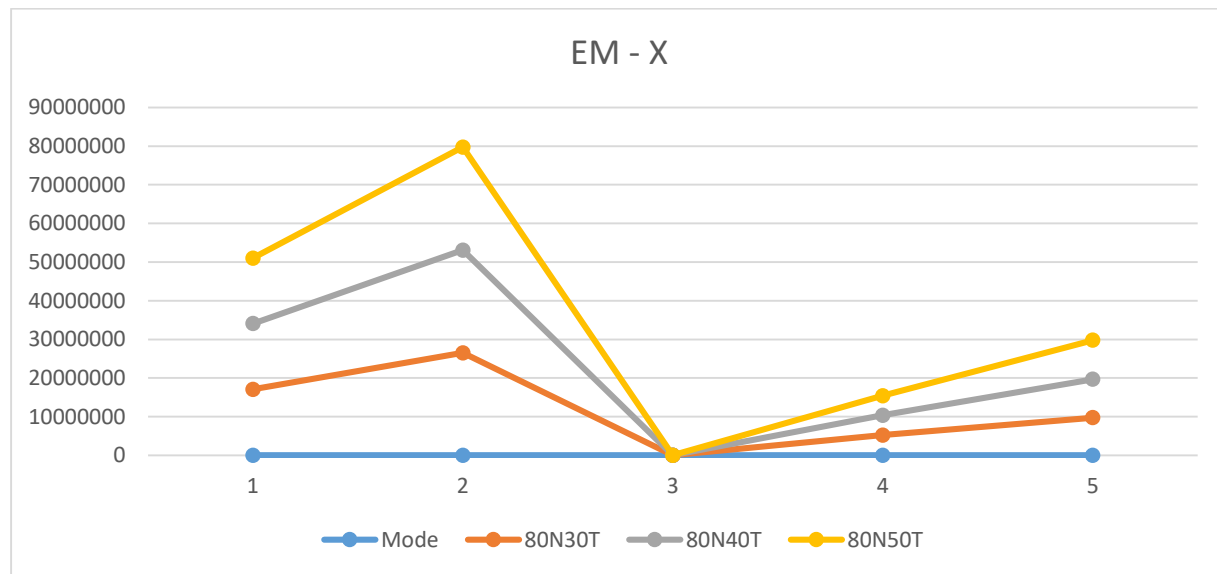


Figure 78: Multiplot Nacelle 80T Effective Mass X

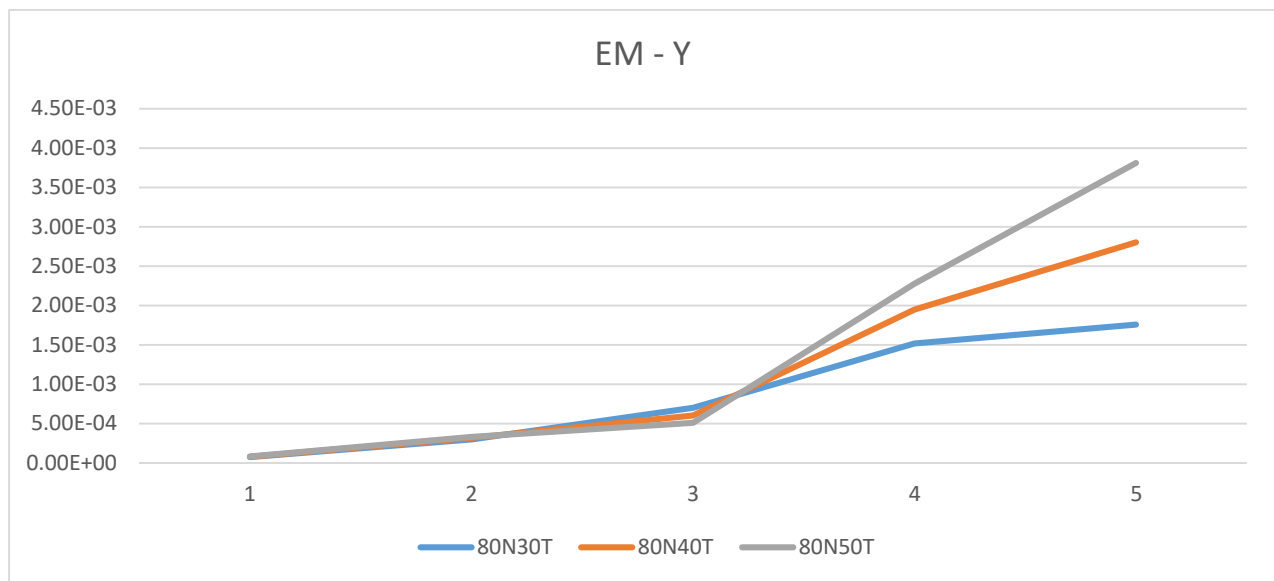


Figure 79: Multiplot Nacelle 80T Effective Mass Y

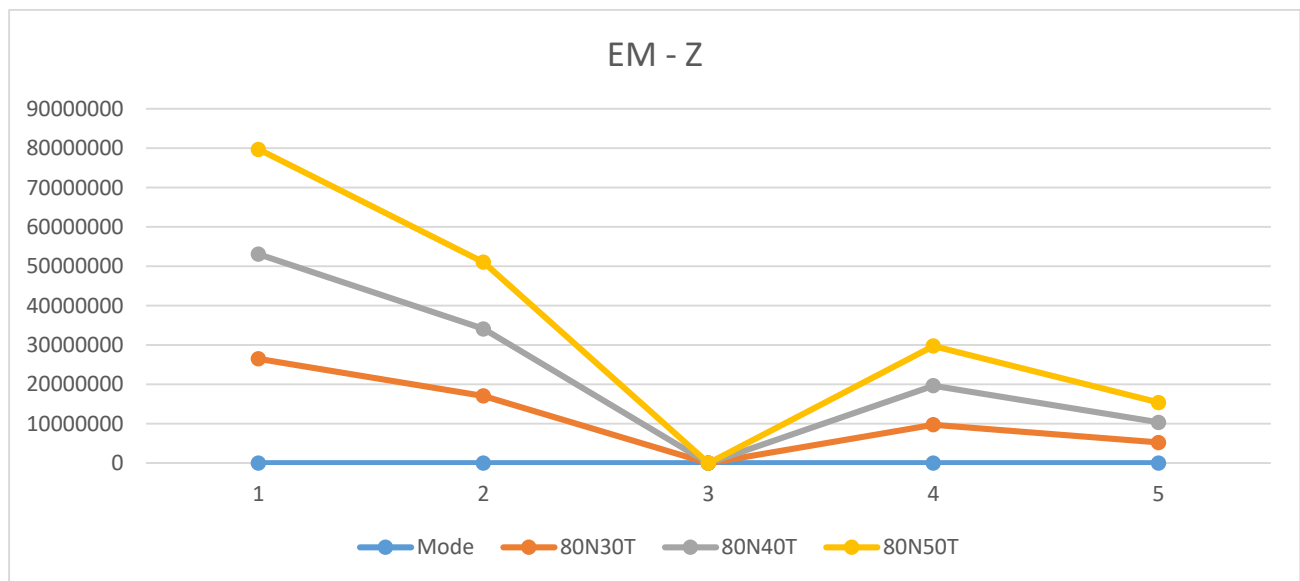


Figure 80: Multiplot Nacelle 80T Effective Mass Z

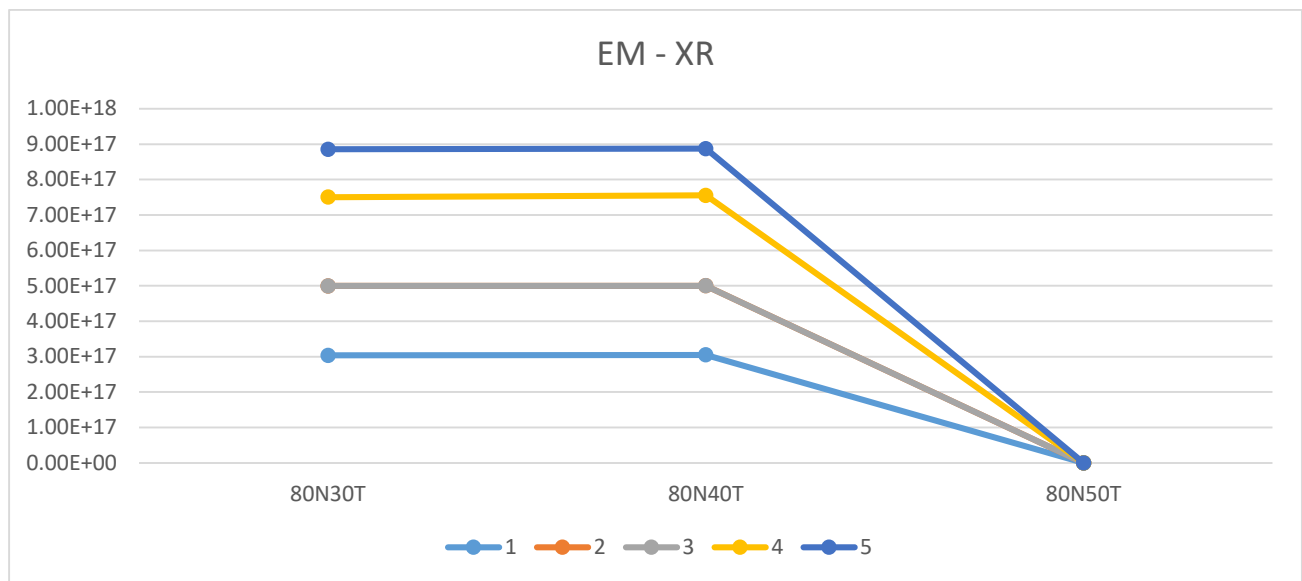


Figure 81: Multiplot Nacelle 80T Effective Mass XR

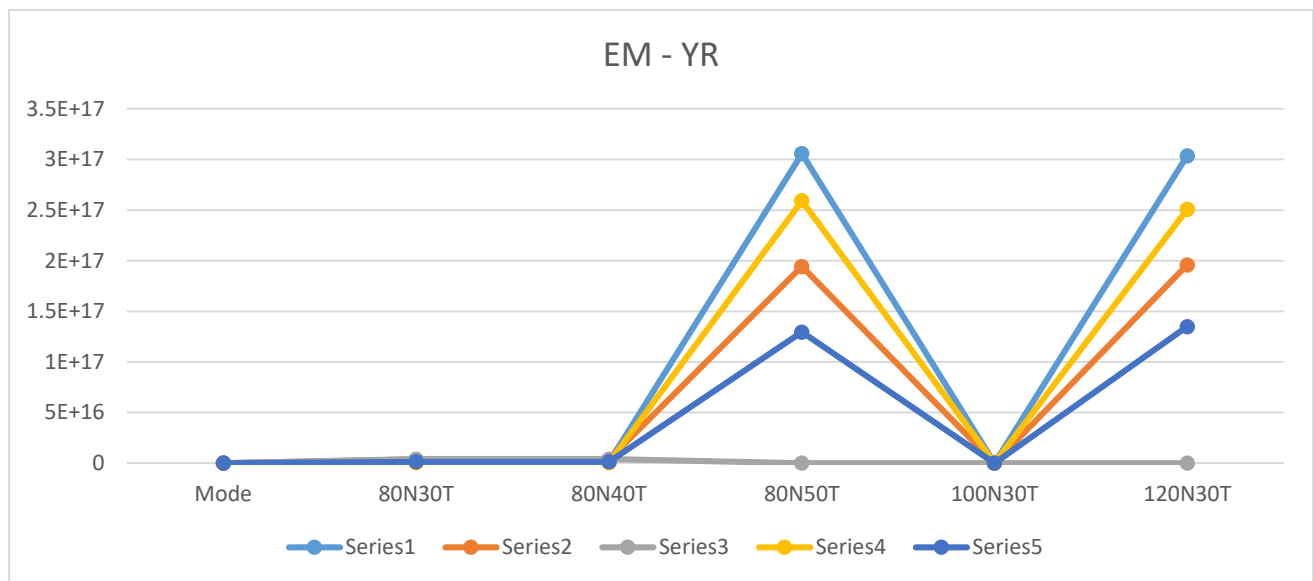


Figure 82: Multiplot Effective Mass YR

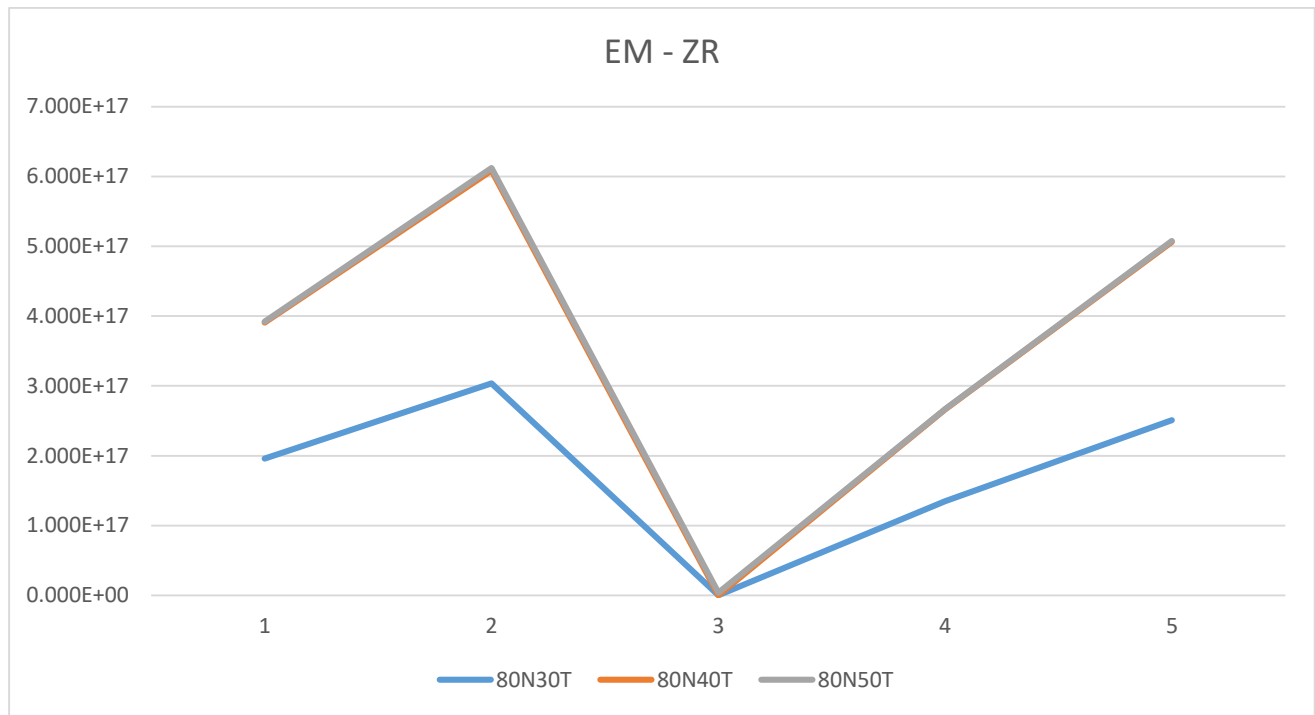


Figure 83: Multiplot Nacelle 80T Effective Mass ZR

9.5 Influence of Increasing Nacelle Load

Shifting focus to simulations with increased nacelle loads while maintaining a constant thickness (50T), here are the observed trends in the effective mass:

The effective mass experiences a notable increase with higher nacelle loads, particularly for translational degrees of freedom. This suggests that an elevated nacelle load amplifies the inertia of the system in response to dynamic forces.

Rotational degrees of freedom also display some variation, but the effect is less pronounced compared to translational degrees of freedom.

9.6 Combined Effect of Nacelle Load and Thickness Variation

In simulations where both nacelle loads and thicknesses are increased, the cumulative effect on effective mass becomes evident:

Effective mass values continue to evolve, emphasizing the intricate relationship between structural parameters and loading conditions.

Translational degrees of freedom consistently demonstrate higher effective mass values, highlighting their greater contribution to the overall inertia of the system.

9.7 Discussion on Effective Mass Patterns

Thicker structural elements contribute to a reduction in effective mass, while increased nacelle loads enhance the system's inertia.

Understanding these effective mass variations is crucial for optimizing the design of offshore wind turbine structures. Engineers can leverage this information to strike a balance between structural robustness and system responsiveness to dynamic forces.

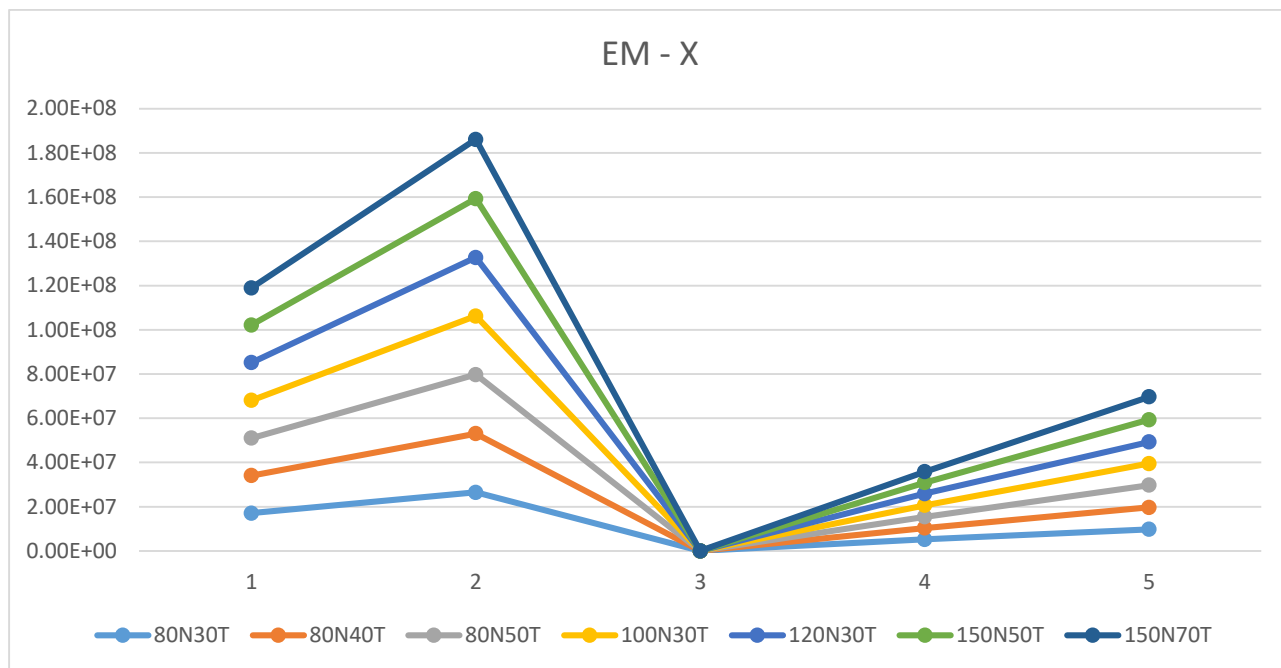


Figure 84: Multiplot Effective Mass X

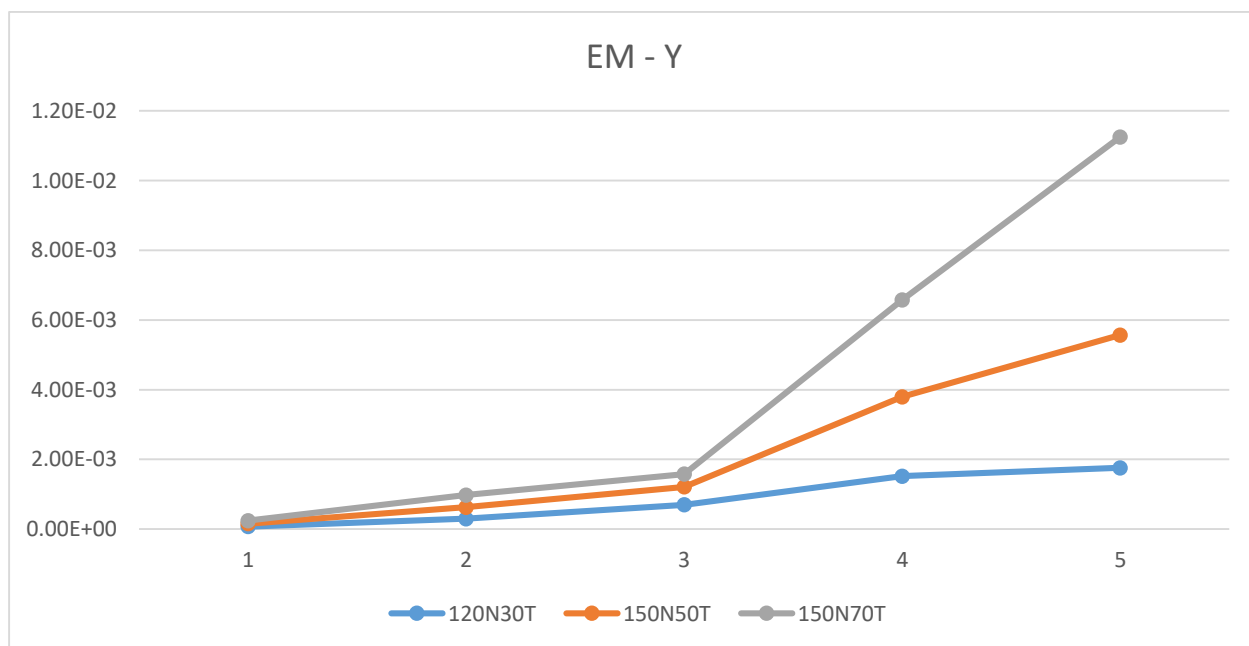


Figure 85: Multiplot Effective Mass Y

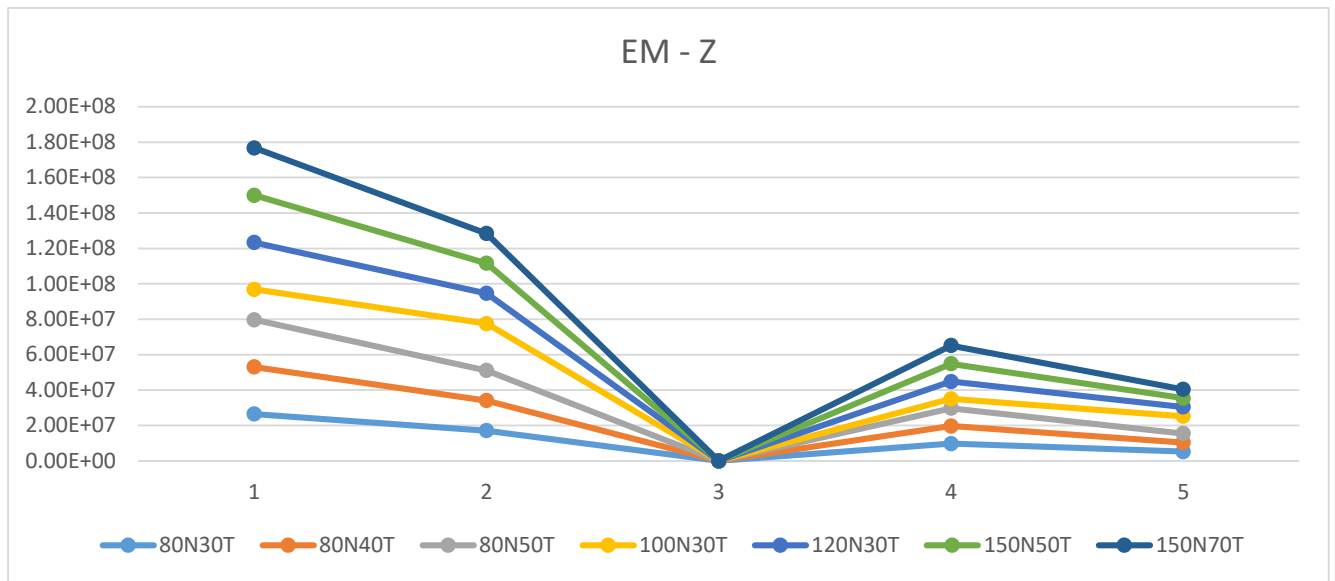


Figure 86: Multiplot Effective Mass Z

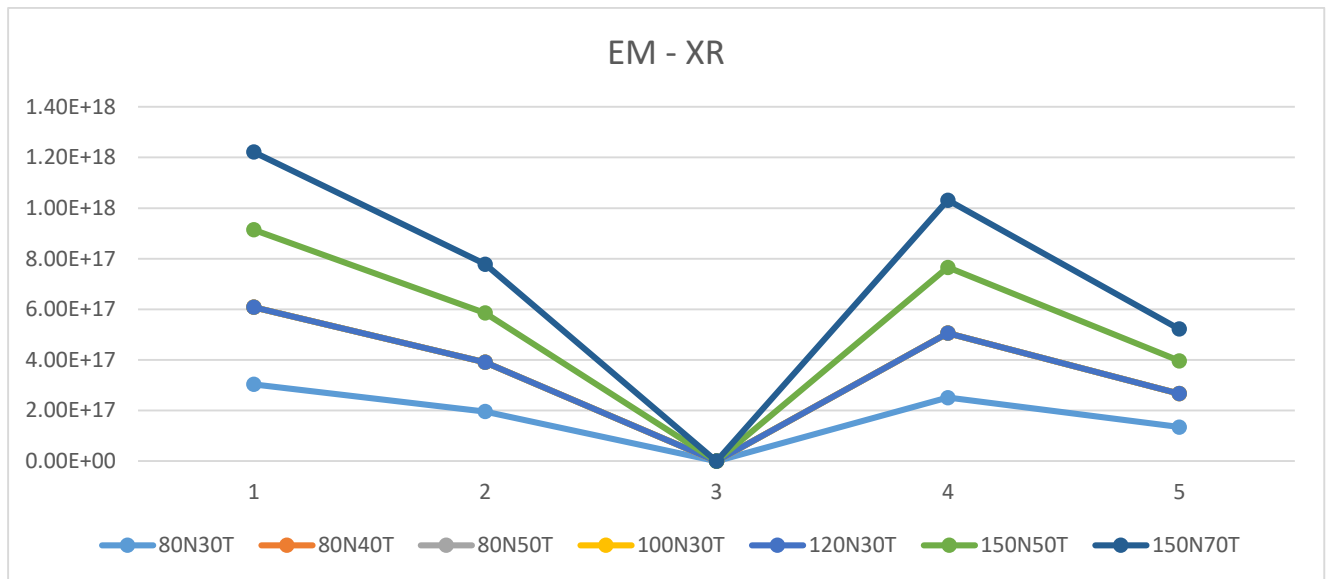


Figure 87: Multiplot Effective Mass X - Rotation

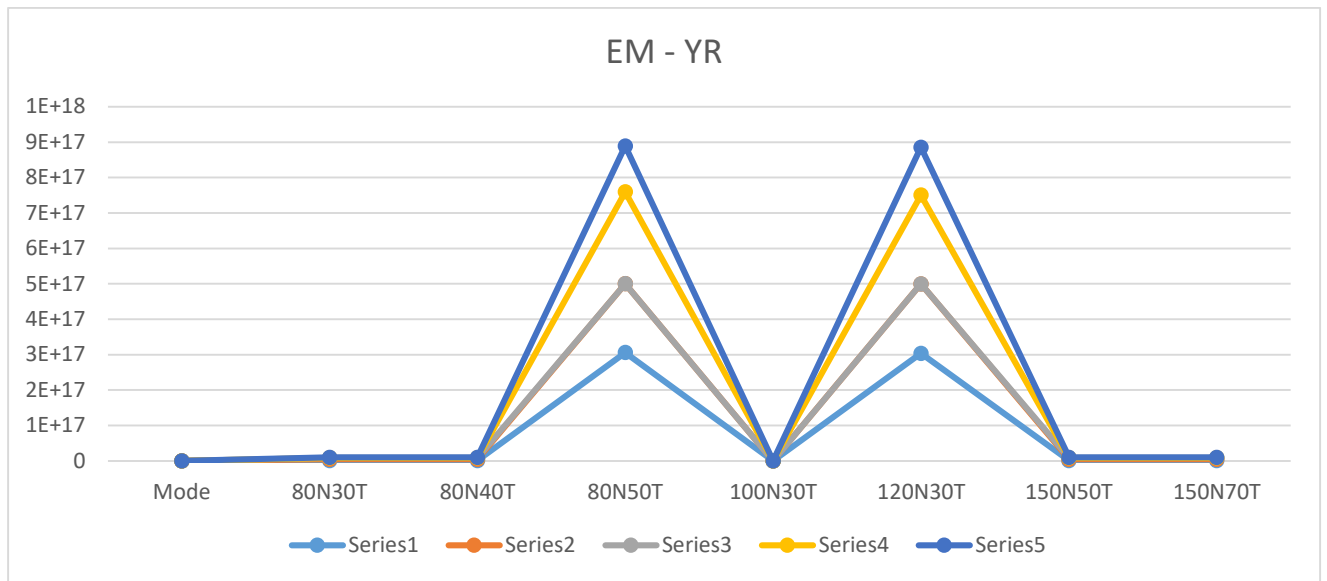


Figure 88: Multiplot Effective Mass Y - Rotation

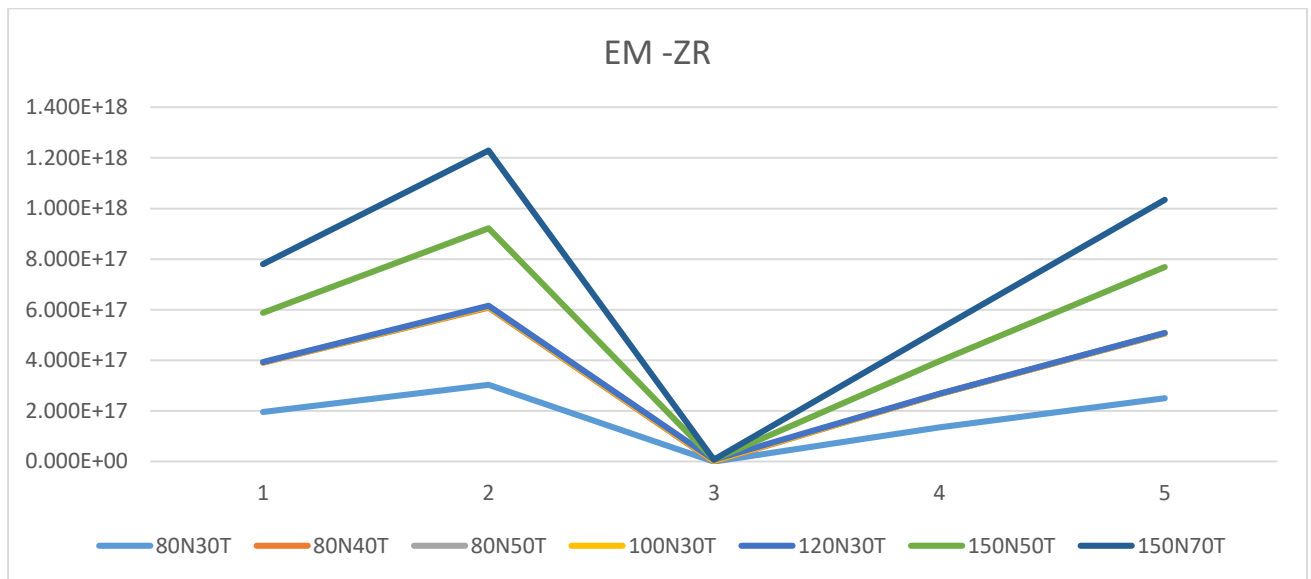


Figure 89: Multiplot Effective Mass - Z - Rotation

Chapter 10: Further Research

This research can be extended to compose a more comprehensive dataset of dynamic behavior of an OWT-Monopile system. This research is very limited in terms of computational complexity. Automation of post-processing via Python scripting allows for curating a comprehensive dataset of parametric variations on dynamic response of the system which will be invaluable in understanding of the dynamic behavior of such complex systems. Moreover, sensitivity analysis could be performed in many different ways. Having access to a large amount of compute will make it feasible to induce every form of dynamic load such as wave loads, inherent motor vibrations, nacelle induced vibrations, wind loading, and even temperature differentials and explore the dynamic behavior.

More in-depth specific dynamic assessments will lead to better standardization of the OWT design process. This emerging industry still borrows design principles and thumb rules from the O&G sector which is totally unreliable as they both serve different purposes and have very different use-cases and behavior with respect to physics.

Creating a comprehensive dataset allows for use of advanced state-of-the-art statistical methods such as artificial intelligence to allow for better optimized designs. Allowing AI to self-learn physics from a wide array of parametric data and feeding it real-world measurements to allow for specific deep neural network based assessments improves the reliability drastically. Excessive compute optimized for this particular problem by using High Performance Computing methods to parallelize advanced finite element computations can lead to high-level understanding of system behavior and improve the design life estimates drastically. This leads to effective utilization of resources and make our journey toward a total sustainable future quicker.

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