Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 196-217

ECCOMAS Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

SEISMIC PERFORMANCE ASSESSMENT OF FLOATING OFFSHORE WIND TURBINES SUPPORTED BY TENSION LEG PLATFORMS

S. Amani[1], A. Prabhakaran[2], and S. Bhattacharya[1]

[1] Department of Sustainability, Civil and Environmental Engineering, University of Surrey, Guildford, GU2 7XH, United Kingdom
e-mail: sadra.amani@surrey.ac.uk, s.bhattacharya@surrey.ac.uk

[2] Department of Structural Engineering, University of California, San Diego La Jolla, CA 92093, USA
email: aparayan@eng.ucsd.edu

Abstract

This study introduces a simplified methodology for evaluating the risk of destabilization or damage to floating offshore wind turbines (FOWTs) due to earthquake-induced ground motions, with a focus on FOWTs supported by Tension Leg Platforms (TLP) in seismic regions. The study first reviews the typical hazards experienced by FOWTs supported by Tension Leg Platforms in seismic regions. The proposed analysis workflow is then presented with the methodology exemplified using the prototype TLPWIND turbine as a case study. Detailed analyses are carried out using both horizontal and vertical ground motions. The response of the floating deck and hub levels of the wind turbine to earthquake motions is investigated, and the findings demonstrate that FOWTs are prone to vertical earthquake motions, while horizontal motions have a minor impact. The results show that tension in the cables increases significantly in response to vertical motions, and RNA acceleration outputs for vertical input motions indicate that a considerable acceleration amplification is expectable for large-scale vertical motions, which can cause gear or electrical failures in FOWTs. The proposed methodology provides a useful tool to inform the design and deployment of FOWTs in seismic regions, particularly by accounting for the effects of vertical motions on cable tension and acceleration amplification. The results of this study can enhance the understanding of seismic risks associated with FOWTs and improve current practices in the design and deployment of offshore wind turbines.

Keywords: Floating Offshore Wind Turbine, Seismic Design, Seismic Motion, Tension Leg Platform, Seismic Hazard

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10398.20788

1 INTRODUCTION

The use of floating offshore wind turbines (FOWT's) is becoming increasingly popular due their lower installation costs and minimal impact on marine ecosystems compared to traditional bottom fixed wind turbines. The global installed capacity of floating offshore wind turbine (FOWTs) farms is estimated to reach 1000 GW by 2050 [1]. These systems are particularly well-suited for water depths greater than 60 m, making them a viable option for regions such as the western coast of the United States and East Asian countries such as Taiwan, Japan, China, and South Korea [2]. As such, these wind farms are increasingly being deployed in historically active seismic zones. Figure 1 illustrates the locations of significant FOWT development projects worldwide with the major tectonic plates.

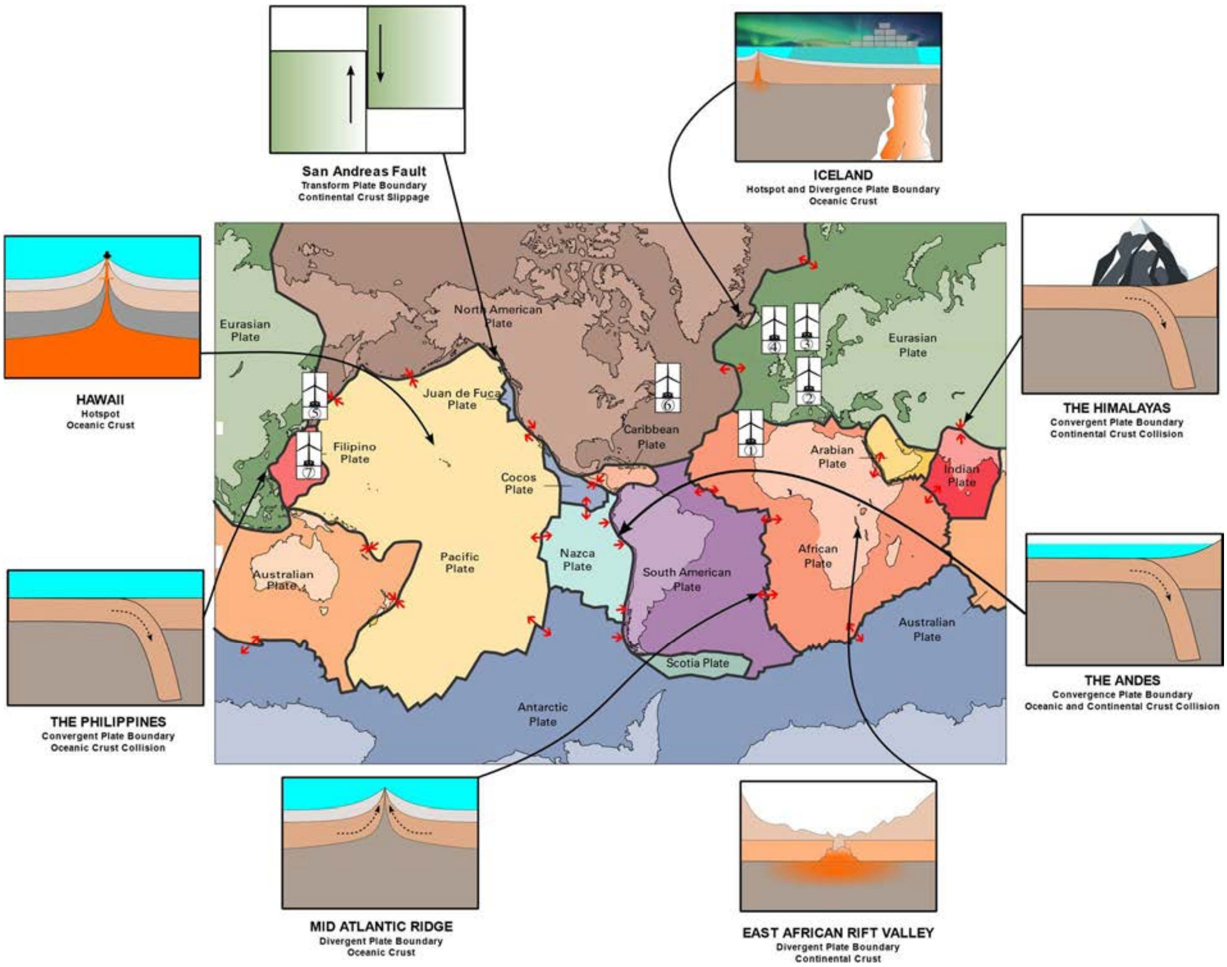


Figure 1: Location of floating wind farms projected on the map of the tectonic plates- The base map is from USGS [2]

The literature review shows a growing interest among developers in considering higher turbine capacities in the near future. This is particularly important because larger turbines require the use of relatively large or novel types of floating systems. As the demand for renewable energy sources continues to increase, there is a need to utilize larger turbines that can produce more power. However, the development of these turbines requires the use of improved floating systems that can withstand the increased load and size of the turbines particularly in seismic zones. Some of the currently installed, ongoing and future projects are described in Table 1.

#	Name	Location	Foundation	Capacity	Turbine	Water depth (m)	Installed year	Ref
Commissioned, Under construction								
1	Wind Float Atlantic	Portugal	Semi-submersible	25 MW	MHI V164-8.4 MW	100	2020	[3, 4]
2	Kincardine	U.K.	semi-submersible	50 MW	5× (V164-9.5 MW) 1× (V80-2 MW)	60-80	2021	[5]
3	Hywind Tampen	Norway	Spar-buoy	88 MW	SG 8.0-167 DD	260-300	2022	[6]
4	Hywind Scotland	UK	Spar-buoy	30 MW	SWT-6.0-154	95-120	2017	[7]
Planned, future developments								
5	K.F. wind	Korea	semi-submersible	1200 MW	IEA 15-theoretical 16 M.W.	>200	-	[8]
6	Redwood coast offshore wind project	USA	Semi-submersible	120-150 MW		610- 1100	2024	[9, 10]
7	Hibiki wind farm	Japan	Barge	3 MW	Demonstration project	55	2030	[11, 12]

Table 1: Some key floating wind turbine projects

In general, based on their nature of stabilization, floating systems can be categorized as ballast, mooring or waterplane stabilized as shown in Figure 2 [13].

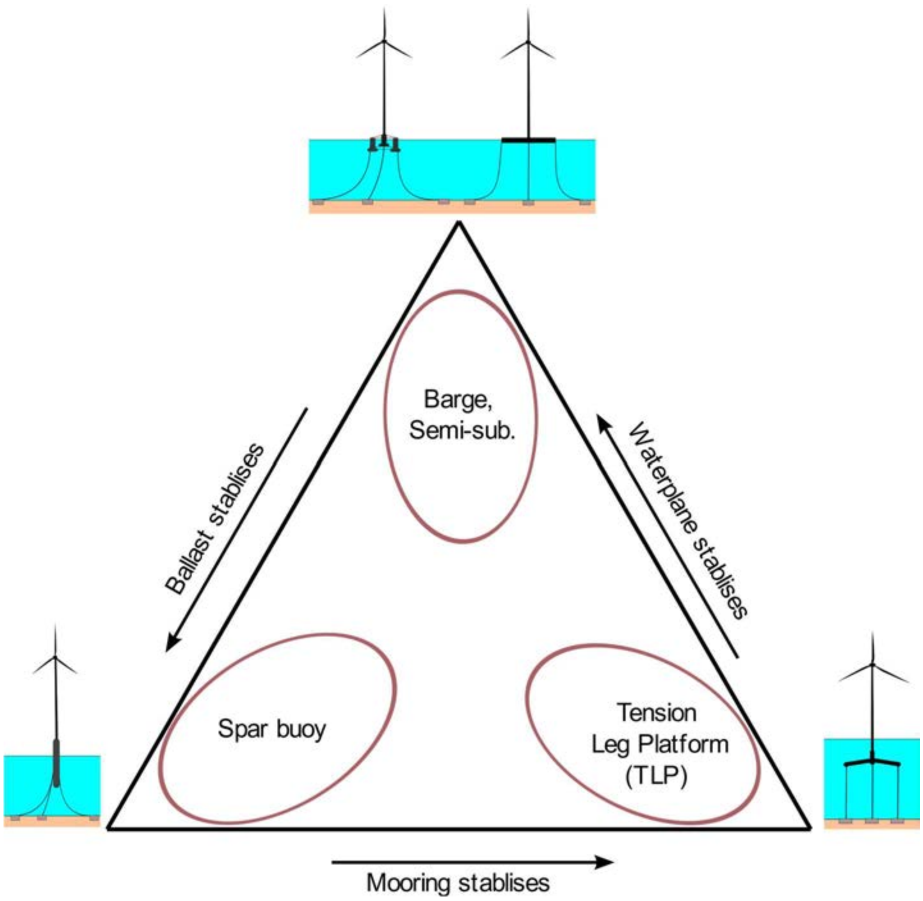


Figure 2: Classification of the floater, based on the stabilizing principle in pitch

This paper highlights considerations towards the seismic design of tension leg platform (TLP) supported offshore wind turbines, with a focus on surface fault rupture and the dynamic response during strong shaking.

2 DESIGN CRITERIA OF OFFSHORE WIND TURBINES (FLOATING)

In the design of offshore wind turbines (OWTs), several limit states must be considered to ensure the safety and longevity of the structure. These include the ultimate limit state (ULS), serviceability limit state (SLS), and fatigue limit state (FLS). The ULS criteria are necessary to ensure that the structure and foundation remain safe and within the elastic zone. The SLS criteria are necessary to ensure that the pile head tilts, rotation, and RNA acceleration are within an acceptable range. The FLS criteria are necessary to evaluate the long-term life of the structure, considering numerous cyclic loadings and seismic events. Limit states considered for seismic design are discussed below:

- *(i)* Seismic considerations-ULS: The presence of liquefaction/strain-softening susceptible layers in the soil can reduce the ultimate capacity of embedded foundations. In addition, static shear stresses can lead to ground failure and increase demands on the foundation system.
- *(ii)* Seismic consideration-SLS: Strong shaking can increase demand for rotor-nacelle assembly (RNA) and permanent tilt/deformation at the pile head.
- *(iii)* Seismic consideration-FLS: The high number of cycles imposed by wind/wave load can induce high cycle fatigue, which must be accounted for in the seismic design of OWTs by reducing the capacity of the foundation system

The summary of the limit states is specified as detailed in Table 2. Readers are referred to Bhattacharya [14] or Amani et al. [15] for further details.

Limit State	**Typical criteria**
ULS	*(i)* Ground Failure (soil failure) causing foundation collapse *(ii)* Tendons failure due to excessive tension *(iii)* Foundation should remain stable (Collapse due to excessive rotation)
SLS	*(i)* Permanent tilt at pile head < 7.5 deg (these are typical for grounded systems) *(ii)* RNA acceleration < 0.2 to 0.4
FLS	*(i)* Wind + wave loading imposes many cycles during the operational life of the turbines *(ii)* Fatigue life needs to be quantified prior to a seismic event

Table 2: ULS, SLS, and FLS Criteria of floating wind turbines.

The typical hazards that are important and require detailed consideration in the design of FOWTs could be fault rupture, blade collision, Submarine landslide, Tsunami, and Liquefaction [16]. Figure 3 is an example to illustrate the potential hazards of TLPs in seismic regions.

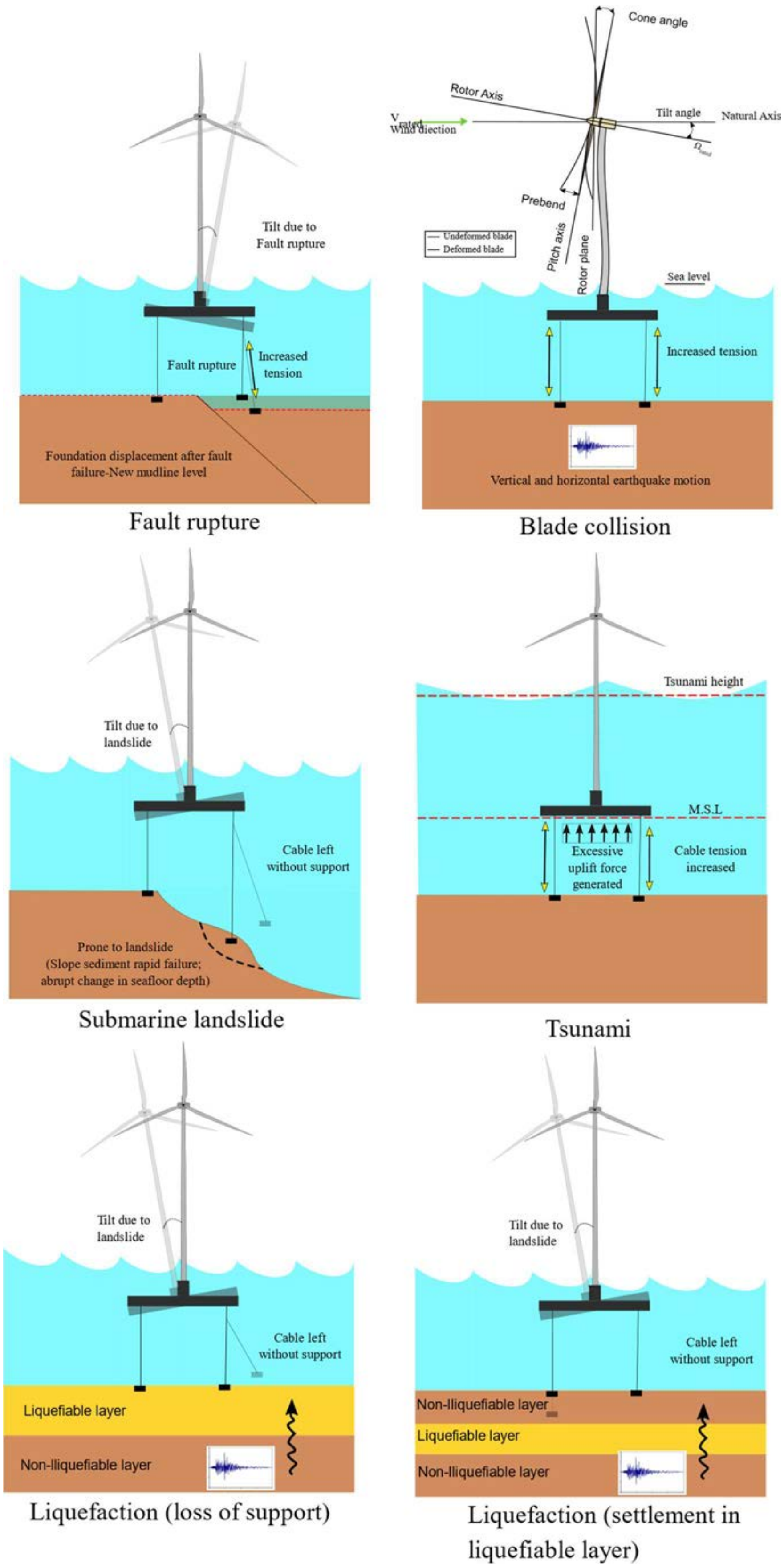


Figure 3: Typical hazards for TLPs [16]

The detailed explanations of hazards shown in Figure 3 are outlined below:

Fault rupture: Surface fault rupture can create significant tensile forces in the cables of FOWTs, creating excessive strain in the cables and resulting in breakage. Estimates for fault rupture displacements can be obtained using either a probabilistic or deterministic surface fault displacement hazard analysis [17]. Readers are referred to Petersen and Wesnousky [18] . In this paper, equations from Wells and coppersmith [19] are employed to assess the vulnerability of floating offshore wind turbines to fault rupture.

Blade collision: Ground vibration induced from an earthquake could transmit through the tension leg system to the platform and, therefore, to the wind turbine system. This vibration could cause instability in the structure; therefore, blade collision is expected. Most offshore wind farms are equipped with seismometers. Once the system detects the ground shake, the whole wind farm will be automatically shut down. However, blade collision could still occur if faults exist in the installed seismometers or even during the shutdown process for motions with higher frequencies.

Submarine landslide: Installation of offshore wind farms typically involves a detailed site investigation and ground improvement works if necessary. However, due to earthquakes, landslides are also possible.

Tsunami: Tsunami could danger the foundation system in two ways. It could increase the buoyancy force and the tension on the platform cables. Alternatively, even it could cause the foundation to tilt, increasing the risk of instability in the whole wind turbine system.

Liquefaction: Due to cyclic loading, pore pressure increases in liquefiable soil, and therefore, the effective stress of soil reduces. FWT foundations are supported mainly by cables (either tensioned cable or catenary). The reduced effective stress results in a weaker anchor condition, making the anchors redundant. Therefore, it is recommended to use cables supported by piles in liquefiable soil.

3 WORKFLOW OF ASSESSING THE VULNERABILITY OF FLOATING WIND TURBINES (TLP TYPE)

This section explains the procedure used to assess the vulnerability of floating offshore wind turbines with tension leg platforms to fault rupture.

1. Data gathering: The data gathering needs to be carried out to have a clear vision for analyzing a problem. These data could be divided into five stages.
   (i) Performance requirement (limit states) includes ultimate limit state (ULS), serviceability limit state (SLS), and fatigue limit state (FLS) checks.
      a. Under ULS criteria, it is expected to find the ultimate load that the foundation could carry.
      b. Under SLS criteria, it is expected to ensure that the tilt of the wind turbine platform under the operating stage is under the allowable limit (typically 7 degrees) [20].
      c. Under FLS criteria, it is expected to ensure that during the long term

   (ii) Turbine data includes wind turbine specifications such as blade diameter, rotor, blade passing frequency (1P, 3P), and tower specifications (height, thickness, diameter).

(iii) *Met-ocean data:* Obtaining the water depth as a critical player in the design of floating wind turbines. The readers are referred to the literature for more details.

(iv) *Seismic hazard analysis* is one of the main scopes of this paper to study the effect of fault rupture on the FWT system. Therefore, the fault rupture type, potential earthquake magnitude, and fault rupture displacement need to be estimated. In addition, the ground motion at the surface level needs to be obtained.

2. Estimation of dimensions for floating offshore wind turbine (platform and tower): An initial estimation could be achieved by considering overturning equilibrium in the floating foundation system.

3. Define appropriate tension leg dimensions: These dimensions could also be estimated by considering an equilibrium between the uplift force (buoyancy) and the cables. The tension of the legs (cables) should be within a safe zone to avoid unexpected plastic failure of the cables.

4. Structural modelling: Apart from structural modelling, using appropriate properties. Imposition of the wind, wave, ground motion acceleration, and fault rupture must be considered. The fault rupture should be applied first in the analysis and followed by earthquake motion. Readers are referred to *section 3* for more details.

5. Checking whether the design criteria meet the design demand. If the foundation collapses or is under or over-designed, the dimensions need to be revised.

Figure 4 shows the workflow that has been used to assess the vulnerability of the TLP floating offshore wind turbines.

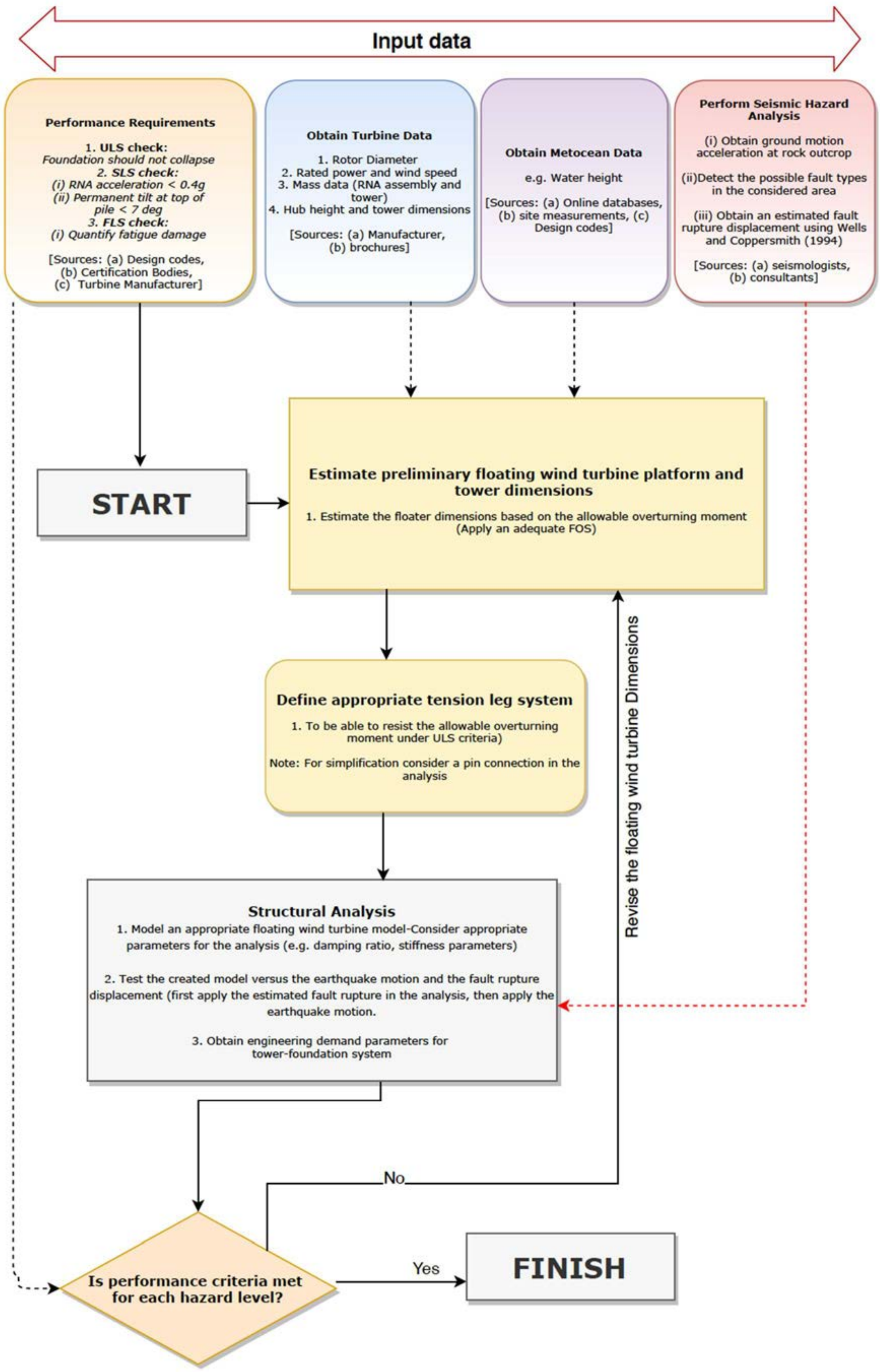


Figure 4: Workflow to analyze the vulnerability of FOWTs (TLP)

3.1 Structural analysis

The equilibrium in floating structures is created by balancing the external loads and the reaction forces (generated due to buoyancy force). The external forces are moment (due to wind and wave load) and vertical load (due to self-weight). Furthermore, the reaction force is typically generated due to the buoyancy effect. The distance between the center of gravity (Cg) and the metacenter (M) is called metacentric height (G.M.). This measures the initial static stability of a floating body [21]. The floating objects start destabilizing as the applied external moment nears the resisting moment due to the buoyancy force, as shown in Figure 5.

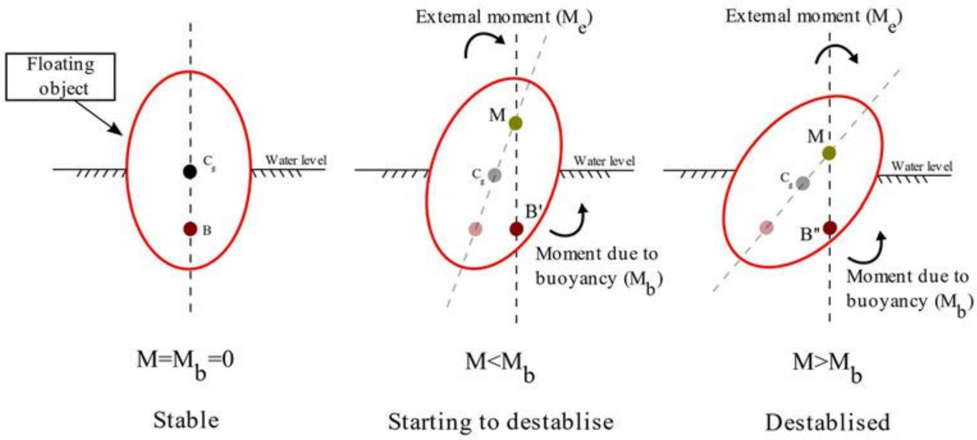


Figure 5: Destabilization due to overturning moment

Floating wind turbines could be modelled by benefiting from the principles of floating objects' stability. The free-body diagram of TLP wind turbines is shown in Figure 6. The T_1 and T_2 represent the tension in the cables (tendons). Under the destabilization process, one of the cables (e.g., T_2) could loosen, and the other cable (T_1) started to generate excessive tension. Moreover, as a result, it increases the risk of a tendon failure.

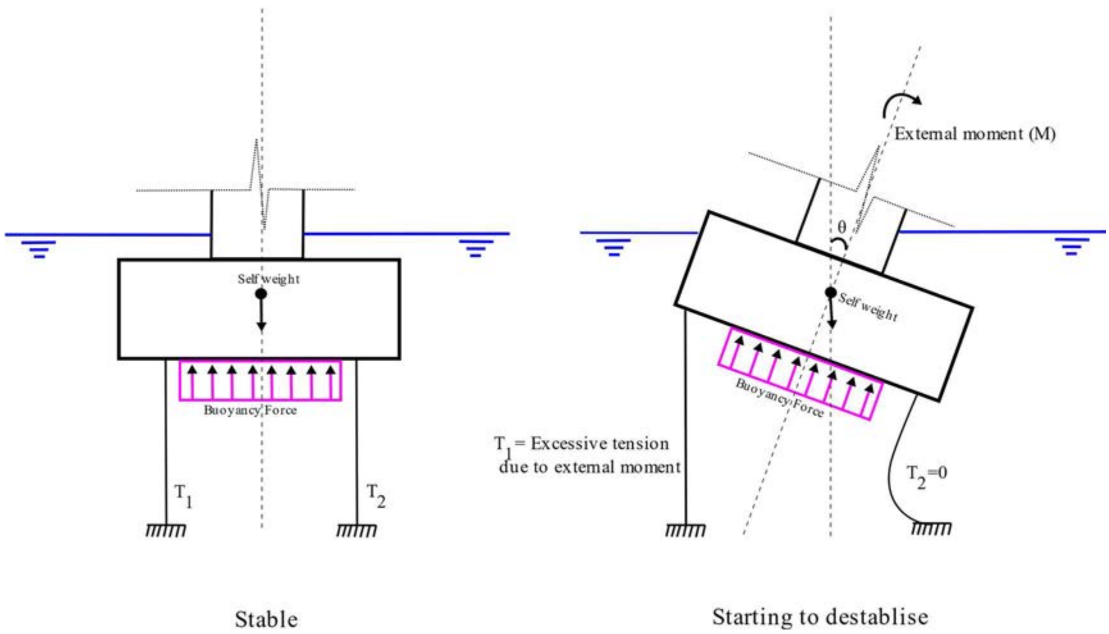


Figure 6: Application of destabilization principles on FWTs (TLP)

Modelling of floating structures often could be complex due to several uncertainties. These could be selecting an appropriate damping factor, stiffness, and definition of a proper tension parameter for the TLP system cables. Therefore, this paper proposes the following stages:

1. Tension legs were defined using cables with tendon properties (pre-stressed)
2. The full-scale RNA is considered in this study
3. Spring damper systems could be implemented at the interface between the mast and rotor and between the seabed and tension legs.
4. The buoyant force (pre-tensioning force in the cables) should be modelled as a uniformly distributed load acting upwards on the bottom surface of the floater.
5. The damping generated at the water and floater surface interface could be modelled through four viscous dampers assigned at the middle of the floater.
6. Aerodynamic damper considered at the RNA level.

The structures schematic model is shown in Figure 7.

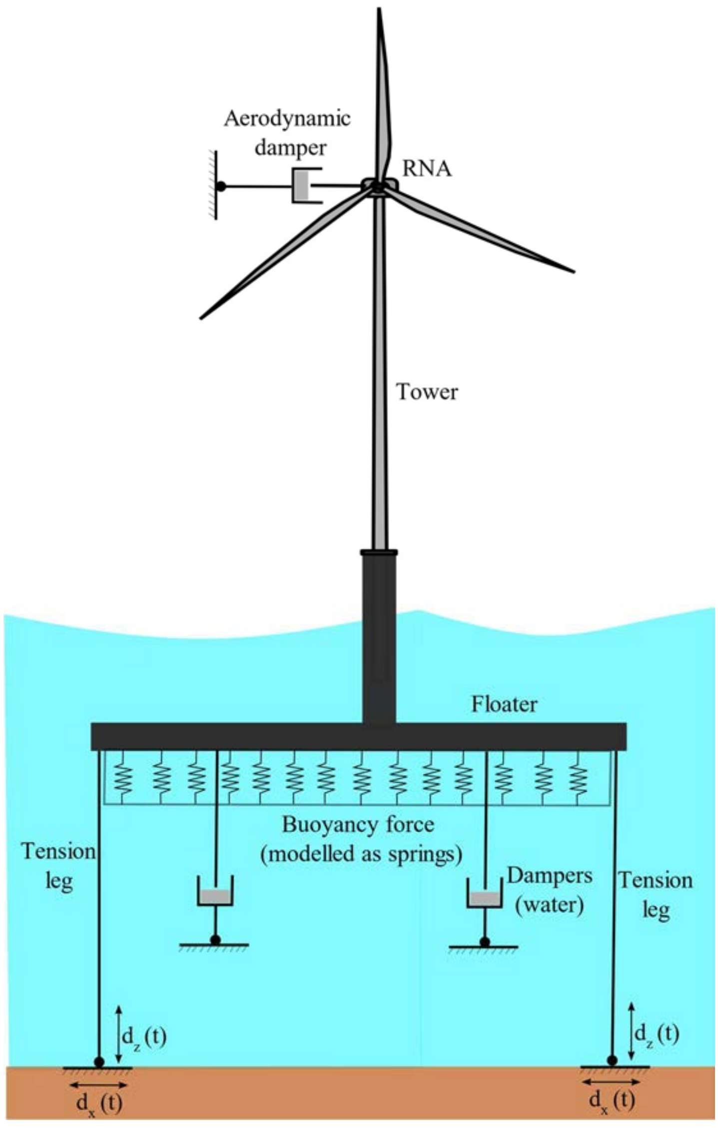


Figure 7: Schematic structural model to analyze TLP structures in seismic regions [22]

4 VULNERABILITY ASSESSMENT OF FLOATING WIND TURBINES (TLP WIND TURBINES)

The behaviour of offshore floating wind turbines is assessed by creating an offshore floating turbine model based on the Iberdrola TLPWind concept in SAP2000. This concept has an 'x-shaped' steel foundation fixed to the seabed with four pairs of tendons. The benefit of this project is the reduction of the LCOE of offshore wind turbines. In this study, the vulnerability of the TLP foundations was assessed based on a seismic event in recorded in Kern County in 1952. Table 3 shows the considered earthquake event with the peak ground acceleration (PGA) in different directions.

Name	Fault Type	Horiz. motion [X] *(g)*	Horiz. motion [Y] *(g)*	Vert. motion [Z] *(g)*
USA-CA-Kern County (7.36 M_W)1952- Santa Barbara Courthouse	Reverse	0.09	0.13	0.04

Table 3: Peak ground acceleration (PGA) in X (E-W), Y (N-S) , Z (U-D) directions

The assessments were conducted in SAP 2000 v.22 using the concept shown in Figure 8.

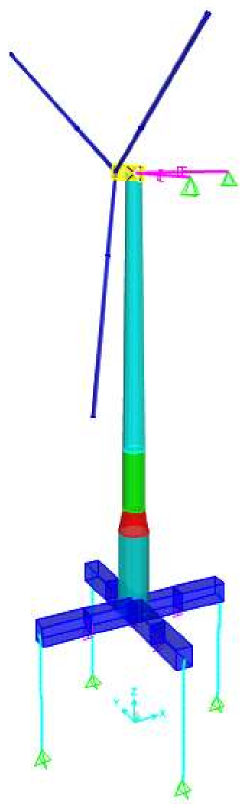


Figure 8: TLPWIND model in SAP2000

TLPWind model employs a 5MW NREL reference wind turbine. Therefore, the parameters outlined by Jonkman et al. [23] as the reference documentation for the 5MW NREL wind turbine model were used to model the TLPWind model in SAP2000. The properties of the modelled system and some of the key assumed parameters are shown in Table 4.

Item	Value [unit]	Item	Value [unit]
Type of the wind turbine	5 MW NREL	Draft (MSL)	35.50 m
Span	55.00 m	Freeboard	16.50 m
Pontoon width	4.40 m	Cable length	34.50 m
Pontoon height	5.50m	Cable diameter	90 mm
Central column diameter	8.20 m	Initial cable tension	2857 KN
Central column height	23.17 m	Nacelle mass	240,000 kg
Transition piece height	6.33 m	Tower mass	347,460 kg
Tower toe diameter	5.59 m	Hub mass	56,780 kg
Tower upper diameter	3.87 m	One blade mass	17,740 kg
Tower height	71.10 m	Viscous damping (water)	6.0e+05 Ns/m
Water depth (MSL)	70.00 m	Spring stiffness (water)	1.9e+05 N/m
Blade stiffness	Rigid	C_M (Hub damping)	[4.27- 427] $*10^2$ N.s/m
Cable material	Steel (S355)	C_J (Hub damping)	[2.16- 216] $*10^2$ N.s/m

Table 4:Properties of the modelled FWT [23]–[30]

In addition to Table 4, the physical shape of the RNA for 5 MW NREL was modelled in SAP2000 *v20* (assuming a rigid line element with concentrated mass at the center of gravity of each line element). The schematic RNA shape of the 5 MW NREL wind turbine is shown in Figure 9.

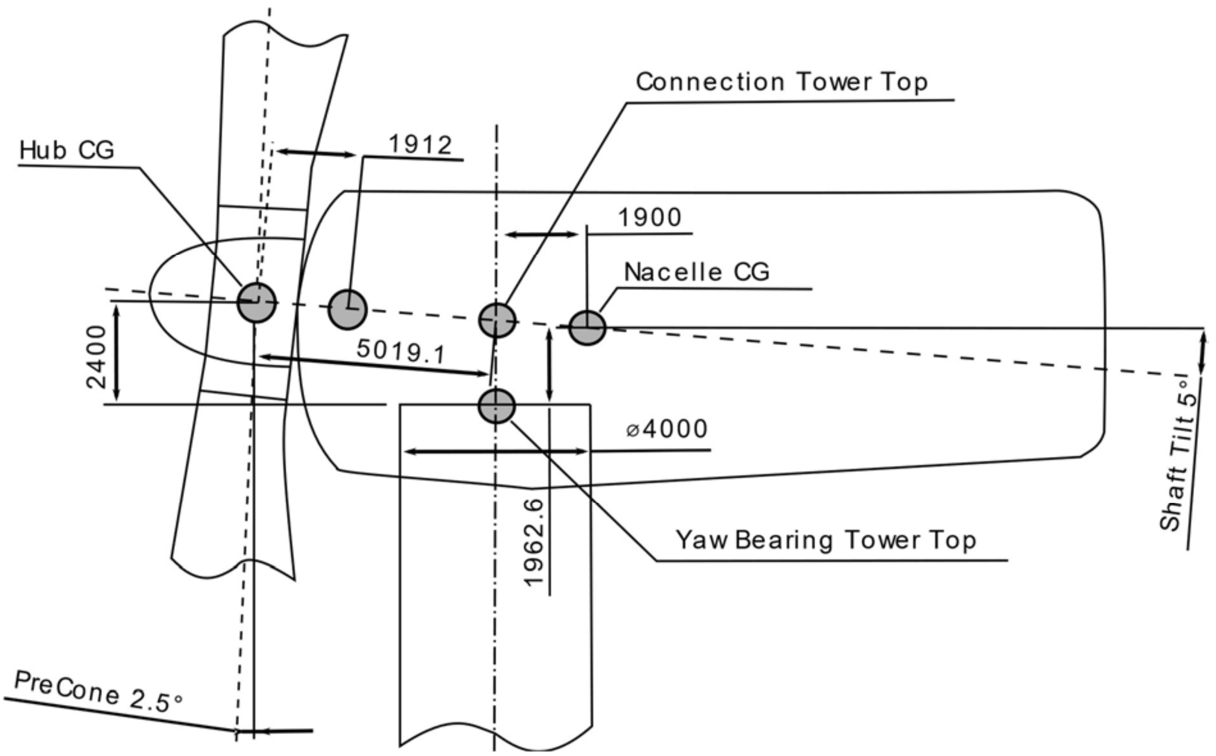


Figure 9: RNA of the NREL 5-MW baseline offshore wind turbine [23]- [Units in mm]

Another critical factor is to consider a Rayleigh damping factor. According to Jonkman et al. [23], in addition to considering viscous dampers for water and hub. A 5% damping ratio was considered in this analysis.

4.1 Analysis definition

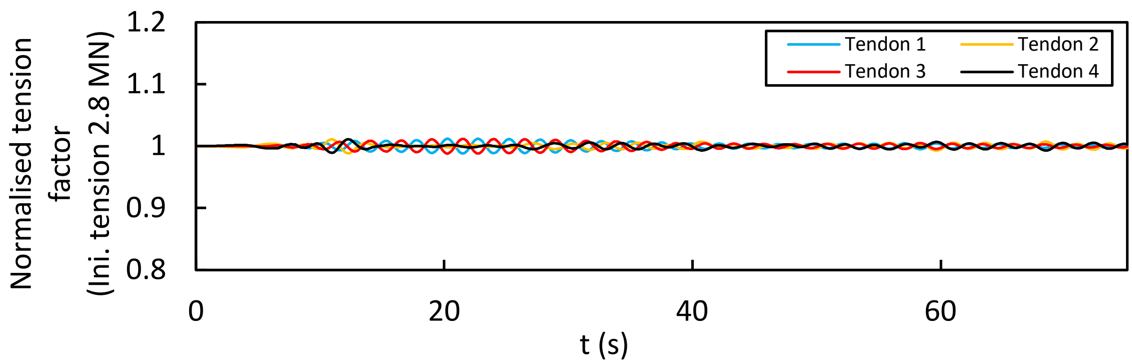
Different scales of earthquake input motions were studied to understand the behaviour of TLP foundations in seismic regions. In total, two earthquake events are considered (strike-slip and reverse). The simulation results are normalized against the design requirements RNA acceleration (<0.4-0.6 g), Floating deck rotation (7 degrees) and initial cable tension for the tension variation for all four cables. The strong motion generated from a fault rupture could impact the stability of the floating offshore wind turbines, particularly the TLP floating wind turbines since they are pre-tensioned, and any vibration may directly impact the foundation stability. However, a giant floating deck minimizes the destabilization. Therefore, analyses were conducted to study the behaviour of these structures against seismic motions. The input motions were studied individually (Horizontal direction or Vertical direction motion) and all together (Horizontal and Vertical direction together). For the individual components of seismic motions, a set of parametric studies is carried out by increasing the scale of input motions (×1, ×2, ×5, ×10) for the mentioned earthquake event in Table 3. Similarly, the results were normalized against the fundamental design criteria.

4.2 Computed Response

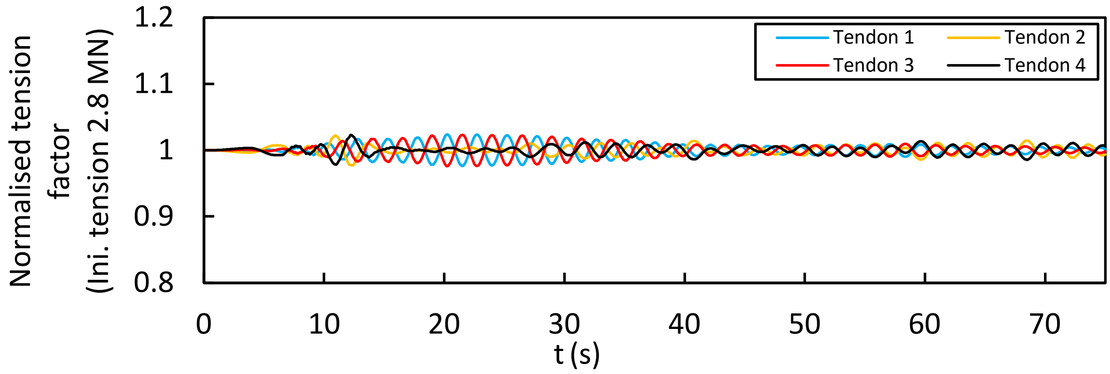
As indicated in the analysis definition section, Kern County, USA 1952 earthquake is considered. The recorded outputs from the analysis include fault rupture and seismic motion studies. In all these studies, three main parameters were recorded and discussed, (1) Tension variation in the cables (4 cables), (2) RNA acceleration, and (3) Rotation at the center of the floating deck (In 3 directions).

4.2.1. Seismic motion in the horizontal direction (X, Y)

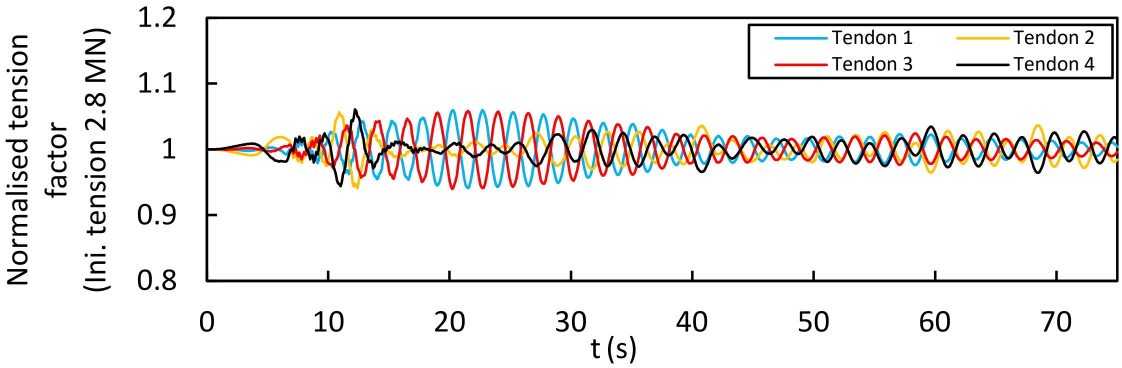
Seismic input motion in the X and Y direction has been applied in this study. The scale of the input motion has also been varied for ×1, ×2, ×5 and ×10 of the initial input motion. It assists in knowing the behaviour of floating structures for larger scales of input motions. Normalized cable tension variation outputs because of the seismic input motions are shown in Figure 10.



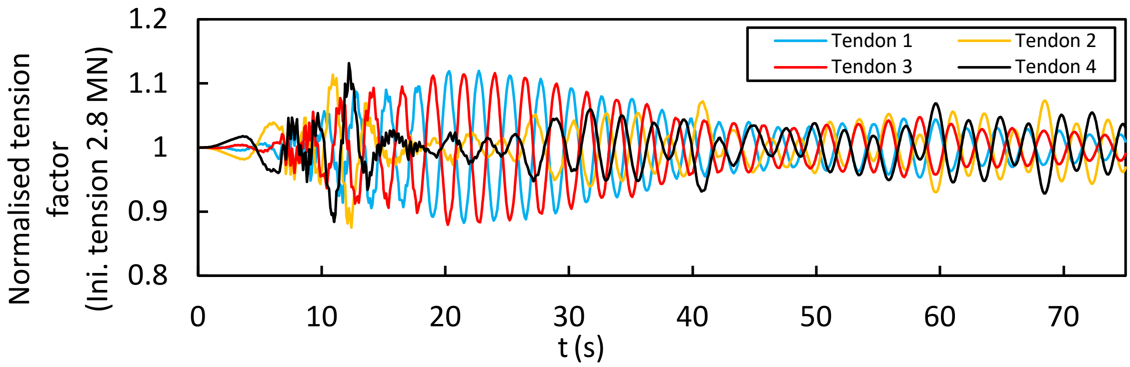
(a) ×1



(b) ×2



(c) ×5

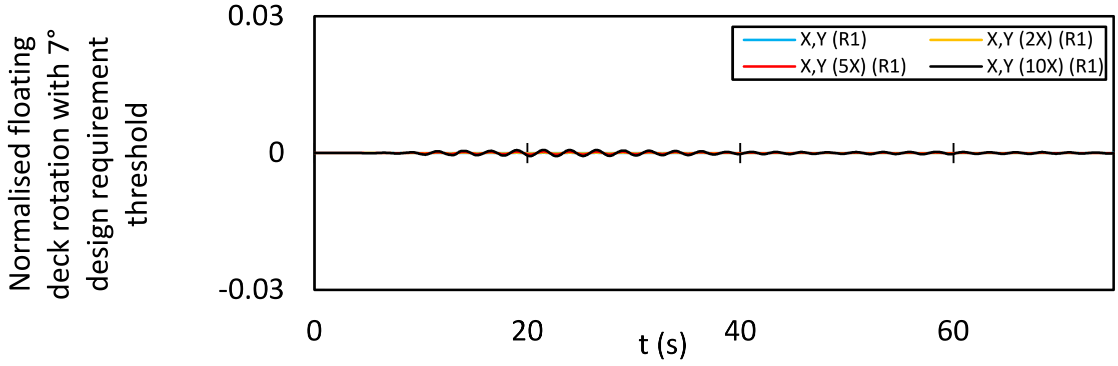


(d) ×10

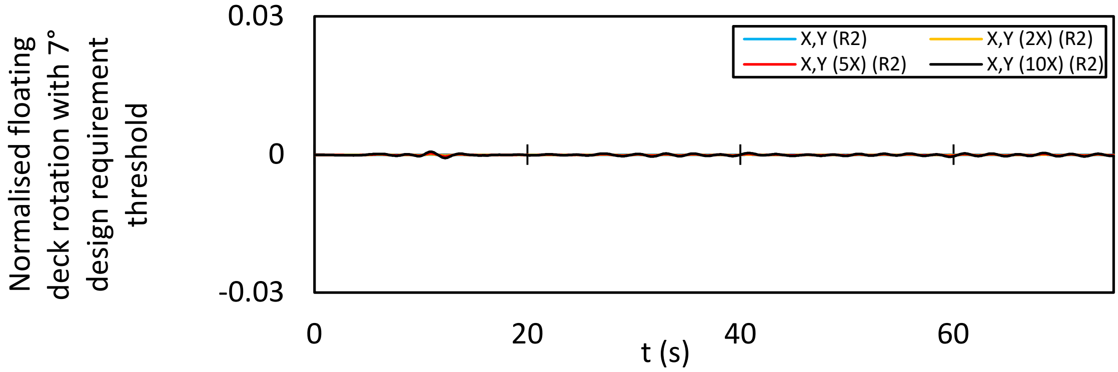
Figure 10: Effect of seismic motions applied in X, Y direction for different scales for 7.36 MW earthquake event

The results shown in Figure 10 indicated that there is little to no impact on the horizontal earthquake motions in the X-Y direction on the cable tension. This is also valid for higher amplitude ground motions (e.g., above 1g PGA).

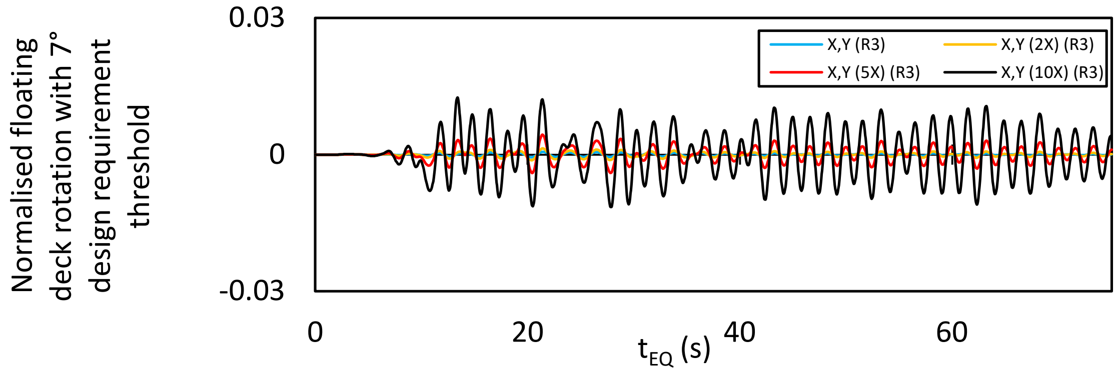
The rotation of floating foundations has been assessed to ensure that the destabilization does not occur, and the rotation does not exceed 7 degrees of rotation part of the design criteria the rotation is measured, as shown in Figure 11. The results showed a safe margin even for a significant scale of earthquake motion



(a) R1 direction (Rotation around horizontal 1 plane)



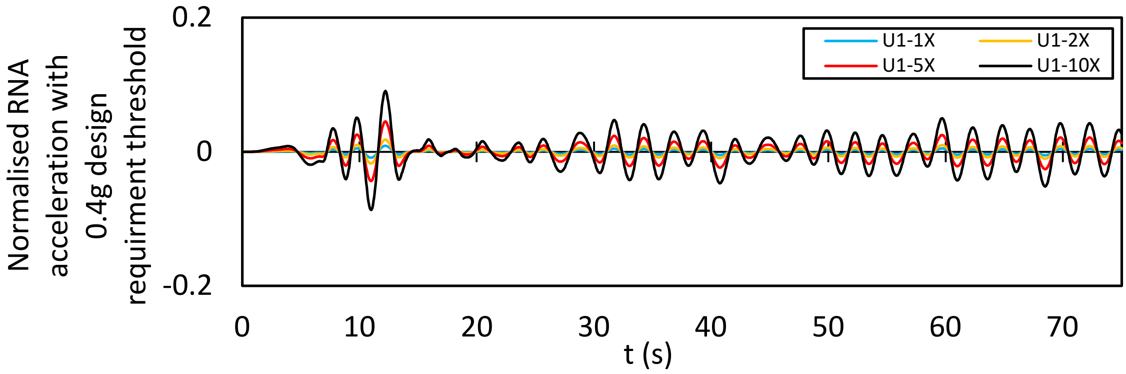
(b) R2 direction (Rotation around horizontal 2 plane)



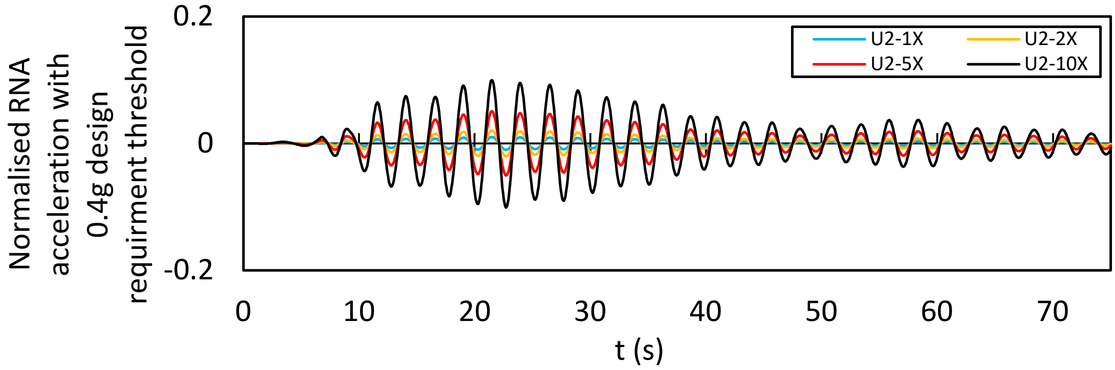
(c) R3 direction (Rotation around vertical plane)

Figure 11: Effect seismic motion in X, Y direction for different scales (×1, ×2, ×5 and ×10)- floating deck rotation for 7.36 MW earthquake event

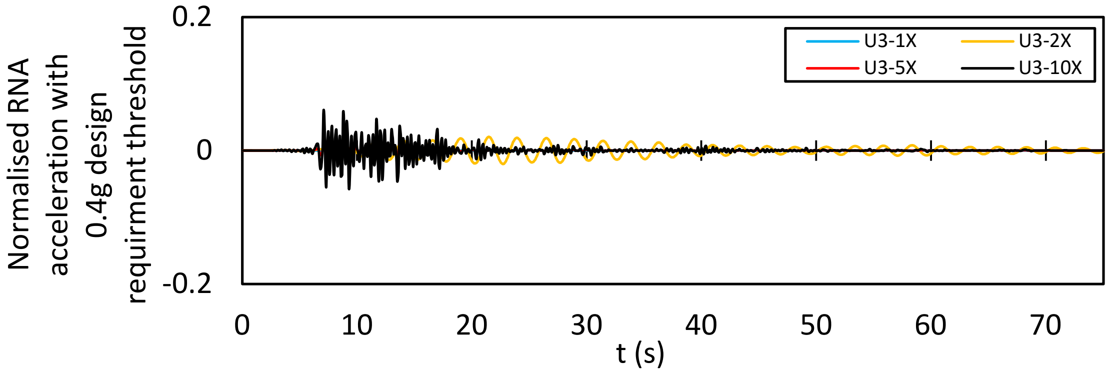
During the considered earthquake event, the RNA acceleration is expected to magnify. Therefore, this was measured for the earthquake motions applied in the X-Y direction; the measured data is presented in Figure 12.



(a) U1 direction (horizontal 1)



(b) U2 direction (horizontal 2)



(c) U3 direction (vertical)

Figure 12: Effect seismic motion in X, Y direction for different scales (×1, ×2, ×5 and ×10)- RNA acceleration for 7.36 MW earthquake event

The results indicate that the RNA acceleration does not increase significantly even in high-amplitude (large scale e.g., ×10) earthquakes.

4.2.2. Seismic motion in the vertical direction (Z)

Seismic input motions in the Z direction have been applied in this study. The scale of the input motion has also been varied for ×1, ×2, ×5 and ×10 of the initial input motion. It assists in knowing the behaviour of floating structures for larger scales of input motions. Normalized cable tension variation outputs because of the seismic input motions are presented in Figure 13.

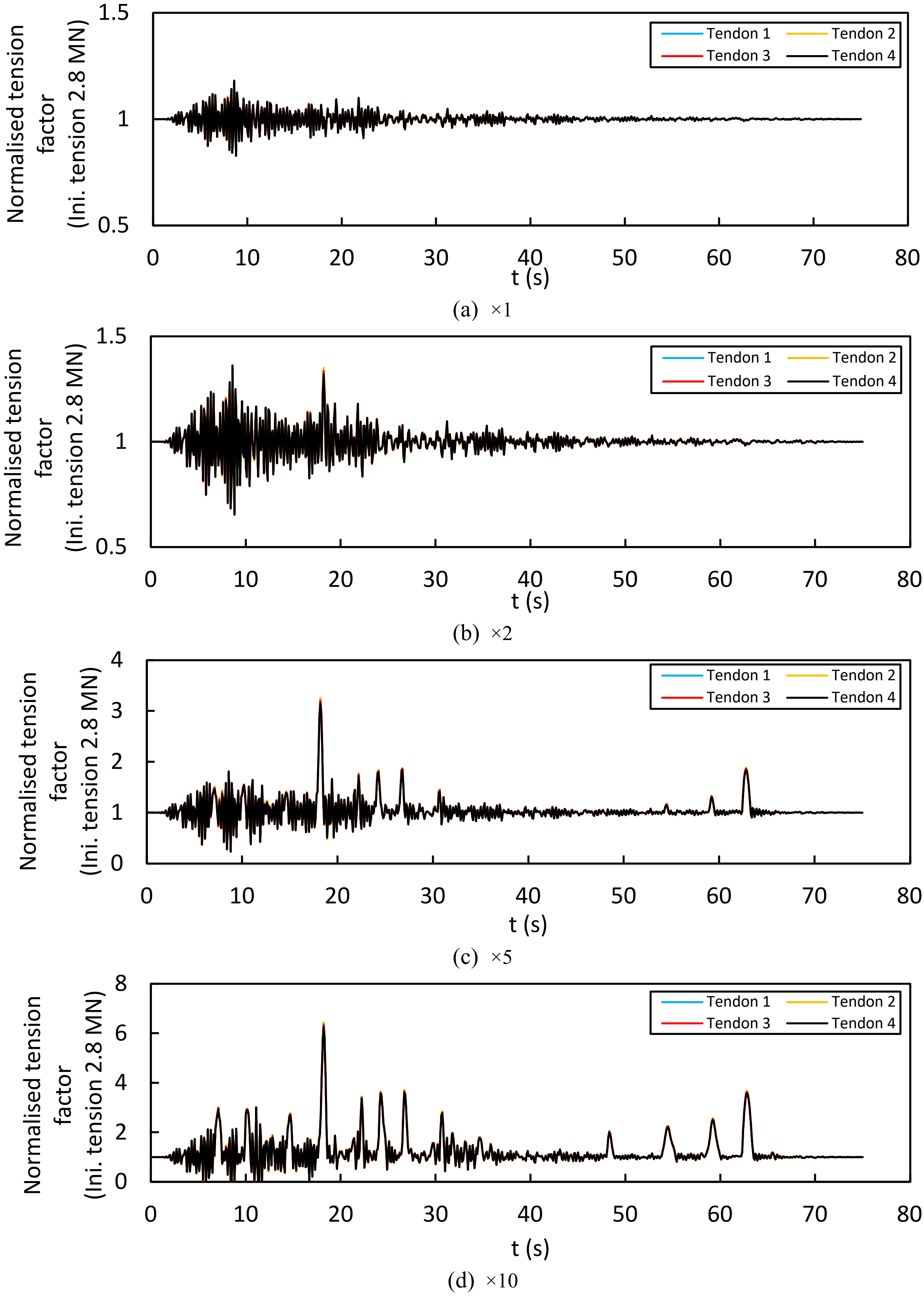
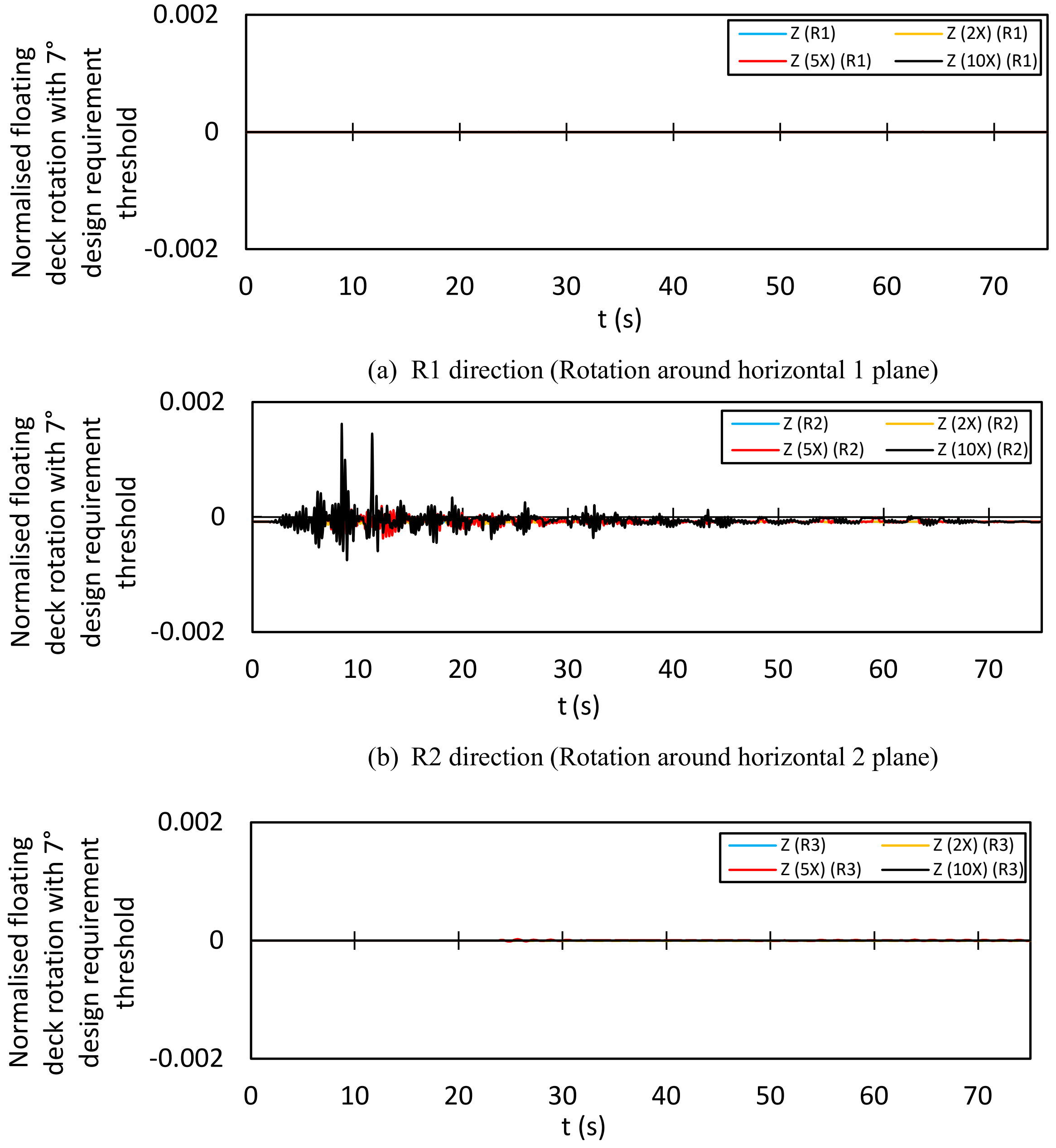


Figure 13: Effect of seismic motions applied in the Z direction for different scales (×1, ×2, ×5 and ×10)-Normalized cable tension variation for 7.36 MW earthquake event

The results presented in Figure 13 showed that the cable tensions could sometimes become near zero and cause destabilization in the floating foundation system. This specifically occurred for the scenario of 10X input motion. Additionally, the normalized tension ratio in the cables rises from 1.18 for ×1 input motion to 6.2 for ×10 input motion. A strong relationship between the application Z direction seismic input motions and the increase in the tension of the floating foundation cables has been noticed. Since this is a dynamic analysis, the other parameters, such as rotation and RNA acceleration, require further investigation. Therefore, since the rotation of floating foundations is limited to 7 degrees. As shown in Figure 14, for different vertical seismic input motions, the floater's rotation is assessed and compared.



(a) R1 direction (Rotation around horizontal 1 plane)

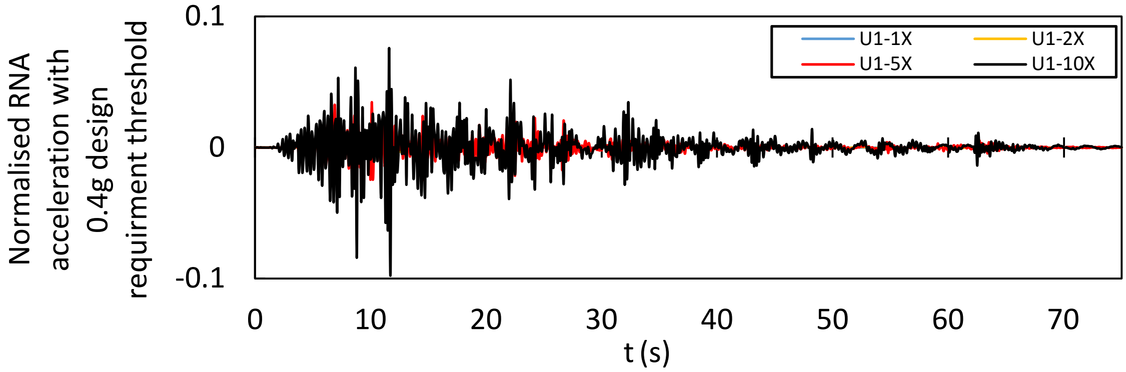
(b) R2 direction (Rotation around horizontal 2 plane)

(c) R3 direction (Rotation around vertical plane)

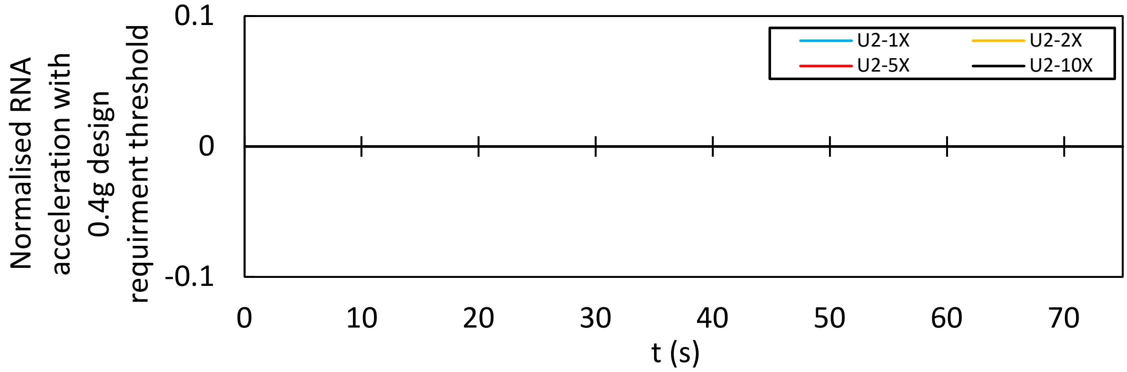
Figure 14: Effect seismic motion in the Z direction for different scales (×1, ×2, ×5 and ×10)- floating deck rotation for 7.36 MW earthquake event

The rotation results showed a minimal vulnerability to the applied vertical excitation in different scales (×1, ×2, ×5 and ×10). This could be due to the large floating platform and viscous damping for water.

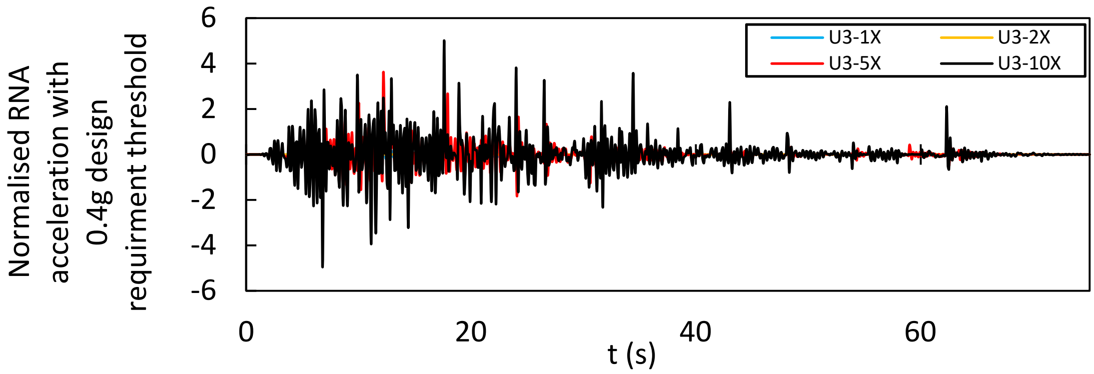
The most critical parameter in seismic excitation analysis could be the assessment of motion amplification within the tower-foundation system. This could lead to damage to the RNA system. Therefore, it must be checked since this is part of the warranty requirements. The results are shown in Figure 15.



(a) U1 direction (horizontal 1)



(b) U2 direction (horizontal 2)



(c) U3 direction (vertical)

Figure 15: Effect seismic motion in the Z direction for different scales (×1, ×2, ×5 and ×10)- RNA acceleration for 7.36 MW earthquake event

There is a risk of damage to the RNA since RNA surpasses the design requirements for ×5 and ×10 input motions. Therefore, considering this system (TLP) for seismic regions might not be a preferable solution.

4.3 Discussion and Conclusion

Along with other floating wind turbine foundations, tension leg platform systems could have the highest risk of seismic hazards because of its pre-tensioned cable characteristics. It could be concluded that the OWTs supported by TLPs are not the best option for the areas where are seismically active. This study illustrates the behaviour of TLP mooring systems to different earthquake amplitudes for horizontal and vertical seismic motion components. The effect of seismic components are studied independently to identify the dominant seismic motion component (i.e., vertical or horizontal motion) in the destabilization of floating with turbines supported by TLPs. In general, the mooring cables of TLPs are pre-tensioned, these systems demonstrated a sensitivity to vertical seismic motions. The results have been reviewed in detail by comparing the effect of each seismic component for three different coordinates (X, Y, Z).

For the horizontal seismic motion, no excessive tension rise in the cables are observed even for the highest given input motion (i.e., ×10 of the main input motion). This is because of the long distance between the anchor point and the floating deck that any tangential would be damped by the time it reaches to the floating deck. Similarly for the RNA acceleration and the floating deck rotation a low risk of effect on the systems is found.

Whereas, the vertical seismic motion, showed an excessive tension rise in the pre-tensioned cables. In this study the cable tension is increased up to 6.3 times for the scenario of ×10 (0.4g-PGA for the vertical motion) in compare with the phase where no earthquake motion is applied. In this analysis no excessive rotation is observed but the RNA acceleration has showed an increase, especially in the Z-direction (vertical). In the maximum applied amplitude case (×10), the RNA acceleration has showed a 500% surpassing the considered SLS design criteria (0.4g). This is important because a large acceleration in the RNA systems could cause damage to the RNA and the other components of the OWT. Furthermore, non-linear relativity between the applied PGA and the measured tension in the cables was observed for different scales of input motions (×1, ×2, ×5 and ×10).

The authors recommend that the TLP systems are vulnerable in seismic regions and therefore other types of mooring systems such as catenary mooring systems could offer a safer solution. Some examples of floating offshore wind turbines are semi- submersible and spar-buoy system. This sensitivity analysis provides an initial hint for the hazards, method of assessment, design of anchors, cables and the offshore floating wind turbines in seismic regions.

Readers are referred to further recent studies by Bhattacharya et al [31, 32] , Amani et al [15, 33] on the seismic design and analysis of offshore wind turbines.

REFERENCES

[1] IRENA, *Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper),* Abu Dhabi, 2019.

[2] S. Nash, *USGS-Tectonic plates*, 2011. Accessed: Feb. 26, 2023. [Online]. Available: https://www.usgs.gov/media/images/tectonic-plates-earth

[3] A. Durakovic, *WindFloat Atlantic Fully Up and Running*, *OffshoreWIND.biz*, 2020. https://www.offshorewind.biz/2020/07/27/windfloat-atlantic-fully-up-and-running/ (accessed Feb. 06, 2022).

[4] OW Ocean winds, *WindFloat Atlantic project*, 2021. https://www.oceanwinds.com/projects/windfloat-atlantic-project/ (accessed Feb. 06, 2022).

[5] A. Durakovic, *World's Largest Floating Offshore Wind Farm Fully Operational*, *offshorewind.biz*, 2021. https://www.offshorewind.biz/2021/10/19/worlds-largest-floating-offshore-wind-farm-fully-operational/#:~:text=The 50 MW Kincardine floating,largest operating floating wind farm (accessed Feb. 06, 2022).

[6] Equinor ASA, *Hywind Tampen*, 2022. https://www.equinor.com/en/what-we-do/hywind-tampen.html (accessed Feb. 06, 2022).

[7] Equinor ASA, *Industrialising floating offshore wind*, 2022. https://www.equinor.com/en/what-we-do/floating-wind.html (accessed Feb. 06, 2022).

[8] OW Ocean winds, *Korea floating wind farm project*, 2021. https://www.oceanwinds.com/projects/korea-floating-wind-farm/ (accessed Feb. 06, 2022).

[9] OW Ocean winds, *Redwood coast offshore wind project*, 2021. https://www.oceanwinds.com/projects/redwood/ (accessed Feb. 06, 2022).

[10] Redwood coast energy authority, *Redwood Coast Offshore Wind*, 2022. https://redwoodenergy.org/redwood-coast-offshore-wind/ (accessed Feb. 06, 2022).

[11] N. Skopljak, *MHI Vestas 9.5MW Turbines in the Game for Japanese Offshore Wind Farm*, 2019. https://www.offshorewind.biz/2019/11/06/mhi-vestas-9-5mw-turbines-in-the-game-for-japanese-offshore-wind-farm/ (accessed Feb. 06, 2022).

[12] M. Ikhennicheu, M. Lynch, S. Doole, F. Borisade, D. Matha, J. Dominguez, R.D. Vicente, T. Habekost, L. Ramirez, S. Potestio, C. Molins, P. Trubt, *D2.1 Review of the state of the art of mooring and anchoring designs, technical challenges and identification of relevant DLCs*, 2020.

[13] M. Borg and M. Collu, A comparison between the dynamics of horizontal and vertical axis offshore floating wind turbines, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **373**, 2035, 20140076, 2015, doi: 10.1098/rsta.2014.0076.

[14] S. Bhattacharya, *Design of Foundations for Offshore Wind Turbines*, *First Edit.* Chichester, Wiley, 2019. doi: 10.1002/9781119128137.

[15] S. Amani, A. Prabhakaran, and S. Bhattacharya, Design of monopiles for offshore and nearshore wind turbines in seismically liquefiable soils: Methodology and validation, *Soil Dynamics and Earthquake Engineering*, **157**, 107252, 2022, doi: 10.1016/j.soildyn.2022.107252.

[16] T. Tajalli Bakhsh, M. Monim, S. Kent, T. Lapierre, J. Dahl, J. Rowe, M. Spaulding, J. Miller, Potential earthquake, landslide, tsunami and geo-hazards for the U.S. offshore pacific wind farms (19-p-202745), 2020. [Online]. Available: https://www.rpsgroup.com/media/5565/potential-earthquake-landslide-tsunami-and-geohazards-for-the-us-offshore-pacific-wind-farms.pdf

[17] R. R. Youngs, W.J. Arabasz, R.E. Anderson et al., A Methodology for Probabilistic Fault Displacement Hazard Analysis (PFDHA), *Earthquake Spectra*, **19**, 191–219, 2003, doi: 10.1193/1.1542891.

[18] M. Petersen and S. Wesnousky, Fault slip rates and earthquake histories for active faults in southern California, *Bulletin of the Seismological Society of America*, **84**, 1608–1649, 1994.

[19] D. Wells and K. Coppersmith, New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement, *Bulletin of the Seismological Society of America*, **84**, 974–1002, 1994.

[20] DNV GL standards, DNVGL-ST-0119: Floating wind turbine structures, 2018.

[21] C. B. Barrass and D. R. Derrett, *Ship Stability for Masters and Mates*. Elsevier, 2012. doi: 10.1016/C2010-0-68323-4.

[22] S. Bhattacharya, S. Biswal, M. Aleem, S. Amani, A. Prabhakaran, G. Prakhya, D. Lombardi, H.K. Mistry, Seismic Design of Offshore Wind Turbines: Good, Bad and Unknowns, *Energies*, **14**, 12, 2021, doi: 10.3390/en14123496.

[23] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, Definition of a 5-MW Reference Wind Turbine for Offshore System Development, 2009. doi: NREL/TP-500-38060.

[24] W. L. Hurley and C. J. Nordstrom, PelaStar Cost of Energy: A cost study of the PelaStar floating foundation system in UK waters, Seattle, Washington, 2014.

[25] E. Oguz, D. Clelland, A. Day, A. Incecik, J.A. López, G. Sánchez, G.G. Almeria, Experimental and numerical analysis of a TLP floating offshore wind turbine, *Ocean Engineering*, **147**, 591–605, 2018, doi: 10.1016/j.oceaneng.2017.10.052.

[26] G. B. and P. Migliore, Preliminary Structural Design of Composite Blades for Two- and Three-Blade Rotors-NREL/TP-500-31486, 2004.

[27] S. Adhikari and S. Bhattacharya, A general frequency adaptive framework for damped response analysis of wind turbines, *Soil Dynamics and Earthquake Engineering*, **143**, 106605, 2021, doi: 10.1016/j.soildyn.2021.106605.

[28] E. E. Bachynski and T. Moan, Design considerations for tension leg platform wind turbines, *Marine Structures*, **29**, 89–114, 2012, doi: https://doi.org/10.1016/j.marstruc.2012.09.001.

[29] Y.-H. Lin, S.-H. Kao, and C.-H. Yang, Investigation of Hydrodynamic Forces for Floating Offshore Wind Turbines on Spar Buoys and Tension Leg Platforms with the Mooring Systems in Waves, *Applied Sciences*, **9**, 608, Feb. 2019, doi: 10.3390/app9030608.

[30] Y.-H. Lin and C.-H. Yang, Hydrodynamic Simulation of the Semi-Submersible Wind Float by Investigating Mooring Systems in Irregular Waves, *Applied Sciences*, **10**, 4267, 2020, doi: 10.3390/app10124267.

[31] S. Bhattacharya, S. Amani, A. Prabhakaran, and S. Biswal, Seismic Design and Analysis of offshore wind turbines, *Wind Energy Engineering, 2nd ed., T. Letcher*, Academic Press, 2023. doi: 10.1016/B978-0-323-99353-1.00011-6.

[32] S. Bhattacharya, D. Lombardi, A. Prabhakaran, H.K. Mistry, S.Biswal, M. Aleem, S.Amani, G. Prakhya, S. Jindal, J. Macabuag, Z. Qiu, Risks and Vulnerabilities in the Design, Construction, and Operation of Offshore Wind Turbine Farms in Seismic Areas. In: Sitharam, T.G., Jakka, R.S., Kolathayar, S. (eds), *Advances in Earthquake Geotechnics*, Springer, 2023, doi: 10.1007/978-981-19-3330-1_1.

[33] S. Amani, A. Prabhakaran, S. Bhattacharya, H. Rashid, and R. Sarkar, Seismic Hazards associated with Offshore Wind Farms, *Wind Energy Engineering, 2nd ed., T. Letcher,* Academic Press, 2023. doi: 10.1016/B978-0-323-99353-1.00018-9.