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FWTGs layout optimization considering geohazard assessment integrating geophysical and geotechnical data

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ABSTRACT: The wind farm layout of Floating Wind Turbine Generators (FWTGs) is a critical factor in maximizing annual energy production (AEP), ensuring structural integrity, and minimizing economic and environmental impacts in offshore wind farms. To achieve these objectives, geohazard risk assessment is essential in selecting suitable anchor types and the locations of anchors for FWTGs in the early stage. Available site specific geophysical and geotechnical data are integrated into a Central Geodatabase (CGDB), enabling to evaluate the geological and geohazard complexities.
This study compares four different turbine layout cases, each addressing different challenges related to AEP, design and construction cost, and geohazard risks. For the optimized turbine layout, the geohazard risks are interpreted by integrating geophysical and geotechnical data and their impact on the FWTGs layout optimisation. The importance of integrating geophysical and geotechnical data into turbine layout design is demonstrated. Addressing seabed variability and geohazard risks through a multi-disciplinary collaboration is pivotal in achieving cost-effective and sustainable offshore wind energy.

Keywords: FWTGs layout, Geohazard assessment, geotechnical, geophysical data, CGDB.

1 OBJECTIVES

The layout of the Floating Wind Turbine Generators (FWTGs) in a wind farm is designed so as to optimize energy production, ensure structural integrity, and minimize environmental and economic impacts. The main considerations for turbine layout are wind, wave, current, seabed conditions, electrical infrastructure accessibiliy and maintenance, environmental impact, cost efficiency, regulatory and safety requirements (Hall, 2024). The assessment of offshore seabed conditions affects the stability and performance of the FWTGs and the design and installation of the anchoring systems. Geohazard assessment is key in determining appropriate FWTGs locations, anchor types and their feasible locations, given the inherent uncertainties of offshore geological conditions. The early-stage evaluation of these geohazards is crucial for ensuring the safety, stability, and efficiency of floating offshore wind projects.

In this study, different cases of turbine layout are compared and optimized taking into account challenging seabed conditions. To address these challenges, integrated geophysical and geotechnical site investigation results are utilized together with historical geological information facilitating a Central Geodatabase (CGDB) system. This approach allows for a better understanding of subsurface conditions and enhances the reliability of geohazard assessments. A particular focus is given to addressing the cost and Annual Energy Production (AEP) effect that is strongly influenced by the layout of FWTGs and anchor locations related to bathymetric features and subsurface soil conditions.

2 TURBINE LAYOUT

2.1 Considerations

Turbines in an offshore wind farm generate wakes which can affect the performance of downwind turbines. To minimize wake losses, turbines should be spaced adequately depending on prevailing wind directions. The typical spacing between turbines is around 7 to 10 rotor diameters in the prevailing wind direction and 5 to 7 rotor diameters cross-wind direction. Adequate spacing also ensures that vessels can maneuver safely between turbines for repairs or emergency situations. Furthermore, turbine spacing affects the fatigue life of the turbine structures by affecting the turbulent wind conditions downwind.

The layout must account for the forces exerted by waves, wind, and ocean currents. Turbines should be positioned to minimize the impact of these forces on structural integrity. The motions of floating turbines due to environmental loads requires strategic placement to prevent mooring line and cable crossings and to ensure safe operation (Sinner, 2024).

The varying depth of the seabed can affect mooring and anchoring systems. The layout needs to accommodate these variations, ensuring that turbines are installed in locations where anchoring systems can be safely and economically deployed. The type of seabed (rocky, sandy, or muddy) influences the choice of anchoring systems and can impact turbine layout (Rattley, 2017). Balancing energy output with the cost of installation and maintenance is crucial. The layout must consider the economic implications of turbine spacing, cable length, and anchoring systems to achieve the most cost-effective design.

The layout of a floating offshore wind farm requires a holistic approach, balancing wind energy capture with structural, environmental, and economic considerations.

2.2 Basic assumptions

Ideally, one could consider an integrated design process in which all relevant aspects and their interactions are regarded. For instance, one could iteratively design the floater, mooring, anchors, wind farm layout, inter-array and export cable design and routing, turbine selection, etc. In practice, this process is simplified. Here, we regard wind farm layout design for a preselected wind turbine, with a predesigned floater and mooring system. The floater is a semisubmersible with one centre column and three outer columns. The wind turbine tower is supported on the centre column. Station keeping is achieved with three 120°-spaced mooring lines with fairleads at the outer columns. The anchor radius is kept constant for all water depths. Given this starting point, the metocean input relevant to layout design is primarily the wind distribution. The wind rose at site is shown in Figure 1.

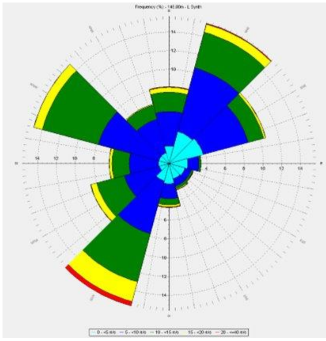

Figure 1. Wind rose for Floating Offshore Wind Farm site.

The wave spectrum and current distribution are considered in a simplified way by setting a constraint on the minimum and maximum allowed floater heading (20 to 40 degrees relative to North). This opens the possibility to modify the heading to further optimize the layout, while ensuring that the floater and mooring have sufficient fatigue resistance.

Additional constraints on layout design were categorized according to "hardness". Hard constraints are requirements such as minimum turbine spacings in prevalent and non-prevalent wind directions, exclusion zones (due to military and other land usage). Soft constraints, on the other hand, may be disregarded at a cost. Examples are avoiding anchors and cable routes at boulders or low and medium severity geohazard areas, avoiding more than 5° gradients at anchor locations because of the installation risk.

2.3 Case-1: Optimal AEP layout

Figure 2 presents the optimal placement of the wind turbine generators (WTGs), determined through a comprehensive analysis focused on maximizing annual energy production (AEP). This optimization process takes into account factors such as wind resource distribution, wake effects, and turbine spacing to identify the locations that yields the highest energy output.

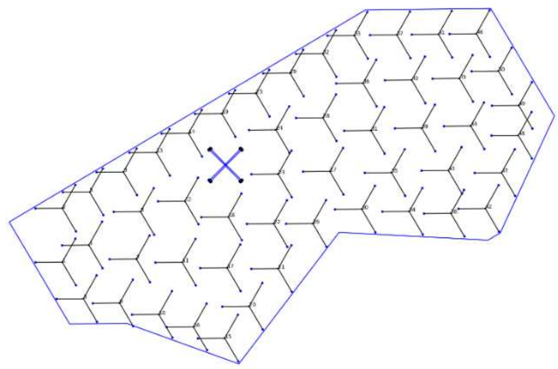

Figure 2. Wind farm layout Case-1, optimal layout excluding geophysical and geotechnical consideration.

The farm comprises 150 anchor locations, each positioned to support the stability and mooring requirements of the turbines. The average turbine spacing results in 6.46 rotor diameters, with a minimum spacing of 4.82 and a maximum of 7.96. Average distance from 6 closest turbines is 9.08. This range was carefully selected to minimize wake effects while maximizing energy production. However, this layout is not feasible because mooring lines cross each other and geohazards are not avoided. The maximum obtainable AEP, $E_{A,max}$ is set equal to 1.0 whereas the AEP of the other layout alternatives are presented relative to this maximum value.

2.4 Case-2: Honeycomb pattern

Alternative Case-2 called as a honeycomb layout is shown in Figure 3. Case-2 is a layout for minimizing the number of anchors by sharing mooring lines with one anchor.

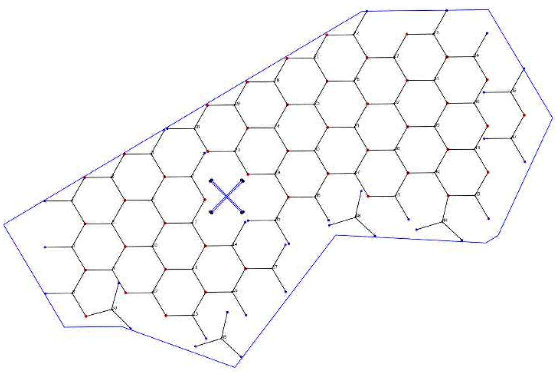

Figure 3. Wind farm layout Case-2

In turbine layout Case-2, a total of 78 anchors are utilized. 18 anchors are equipped with two mooring lines each, while 27 anchors are designed with three mooring lines. The average spacing between turbines is 7.13 rotor diameters, with a minimum spacing of 5.75 and a maximum spacing of 7.44. Average distance from 6 closest turbines is 8.65. The estimated annual energy production for this layout configuration is $E_{A,max}$ = 0.993.

2.5 Case-3: Grape pattern

Alternative Case-3 called as a grape type layout is shown in Figure 4. The naming "grape" comes from the similitude to a bunch of grapes of the string of connected mooring systems with alternating floater headings. Case-3 is a layout for avoiding anchors with 3 mooring lines to increase flexibility of the location of anchors.

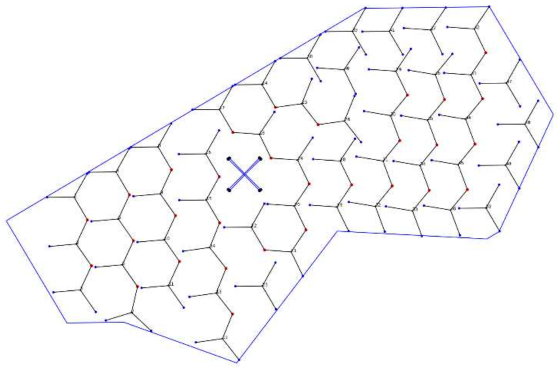

Figure 4 Wind farm layout Case-3

In turbine layout Case-3, the design incorporates 120 anchors, consisting of 30 anchors with two mooring lines. The turbines are spaced at an average distance of 6.76, with a minimum spacing of 5.71 and a maximum spacing of 7.56rotor diameters. Average distance from 6 closest turbines is 8.92. This configuration results in an estimated annual energy production, $E_{A,max}$ = 0.996.

3 GEOHAZARD ASSESSMENT

3.1 Geophysical data

A comprehensive seabed survey was conducted using a multi-beam echosounder with a resolution of 2m, alongside side-scan sonar and single magnetometer. For sub-seabed investigations, a sub-bottom profiler was utilized with a line spacing of 200 m, complemented by a 2D high-resolution seismic survey, also performed with a line spacing of 200 m. Based on the available geophysical survey data, the bathymetry was found to be highly variable due to the presence of the Western Channel Trough cross cutting the middle of the WTG area at a NE/SW orientation. Water depth in the WTG area ranges from approximately 150 m to 250 m below seafloor at the flanks to approx. 350m at the deepest part of the Western Channel Trough. Side slopes of the Western Channel are generally in the order of 8° to 10°, with occasional localized steeper slopes (Figure 5).

Shallow seismic data shows that the site is underlined by a series of sedimentary sequences. Each of these sequences comprises of at least one cycle of sea-level lowstand, transgression and highstand deposits. A series of more recent channels, possibly formed during the last sea-level low stand, are also present cross cutting each other close to seabed. At the flanks of the Western Channel Trough, several individual units of channel deposits also found to be present. These deposits are likely to be deposited by the bottom currents in the current marine setting or as point bar deposits from the last sea-level low stand.

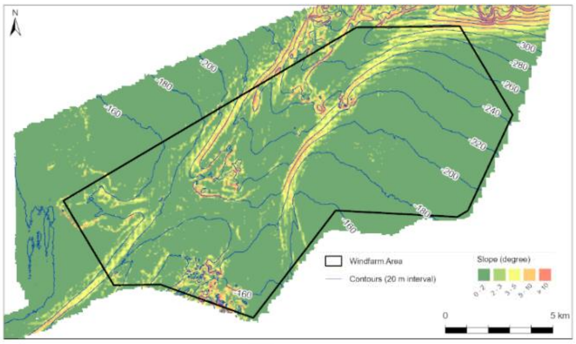

Figure 5 Geophysical survey results illustrating the slope of the site.

3.2 Geotechnical data

The available geotechnical data comprises of Cone Penetration Tests (CPT) conducted to a depth of 20 m below the seabed at 10 locations, as well as vibrocore samples collected to a depth of 3 m below the seabed at 10 locations within the WTG site. In general, the seabed soil condition is characterized by typical dense Sands overlying dense to very dense Silty Sand and partially Gravelly Sand. The area of the Western Channel crossing the middle of the WTG area is composed of Sand and partially Gravelly Sand overlying Silty Sand and Silt. Basic soil parameters for each unit are presenting in Table 1.

Table 1. Representing geotechnical soil properties for units

Layer	Depth range (m, bsf)	Water content (Wn, %)	Unit weight (kN/m^3)	Relative density (Dr, %)	Friction angle (Φ, °)
Sand (silt)	8.9~21.0	27.0	19.3	75~85	41~43
Sand	0.0~11.8	21.8	20.4	70~90	42~47
Sand(gravel)	14.4~15.7	14.2	20.5	100	44

3.3 Geohazards – Unfavourable ground condition

Within the site, several unfavourable ground conditions have been identified on geophysical and geotechnical data. These are categorized into "Low", "Medium" and "High" severity based on their impact on the proposed anchor systems (Figure 6). In particular, the Western Channel Trough crosscutting the WTG area is linked to steep slopes and gravity related mass movement such as slumps, landslides and failure crests, indicating potential submarine slope instability. This influences the choice of location and type of anchor systems required. Submarine slope stability is also influenced by various factors, including bathymetry, soil lithology, excess pore pressure, and soil strength. These factors can vary significantly across large offshore areas, especially in a complex geological environment that has experience cycles of sea-level rise and falls. Traditional geotechnical investigations often provide localized data, which may not fully capture these variabilities across the WTG area. An holistic approach integrating the more "localised" geotechnical data and the more "site-wide" geophysical data is therefore key to understand the severity of these geohazards.

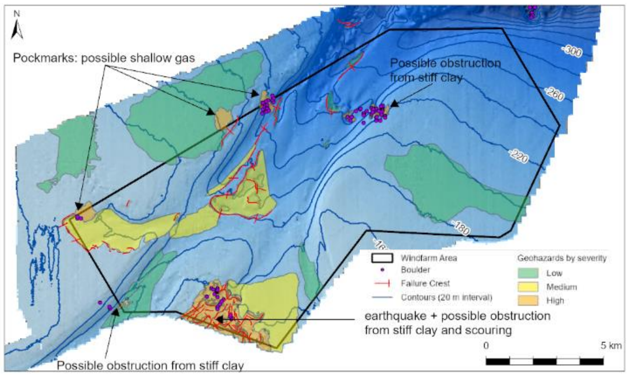

Figure 6 Geohazard risk integrating geophysical and geotechnical survey results with the site.

A zone of faults mapped in the southern part of the site is also found to have an unfavourable impact to the anchor and cables. These faults can be potentially re-activated by an earthquake, resulting in reduced loading capacity of the anchor and cable damages.

Other geohazards identified include potential shallow gas, areas of stiff clay and current related features. Shallow gas has been identified both sub-surface and as pockmarks on seabed, which can be a health hazards during installation and marine operations. Areas of stiff clay identified can cause possible obstructions and increase lateral variations in soil parameters. Current related features such as ripples, sand waves, Barchan dunes and scouring depressions indicate potential sediment mobility scouring on the seabed which may reduce anchor stability and cause over burial or free span in cables.

3.4 Central Geodatabase (CGDB)

To facilitate a multidisciplinary assessment of the layout alternatives, all relevant geospatial data was integrated into one geographic information system. This ensures consistent data formatting and alignment of the data into one common coordinate system. Using available software tools and input from the different disciplines, new data layers were generated such as slope maps, mapping of geohazards by severity, FWTGs and anchor locations. **Erreur ! Source du renvoi introuvable.**The data was uploaded to a CGDB in a cloud-based environment ensuring easy

access, consistency of data used and further visualization in a web application.
Multiple disciplines can then work together on a single platform or individually compare the different layouts, assessing their implications and discuss possible adjustment to mitigate risks. As new revisions of the layout were generated, they are added the CGDB and visualized in the application, ready for a new assessment by the team. This process allows an efficient iterative workflow to optimize the FWTG layout design.

4 TURBINE LAYOUT OPTIMIZATION

4.1 Case-4: Optimize layout considering geohazard risks

Case-4 is an optimized layout combining Honeycomb and grape pattern considering geohazard risks addressed in Section 3.3. The geohazard risks shown in Figure 7 were superimposed on the turbine layout planning shown in Figure 7. The optimisation focuses on minimizing the number of anchors in areas of "Medium" or "High" severity, while maintaining a high AEP output.

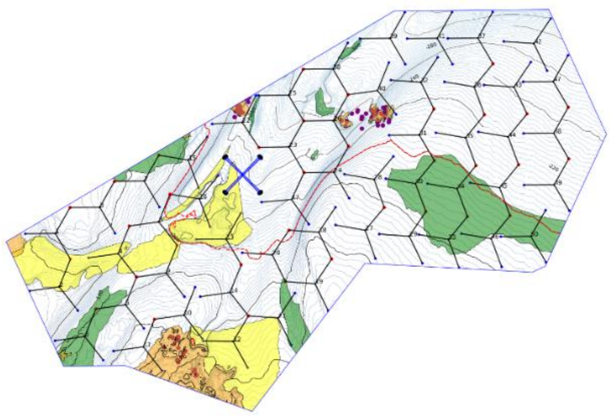

Figure 7. Wind farm layout Case-4, including mooring system and with superimposed geohazard risk zones.

This layout has been optimized with 111 anchors, consisting of 29 anchors with two mooring lines and 3 anchors with three mooring lines. The turbines are spaced at an average distance of 6.48, with a minimum spacing of 5.66 and a maximum spacing of 7.66. Average distance from 6 closest turbines is 8.75 . This configuration results in an estimated annual energy production, $E_{A,max} = 0.998$.

5 COMPARISION OF LAYOUTS

Table 2 presents a comparison of the number of anchors, WTG spacing, annual energy production (AEP), and anchor costs. Case 1 represents the optimal scenario for maximizing AEP, utilizing one anchor per mooring line, which results in the highest anchor costs. It is a reference value for comparing other cases. Case 2 is designed to minimize the number of anchors by maximizing the sharing of anchors, with 27 anchors sharing three mooring lines, thereby achieving minimal anchor costs but the lowest AEP. Case 3 provides a balanced layout aimed at increasing AEP and enhancing the flexibility of anchor numbers and locations. It is noted that none of the cases (Case 1 to 3) account for geohazard risks that involve integrated geophysical and geotechnical data.

Case-4 is an optimized layout considering geohazard interpretation (chapter 3) integrating geophysical and geotechnical data by implementing Central Geodatabase (CGDB) system. This optimization presents higher AEP with less anchor cost than Case 3 by using more shared anchors and changing layout of turbines. Figure 10 shows the differences in AEP and Anchor cost ratio for each layout indicating 99.8% AEP ratio and 74% of Anchor cost ratio for the optimal layout considering geohazard risks (Case-4).

Table 2. Comparison of different layouts of WTGs. Spacings are measured in number of rotor diameters.

WTGs Layout comparison	Case-1: Optimal AEP	Case-2	Case-3	Case-4
Anchors	150	78	120	111
Lines per anchor	1	1.92	1.25	1.35
Anchors with 2ML	0	18	30	29
Anchors with 3ML	0	27	0	5
Avg WTG spacing	6.46	7.13	6.76	6.48
Avg to 6 closest WTGs	9.08	8.65	8.92	8.75
Min WTG spacing	4.82	5.75	5.71	5.66
Max WTG spacing	7.96	7.44	7.56	7.66
Relative AEP	1.0	0.993	0.996	0.998
Relative anchor cost	1.0	0.521	0.800	0.740

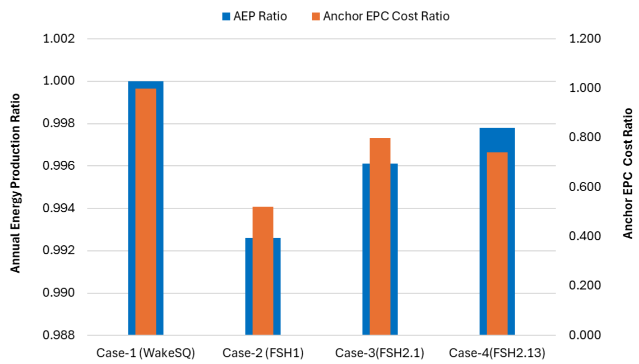

Figure 8. AEP and Anchor cost ratio for different layouts

6 SUMMARY AND CONCLUSION

This study has explored and compared four different layout designs for Floating Wind Turbine Generators (FWTGs) in offshore wind farms, each layout to address distinct challenges related to energy production, anchor costs, and geohazard risks. The analysis highlights the trade-offs in maximizing Annual Energy Production (AEP), minimizing anchor costs, and mitigating geohazard risks, which are critical to the success of floating offshore wind projects.

Case-1 demonstrated the highest achievable AEP but was not feasible due to overlapping mooring lines and unaddressed geohazard risks. Case-2 introduced a honeycomb layout, minimizing anchor costs by maximizing shared mooring lines. Case-3 offered a balanced grape-pattern layout, improving flexibility in anchor placement while achieving higher AEP than Case-2 but at increased anchor costs.

The optimized layout in Case-4 incorporated geohazard assessment using a Central Geodatabase (CGDB) system, combining geophysical and geotechnical data. By integrating geohazard considerations, Case-4 achieved a near-maximal AEP (99.8% of the maximum AEP) while significantly reducing anchor costs to 74% of Case-1. This optimization underscores the importance of addressing subsurface variability, bathymetric features, and geohazard risks early in the design process to enhance both economic and operational feasibility.

The findings demonstrate that integrating geohazard assessments into layout planning not only mitigates risks but also enables the optimized turbine layout aiming cost-effective and efficient configuration for floating offshore wind farms. This study emphasizes the value of leveraging advanced geospatial tools and multi-disciplinary data to optimize offshore wind energy systems, contributing to safer and more sustainable energy solutions.

AUTHOR CONTRIBUTION STATEMENT

Yun Sup Shin : Conceptualization, writing-original manuscript, geotechnical data., **Jorge Mendoza Espinosa**, **Charlotte Obhrai**: Wind data, AEP, cost, turbine layout., **Clement Ka Man Tam, Nora Kjørlaug**: Geophysical data, geohazard risks., **Hilde Daugstad Oterhals**: Central geodatabase system., **Øystein Johannessen, Kenneth Skarstein**: Supervision.

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