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Cost optimization of dynamic cable lazy wave configurations for floating offshore wind turbines

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Abstract. This research aims to design a low-cost dynamic cable lazy wave configuration at different curvature factors by adopting an integrated approach to optimally size the length of different sections of the dynamic cable accounting for maximum allowable tension, maximum allowable curvature, minimum allowable sag position and maximum allowable hog position. The research explores trade-offs associated with the increase in costs as curvature factor decreases. The configuration is subjected to Near, Far and No offset scenarios to analyse the impact on costs and its performance. The assessment includes determining configuration costs and optimal lengths at different curvature factors for each scenario. Observations reveal that the hang-off point consistently experiences the highest curvature across the arc length in all configurations and scenarios. Optimal configurations for Far scenario outperform configurations designed for No offset scenario when subjected to the remaining two scenarios. Optimal configurations of Near scenario failed to adhere to the maximum allowable curvature limit when subjected to Far and No offset scenarios. The study highlights the sensitivity of the curvature factor to the ratio of lengths of each section in the configuration. These results indicate that a configuration designed for Far offset is more likely to perform well under all scenarios due to its unique section length ratios. The results also portray the possibility of a fit configuration with lower number of buoyancy modules.

1. Introduction

As the offshore wind market approaches deeper waters in search of higher annual energy productions, Low-cost Energy transmission poses a challenge both in terms of cost and performance. Several types of cable configurations have been developed so far to face various environmental challenges. While Catenary configurations are suitable for shallow waters, steep wave, lazy wave, tethered lazy wave are some of the configurations being investigated for deeper waters due to their performance under extreme environmental loads in deeper and hostile waters. An estimate of four cable failures are expected over a typical array design life. Reportedly 80% of total project insurance claims are being made for cables. And the costs incurred due to an average of 38 day downtime for inter array cable failures and replacement are estimated to be extremely high [1] . It is necessary to optimize a dynamic cable configuration for both operation and installation conditions to retain an acceptable power loss across the system during operations. Apart from optimizing a cable configuration from performance perspective it also is extremely important to consider dynamic cables for floating offshore wind turbines from cost perspective [2]. As improving the configuration from an operation performance perspective without cost constraints is not feasible. Joana [5] studies the catenary configurations through static analysis in shallow waters. Rentschler et al. [3] performs a comparative study between catenary and lazy wave configurations and presents a general recommendation for a first umbilical design. His comparison concludes that in most cases, the lazy wave configuration is preferable over catenary configurations due to its handling of overbending and high tensions. Rentschler et al. [3] performs an optimization of lazy wave configurations using a genetic algorithm for various water depths by varying the position of the buoyancy modules while having a fixed sectional length ratio. Nguyen et al. [5] studies the effect of varying the buoyancy section height on the fatigue life of the cable, in a way optimizing the cable configuration for an improved fatigue life. Nguyen et al. [7] studies the lazy wave riser in deep waters to categorize safe configurations. This paper deals with optimizing the lazy wave configurations for 200m water depth by varying the design variables including ratio of sectional lengths of the cable, total length of the dynamic cable and number of buoyancy modules.

This approach also uses a fixed anchor position and constant spacing between buoyancy modules due to an underlying assumption of easy installation and maintenance. The configurations are optimized based on their performance in terms of maximum curvature and maximum tension across the arc length under static analysis only using ORCAFLEX. The objective of this paper will be to model a low-cost dynamic cable configuration which is able to achieve a balance between cable statics, curvature constraints, tension constraints, and associated costs, ensuring optimal performance under operational conditions within the constraints using a numerical optimization algorithm, iterating through design variables. This optimization method integrates the COBYLA (Constrained Optimization BY Linear Approximations) algorithm within the framework of Multidisciplinary Design Analysis and Optimization (MDAO).

2. Methodology

The optimization methodology is built on a component-based modelling structure within the MDAO framework. It incorporates explicit components to represent cable dynamics, cost analysis, Tension, and curvature factor evaluation. COBYLA optimization algorithm is used for its suitability in derivative-free optimization scenarios. This allows effective exploration of the design space without the requirement of analytical gradients. Lazy wave configurations are deemed as a low-cost solution suitable for applications with reasonable dynamic motion and offset is expected [2]. High Tensions, excessive bending, twisting, and compression are some of the most common failure modes of dynamic cables. Water treeing caused due to over bending and compression are responsible for unexpected failures [2]. Optimizing dynamic cable lazy wave configuration to reduce both tension and curvature leads to increased costs due to increased length, number of buoyancy modules and spacing between the buoyancy modules. Hence a better approach to optimize dynamic cable configurations would be to consider reduced maximum Tension and Maximum curvature as constraints to develop a low-cost configuration by tuning the design variables within these constraints.

Design variables can be distinguished in two categories, Continuous (Cable Length, spacing between buoyancy modules) and Discrete (Number of buoyancy modules, buoyancy module type, cable type). Mixed design variables complicate the optimization problem. Evolutionary and mixed-integer algorithms can handle discrete design variables but are also computationally expensive. Hence optimization was performed using only continuous design variables followed by brute analysis for discrete design variables. Since the number of discrete design variables in this model is low, it is efficient to perform brute analysis as compared to a complicated problem with a mixture of continuous and discrete design variables. Apart from maximum tension and maximum curvature this problem includes positional constraints, maximum hog position and minimum sag position. Figure 1 Shows the flowchart representing the optimization process. It is to be noted that cost, which is an objective function of this optimization process, refers to only acquisition cost and does not consider installation and O&M costs.

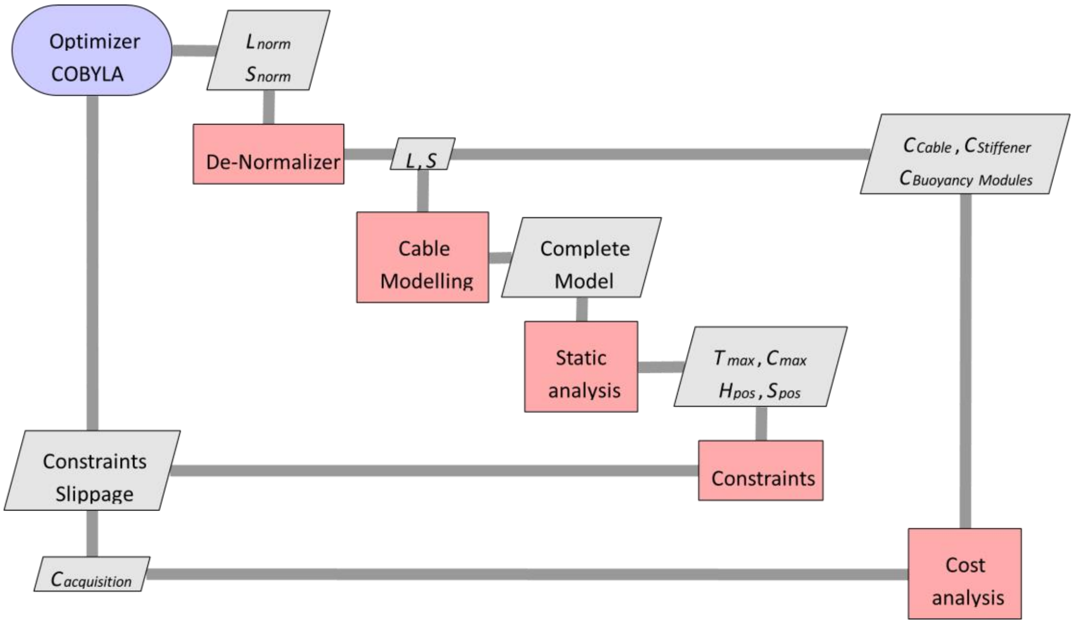

Figure 1. Cable cost optimization framework

Figure 2 shows the dynamic cable lazy wave configuration used for static analysis on OrcaFlex. The anchor position is fixed to $2h$, were h is the distance from hang-off position to the seabed. The hog and sag positions refer to the peak position of their respective bends. Both Maximum Hog position MHP and minimum sag position MSP are geometric constraints and must not exceed 0.1d. Other constraints such as Maximum allowable curvature MAC and Minimum breaking load MBL also known as maximum allowable tension directly depend on the type of cable being used. If the model succeeds static simulation, maximum tension T_{max}, maximum curvature ρ_{max}, hog position H_{pos} and sag position S_{pos} are extracted from the model to evaluate curvature factor CF, Tension factor TF, Hog slippage $H_{slippage}$, and Sag slippage $S_{slippage}$. While maintaining all the constraints and design variables within prescribed ranges , Total cost is minimized iteratively with a certain tolerance. Cost of cable C_{Cable} , cost of buoyancy modules $C_{Buoyancy\ Modules}$ and cost of bend-stiffener $C_{Stiffner}$ refer to only the acquisition costs of the respective parts. Note that these costs are dependent on the type of cable, net buoyancy of the buoyancy modules, and design of the bend-stiffener, respectively.

$$CF = \frac{\rho_{max}}{MAC} \quad 1$$

$$TF = \frac{T_{max}}{MBL} \quad 2$$

$$H_{slippage} = \frac{H_{pos}}{MHP} \quad (3)$$

$$S_{slippage} = \frac{S_{pos}}{MSP} \quad (4)$$

$$C_{aquisition} = C_{Cable} + C_{Buoyancy\ Modules} + C_{Stiffner} \quad (5)$$

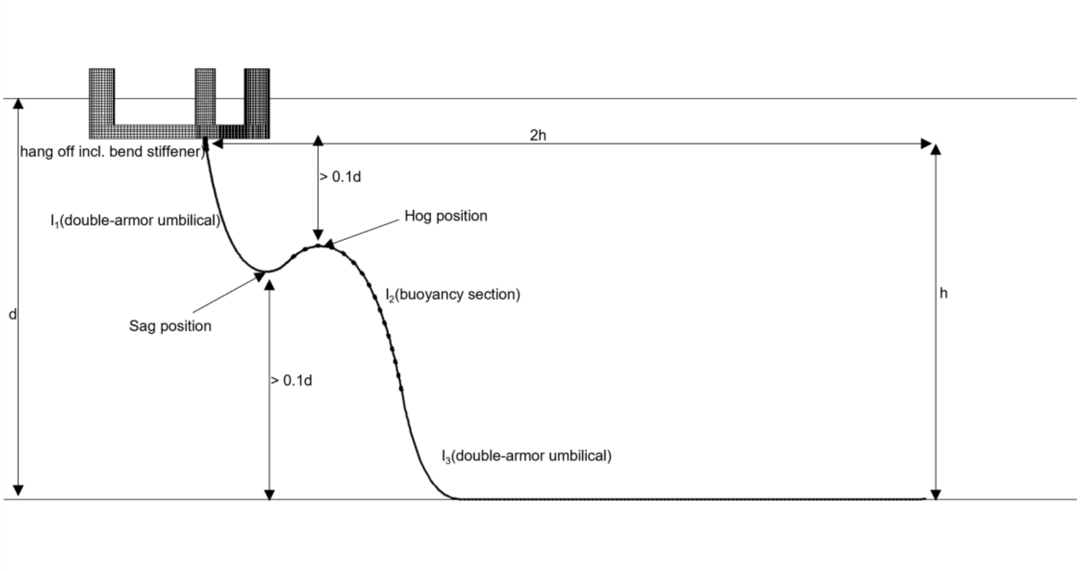

Figure 2. OrcaFlex Base cable model

3. Case Study

In this case study, the focus is on optimizing lazy wave configuration through static analysis (offset and current contribution) for the site of Gran-Canaria [2] with 200m water depth. Configuration is limited only to lazy wave by forceful imposition of a hog and sag bend. These configurations are optimized for scenarios including no offset, Near and Far (from top Figure 3) conditions with a constant hang-off and anchor position through static simulation. Near refers to when current (-1.471 m/s) and extreme offset (-30m) are aligned in a way that brings the fairlead closer to the touchdown point. Far refers to when current (1.471 m/s) and extreme offsets (+30m) are aligned in a way that extends the gap between fairlead and touchdown point. The direction of current imposed can be seen on the top right (represented by an arrow) of each scenario. These scenarios are defined to evaluate the suitability of the dynamic cable configurations for the site of Gran-Canaria through static analysis only. The environmental loads and extreme offsets can be found in Ref [2].

Table 1 and Table 2 Show the cable and ancillaries properties and lazy wave constraints of this optimization, respectively. 66kV Cable of cross section 240 mm^2 with a power capacity of 3x15MW was chosen for this optimization. The costs related to the cable and ancillaries are estimated based on talks with industry as this data is not publicly available. The cost of cable considered for this study is 415 Euros/m, and cost of a buoyancy module incorporated in this model is estimated to be 3650 euros/module. The bend stiffener costs are roughly estimated to be 80000 euros/ bend-stiffener. Due to its discrete nature, Number of Buoyancy modules is kept constant for each round of optimization and the process is repeated for 10, 12 and 14 Buoyancy modules to highlight the impact of number of buoyancy modules on the total configuration cost. Buoyancy modules are designed to provide 100kg net buoyancy force per module. To provide a broader perspective into the trade-off between Cost and curvature factor, the configuration optimization is performed by considering Curvature factor limits ranging from 1 to 0.4.

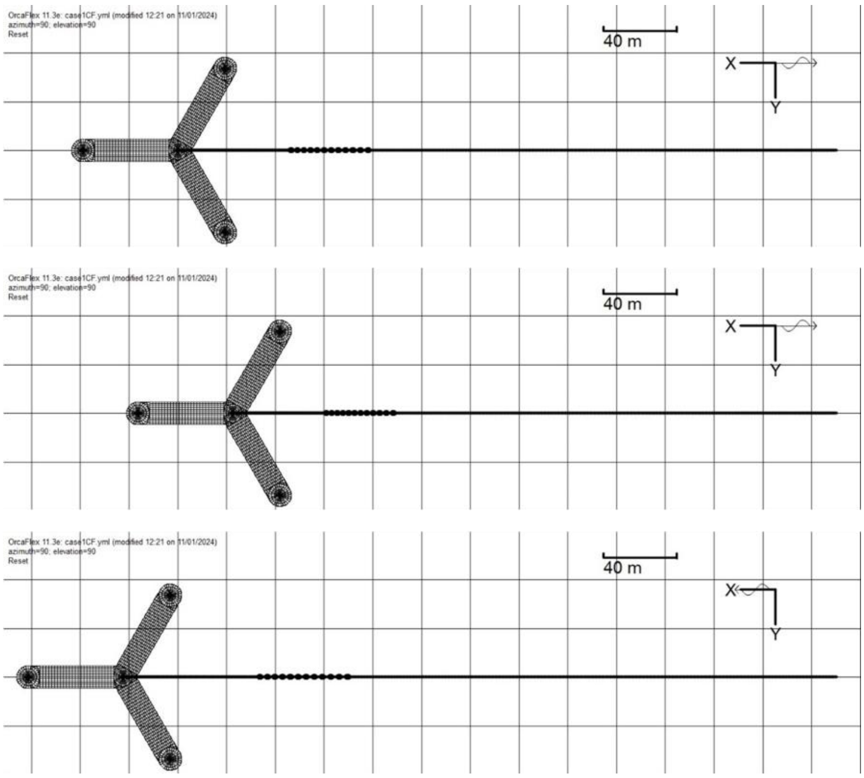

Figure 3. Environmental scenarios for static analysis (from top: No offset, Near offset, Far offset)

Table 1. Lazy wave design constraints

Parameter	Unit	Max Allowable value	Safety factor	Value with safety factor
Max tension in the cable	kN	120	-	120
Minimum value of bend radius	m	2.3	2	4.6 m
Hog highest position	m	-20	-	20 m below surface
Sag lowest position	m	-180	-	20 m above seabed

Table 2. Cable and ancillaries properties

Power cable mechanical characteristics		
Lineic Weight in air (kg/m)	29	
Bending Stiffness (kNm^2)	7.46	
Axial Stiffness (MN)	578.73	
Torsional Stiffness (kNm^2/rad)	83.23	
Cross section (mm^2)	240	
Minimum bend radius (m)	2.5	
Allowable Compression (kN)	10	
Cable hang-off point	X	0
	Y	0
	Z below sea surface	20
Buoyancy modules (BM) properties		
BM outer diameter (mm)	560	
BM inner diameter (mm)	165	
BM height (mm)	1000	
BM density (kg/m3)	291	
Buoyancy lineic mass in air (kg/m)	73.1092	
Number of Buoyancy modules	10, 12,14	
Bend-Stiffener properties		
Outer diameter at arc length 0m (m)	0.54	
Outer diameter at arc length 5.6m (m)	0.18	

4. Results

The results of the lazy wave configuration optimization study are presented below. The least possible maximum curvature across the cable arc length of the optimized configurations in all the cases considered was found to be 40% of the maximum allowable curvature. All the optimized configurations were found to stay well within the tension limit. Figure 4 (No offset) ,Figure 5 (Far) and Figure 6 (Near) represent the change in cost and total length of the cable with respect to curvature factor for each optimized configuration. The optimized configurations with the least curvature factor are of longer length as compared to those with a higher curvature yet within the maximum allowable curvature. The configurations with ten buoyancy modules were found to be the cheapest and still within the limits of CF. The configuration highlighted in Figure 5 is chosen to be the best configuration among all the other optimized configurations.

Table 3 shows along with TF the ratio of $l_1 : l_2 : l_3$ and $\frac{l_{total}}{h}$ required to model low-cost configuration with least CF and low-cost configurations with a higher CF but still within maximum allowable curvature. These results help in understanding and differentiating the combination of lengths of each segment necessary to obtain lower costs and those required to obtain lower CF. All three scenarios highlight a clear correlation between cost and curvature factor in the optimization study. The observed trend indicates that configurations with lower curvature factors tend to have higher associated costs, while configurations with higher curvature factors exhibit lower costs. This correlation reflects the inherent challenge in optimizing dynamic cable configurations, as reducing curvature to meet operational constraints often results in increased cable lengths, buoyancy modules, and associated costs.

The optimization process, driven by the objective of minimizing the total acquisition cost within the specified constraints, inherently balances the trade-off between cost and performance. As curvature factors are constrained to remain within acceptable limits, the optimization algorithm navigates the design space to find configurations that strike an optimal balance between minimizing costs and meeting operational requirements. It is assumed that a tolerance of 10-3 for the resulting costs is sufficient for an accurate estimation. An increased tolerance would require many more iterations to converge but would have less impact on the results merely due to its scale.

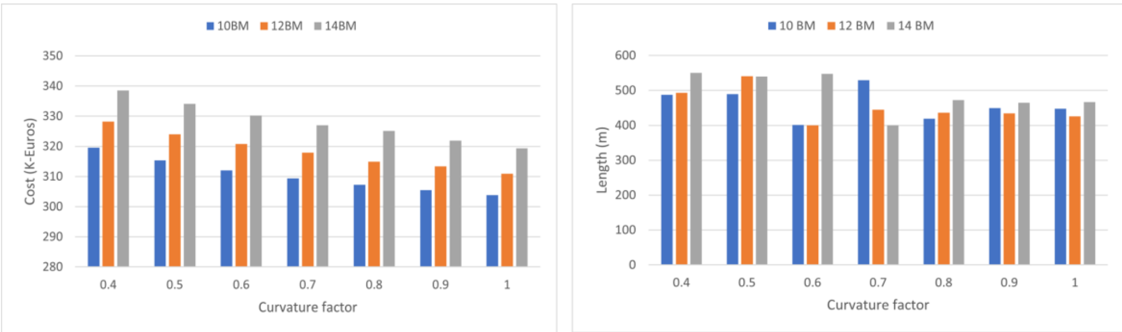

Figure 4. No offset

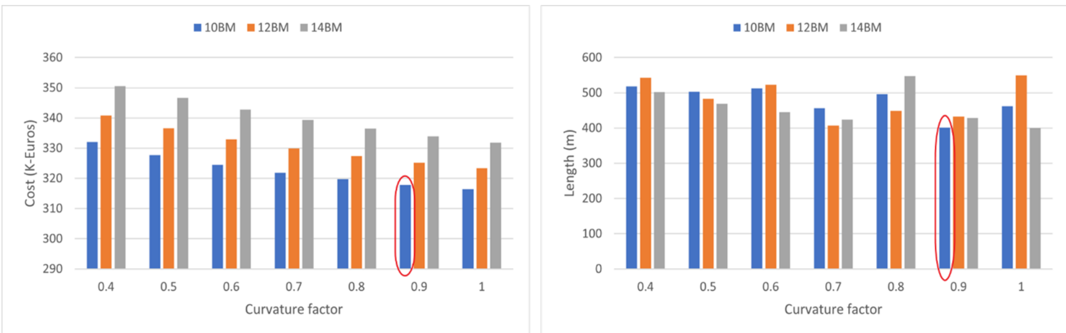

Figure 5. Far offset

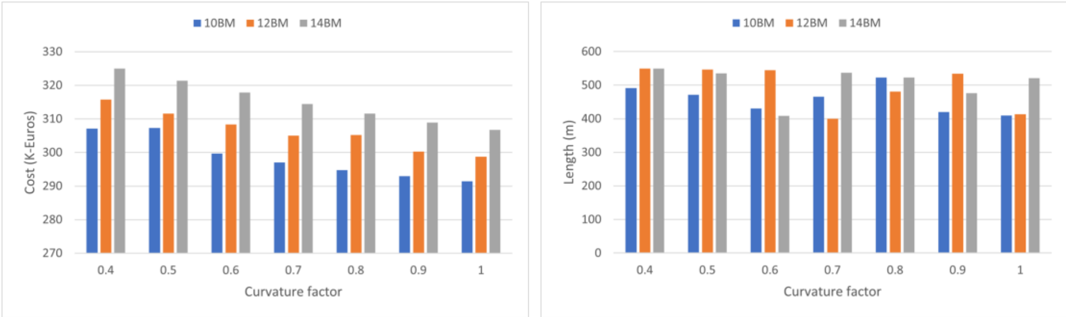

Figure 6. Near offset

Table 3. Lazy wave optimization results

Parameter	No offset		Near offset		Far offset	
	CF	$C_{aquisition}$	CF	$C_{aquisition}$	CF	$C_{aquisition}$
l_1	0.18	0.29	0.18	0.33	0.17	0.26
l_2	0.16	0.17	0.22	0.16	0.15	0.16
l_3	0.66	0.54	0.60	0.52	0.68	0.58
$\frac{l_{total}}{h}$	2.72	2.51	2.55	2.34	2.88	2.23
TF	0.10	0.17	0.10	0.17	0.10	0.14

The configurations optimized for each scenario are then subjected to the remaining two scenarios to observe its performance. It was observed that only four configurations from no offset scenario survived both Near and Far scenarios, and almost all the optimized configurations from the Far scenario performed well in the remaining two scenarios. No configuration from Near offset has failed to maintain
CF less than 1. The highlighted Dimensions in Table 3 are that of the best performing low cost ($C_{aquisition}$=317.88 K-Euros) configuration with an average TF of 0.14 and average CF of 0.575 in all three scenarios.

Figure 7 shows the best performing low-cost optimized configuration with 10 Buoyancy modules at all three scenarios (No offset, Near and Far). Figure 8 shows the comparison of Curvature and tension across the configuration arc length in these scenarios. These findings emphasize the resilience and versatility of configurations optimized for specific scenarios, particularly those tailored for the Far offset condition. The successful adaptation of these configurations across various scenarios underscores their effectiveness and potential robustness in different operational conditions. The ability to maintain acceptable curvature factors and Tension factors in Near, Far and No offset scenarios demonstrates the adaptability of the optimized configurations, contributing to their reliability in real-world offshore wind applications.

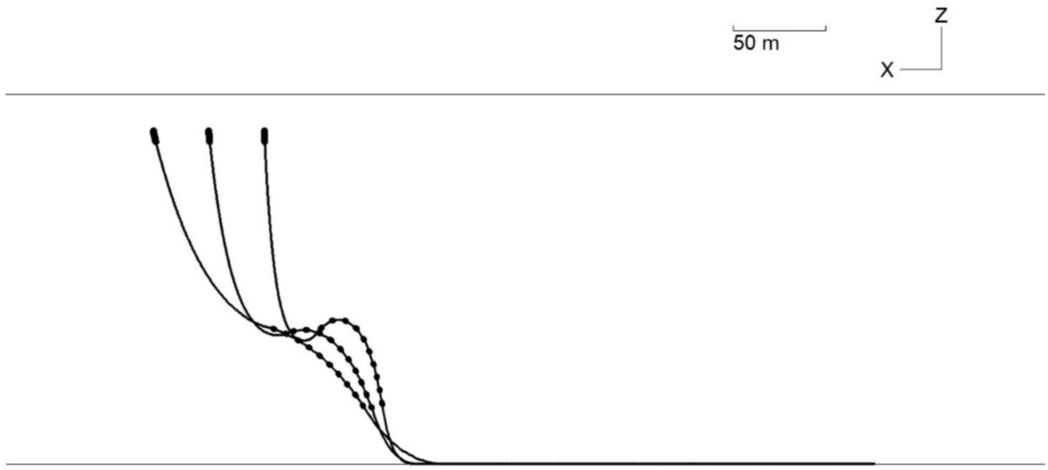

Figure 7. Optimized lazy wave configuration

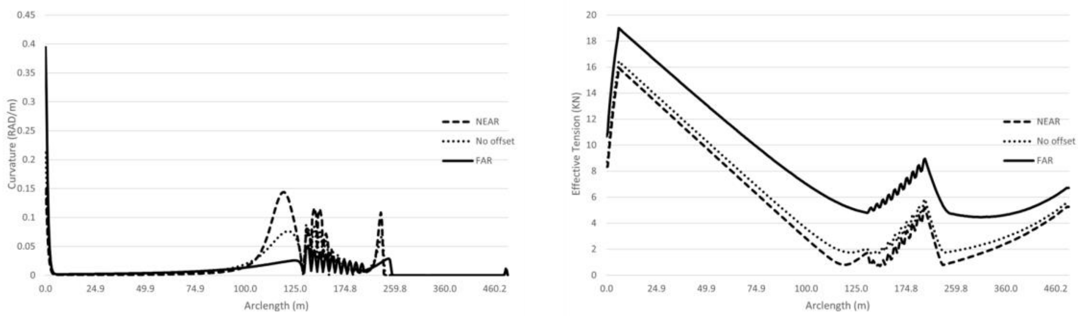

Figure 8. Curvature and Effective tension of best configuration

5. Conclusions & Discussion

The optimization study of dynamic able lazy wave configurations performed provides valuable insights into achieving a balance between cost and performance. The clear correlation between cost and curvature factor underscores the complexity of designing dynamic cable systems.

Configurations with lower curvature factors tended to incur higher costs, emphasizing the trade-off in meeting operational conditions. The survivability analysis across different scenarios revealed the robustness of configurations optimized for the Far and No offset scenarios. Notably configurations developed for Far configurations demonstrated consistent performance across all scenarios. Configurations optimized for the Near offset conditions failed to maintain curvature factors below the acceptable threshold in the remaining two scenarios. The best-performing low-cost configuration, with ten buoyancy modules, showcased adaptability and efficiency in all scenarios, achieving average tension factors of 0.14 and an average curvature factor of 0.575. The findings highlight the importance of considering the impact of curvature factor and tension factors on the cost-effectiveness of cable configurations.

This research informs the design process for dynamic cables, emphasizing the need for a comprehensive understanding of the trade-offs involved. The optimization methodology, integrating COBYLA algorithm and MDAO framework, proves effective ion navigating the design spaces and arriving at configurations that meet both operational and economic constraints. While this optimization is based only on static analysis, a natural extension involves subjecting the optimized configurations to dynamic simulations. Which could offer a more comprehensive understanding of how these configurations perform under real-world operational conditions, considering factors such as wave-induced motions, dynamic loading, and response to environmental variations. Expanding the study to encompass a broader range of environmental loads and diverse offshore sites would contribute to a more robust and versatile set of optimized configurations. Moreover, future optimization efforts could introduce additional design variables to the model. For instance, anchor positions and cable diameters could further refine the optimization process.

Acknowledgements

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