STRESS ENGINEERING SERVICES INC.

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Modular Group Helical Pile Anchor

Structural Analysis

Prepared for:
Triton Anchor, LLC

27 February 2026

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Post Access Report

Modular Group Helical Pile Anchor Structural Analysis

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Date: February 27, 2026

EXECUTIVE SUMMARY

The Modular Group Helical Pile Anchor Structural Analysis project aimed to evaluate and optimize the anchor's structural performance, fatigue resistance, and load distribution through finite element analysis (FEA) and advanced computational modeling. The study covered finite element modeling, static load assessment, fatigue analysis, and optimization to enhance the anchor's performance under operational loads.

Key Findings

- The p-y Spring Model was identified as the most effective soil-structure interaction model, offering computational efficiency and accurate stress distribution.
- The initial anchor design exhibited excessive peak stresses (42 ksi) and failed fatigue criteria, exceeding DNV allowable limits by 300 times, primarily due to high-frequency, high-load cyclic events in the load spectrum considered.
- Optimization efforts successfully reduced peak stress by 67% (to 14 ksi), reduced stress range by 40% and hence reduced fatigue damage by 78%, yet fatigue damage remained 80 times above allowable limits.
- The optimization determined that the minimal stress solution located the helical pile ring closer to the skirt. Additionally, the openings in the top of the template were shown to have little impact on the stress.
- A dual-anchor ring concept was evaluated, revealing that the inner ring carried most of the load, indicating the need for further optimization to balance load distribution.

Lessons Learned

- Early selection of the appropriate soil-structure interaction model is critical to avoid unnecessary modeling iterations.
- Computational efficiency should be prioritized, as switching from continuum soil models to p-y springs significantly reduced processing time.
- Fatigue life assessment should be integrated from the beginning of the design process, and loading spectra should be refined through collaboration with load definition teams to ensure realistic conditions.
- The Design of Experiments (DOE) approach was highly effective, but future projects could focus directly on eliminating low-impact variables to streamline optimization.

Recommendations for Future Work

- Further fatigue optimization and load spectrum refinement to mitigate high-cycle loads and reduce fatigue damage.
- Additional studies on dual-anchor ring load balancing to optimize load-sharing efficiency.
- Laboratory testing and field validation of a prototype to compare real-world performance with simulation predictions.
- Enhanced computational efficiency, including potential integration of machine learning techniques for accelerated optimization.

Conclusion

The project successfully developed and optimized anchor design for minimal stress performance; however, fatigue challenges remain unresolved due to the prescribed high-frequency load spectrum. While significant improvements (67% reduction in peak stress, 40% reduction in stress range, and hence

78% reduction in fatigue damage) were achieved, further design effort should be undertaken to develop an anchor that satisfies the fatigue life requirements. The insights gained from this study will guide future research in helical pile anchor design, fatigue resistance improvements, and soil modeling advancements.

1 INTRODUCTION TO THE PROJECT

Triton Anchor's mission is lowering the levelized cost of energy (LCOE) for the marine renewable energy (MRE) industry by focusing on one of the costliest portions of offshore field development, anchoring. Triton Anchor's collaboration with Stress Engineering Services (SES) is focused on providing cost-effective anchoring solutions for the MRE industry unlike anything in the market. This solution is aimed at optimizing the design structure of Triton's anchoring system to minimize material and manufacturing costs while effectively increasing the holding capacity per unit weight. SES with its nearly 50 years of experience in offshore Finite Element Analysis (FEA), will provide structural numerical capabilities to analyze the anchor beam members under realistic MRE loading scenarios to lower the total steel weight of the anchor without minimizing its capacity.

2 ROLES AND RESPONSIBILITIES OF PROJECT PARTICIPANTS

2.1 APPLICANT RESPONSIBILITIES AND TASKS PERFORMED

Triton Anchor Team:

Triton Anchor will guide the direction of the modeling, design, and analysis to an overall goal of de-risking the anchor technology with proven, tested structural design methods. The Triton Anchor team, including but not limited to those listed below, will provide the analysis geometry and design space, ensuring the continued research and analysis is in line with the needs of MRE industry, including modularity and manufacturability.

At the time of executing the project:

Nathan Krohn was Triton Anchor's Installation Operations Manager and was the Principal Investigator of this program. He was Triton Anchor's point of contact supervising the work.

Zachary Miller was Triton Anchor's CTO and was the Project Manager of this program.

Michael Davis was a Structural Engineer with Triton Anchor and was a supporting member of this program.

2.2 NETWORK FACILITY RESPONSIBILITIES AND TASKS PERFORMED

Stress Engineering Services Team:

Stress Engineering Services, Inc. (SES) will be responsible for:

- Building the finite element model from geometry provided by Triton Anchor
- Executing finite element analysis for load conditions provided by Triton Anchor

- Performing fatigue analysis, including executing the associated finite element analysis for the load spectrum provided by Triton Anchor
- Leading the optimization process. For this, SES will work closely with Triton Anchor to:
  - Review the design space provided by Triton (i.e., the design variables and constraints)
  - Define the objective function for the optimization
  - Perform optimization analysis
- Implementing the optimized structure on a larger scale anchor with more than one ring of helical piles and quantifying the load transfer between them.

At the time of executing the project:

Ryan Williams was an Associate II and performed the FEA and optimization work.

William Walker was a Senior Associate and was the Project Manager of this project within Stress Engineering Services.

Carlos Lopez was a Senior Associate and served as a consultant and technical reviewer for this work.

3 PROJECT OBJECTIVES

Currently, mooring represents one of the costliest factors of field development due to the excessive size and material usage of traditional anchors (steel and concrete) as well as their installation methodologies. Unfortunately, these antiquated anchor technologies make up the majority of the market due to their decades of proven use and the lack of new and tested innovative anchors. Known to developers and regulators, traditional anchors often lead to complicated permitting challenges due to their harmful installation impacts to marine life and their inability to be decommissioned. The MRE industry is looking for an alternative solution that is cost effective, quicker to procure, and is not harmful to the environment or marine life.

As such, the impact of optimizing Triton's anchor option for the MRE industry is paramount to the industry's success and viability as a future means of energy. Triton's modular and silently installed helical anchor solution will make each MRE technology more feasible while mitigating negative environmental impacts.

To prove the anchor's economic impact to the industry, the objective of this research is to develop a scalable, less expensive, and more efficient anchor structure with less material and fabrication limitations through FEA structural optimization. This numerical analysis is crucial to understanding the complex loading path from the mooring connection to the soil through the anchor structure and engineering a more efficient structure.

The results of this numerical analysis will ultimately de-risk the anchor technology with a structural FEA-based optimization for anchor solutions.

The goal of this project is to analyze and optimize an efficient, cost-effective anchor for MRE applications. To this end, these anchors need to be easily manufactured with effective use of materials to keep costs down while also having good strength and fatigue properties to ensure a reliable solution for a long

operational life. The Triton Anchor design consists of a template and skirt arrangement with a circle of helical piles installed through the template. In addition, there is a pad eye in the center of the template for a connection to the mooring line.
This study will investigate:

- The strength and fatigue performance of the baseline anchor design for expected environmental conditions (i.e., loads, soil properties, water depth, etc.).
- The optimal design parameters (i.e., skirt diameter, skirt wall thickness, template wall thickness, helical pile arrangement) for a range of expected environmental conditions (clay/sand soil, mooring load spectra, etc.)
- The load transfer between piles for a larger design

As stated above, the overall goal of the optimization is to reduce LCOE with a cost-effective anchor solution. There are numerous ways to optimize a design; a design of experiments methodology will be used for this project. This creates a significant opportunity to investigate multiple objective functions since the FEA cases will have mapped the design space. As a result, the team will assess multiple objectives which include, but is not necessarily limited to:

- Minimizing weight and therefore capital expenditure (CAPEX),
- Maximizing strength to weight ratio,
- Maximizing fatigue life to weight ratio,
- Minimizing surface area exposed to corrosive environment.

Triton’s anchor design can utilize a wide range of structural members to provide the required levels of integrity and capacity for varying mooring and soil loads. During this program, SES will investigate the use of different structural design configurations that Triton has proposed. This may include the use of I-Beams, hollow or solid square and round tubing, channels, plates, and various connection methodologies such as welded and bolted connections.

The goal of this work is to find the benefit of an optimal solution (e.g., minimized weight, minimized LCOE, maximized fatigue life) for the design space and objective function considered under the given design constraints and conditions. As a result, showing a significant change in key metrics such as reduction in LCOE, reduction in weight or increase in fatigue life would be a successful project. By optimizing, this project will assess the biggest increase (or decreases) in these metrics, rather than attempting to achieve a specific target value.

4 TEST FACILITY, EQUIPMENT, SOFTWARE, AND TECHNICAL EXPERTISE

Stress Engineering Services, Inc. is uniquely capable of performing structural analysis of offshore components due to our decades of experience in providing technical engineering solutions to the offshore industry. Our team of expert engineers routinely analyze the strength and fatigue performance of structures such as floaters, mooring lines, risers, subsea equipment, and piles when subjected to actual environmental loads from wind, waves, and currents.

To perform these assessments, SES utilizes various industry-standard software packages, often including Abaqus, ANSYS Mechanical/Fluent, OrcaFlex, and MATLAB, along with in-house developed software such as RAMS, DERP, NeoSight, and others. To achieve the objectives of this project, SES expects to use ANSYS Mechanical and the MATLAB Statistics and Machine Learning Toolbox to analyze the anchor structural performance and perform parameter optimization respectively.

SES uses both on-premises and cloud computing hardware in the execution of numerical simulations depending on the needs of the analysis. Based on the expected model size and number of runs, SES expects to use our on-premises resources for both structural analysis and optimization. The on-premise cluster that will be used is an Intel Xeon Gold 6152 processor with 44 cores and 250 GB of usable RAM. SES has several other clusters that may be used if required. The expected run time for the structural analysis and optimization is on the order of several hours to several days.

The key SES personnel are well qualified to support this project. A brief description of background and experience for each personnel who worked on this project is listed below.

William Walker, PhD

Dr. Walker had 11 years with Stress Engineering Services, Inc. at the time of this project, and his Specific experience included:

- Simulation and global analysis of floating structures, moorings, and riser systems
- Finite Element Analysis
- Fatigue analysis using S-N fatigue and Linear Elastic Fracture Mechanics (LEFM)
- Asset life assessment and design life extension
- Frequency domain and time domain analysis
- Programming and code development (MATLAB, Python, Fortran)
- Numerical optimization for constrained and unconstrained systems
- Development of remote monitoring systems for asset integrity management
- Project management

Ryan Williams, PE

Mr. Williams had almost 2 years with Stress Engineering Services, Inc. at the time of this project, and his specific experience included:

- Finite Element Analysis to predict stress, dynamic behavior, and vibration.
- System design, manufacturing planning, and maintaining system components.
- Structural optimization
- Designing cryogenic propellant feedline systems for rocket engines.
- Developing and implementing remote monitoring systems.
- Utilizing data analysis, pattern recognition, and machine learning techniques.
- Conducting research and developing methodologies for equipment condition monitoring and performance optimization.
- Employing numerical analysis and data-driven modeling using sensor field data (digital twinning).

- Utilizing statistical analysis and machine learning for mechanical equipment diagnostics and prognostics.
- Designing and validating high-pressure, high-temperature (20ksi-400°F) subsea oil and gas production systems.

Carlos Lopez, PE

Mr. Lopez had 8 years with Stress Engineering Services, Inc. at the time of this project, and his specific experience included:

- Computational fluid dynamics (CFD) analysis of various systems including battery thermal management systems, offshore components, process equipment/reactors, and test apparatus
- Heat transfer analysis of exchangers, riser systems, wellheads, and pipeline systems
- Thermal safety, performance testing, design, and analysis of lithium-ion batteries
- Full and sub-scale destructive testing andFEA of pipeline systems
- Coupled CFD/FEA and conjugate heat transfer analysis of various components
- Fully coupled global structural and fatigue analysis of riser systems and subsea equipment in frequency and time domain

5 TEST OR ANALYSIS ARTICLE DESCRIPTION

Triton Anchor's system is intended to provide a better, lower cost anchoring solution for marine energy technologies. MRE technologies present particular challenges compared to other energy developers due to their commonplace in areas without vast supporting maritime and industrial infrastructure. Although commonly smaller in size and displacement than floating wind turbines and oil and gas platforms, they still require a vast network of subsea infrastructure able of withstanding harsh environments for long service lifespans. Specifically, they require a robust high-capacity anchoring system that is cost effective and able to be procured locally to the area of deployment.

The anchor system being analyzed in this program, shown below in Figure 1, requires structural optimizations with these key factors considered to enable more developments of MRE units.

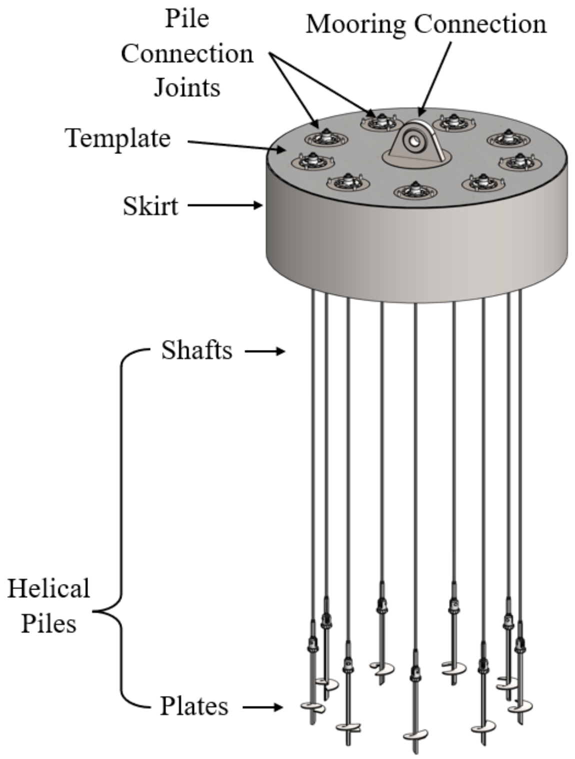


Figure 1: Triton Anchor Diagram

As shown above, the Triton Anchor is comprised of helical piles connected to the anchor skirt through the template. Each helical pile is comprised of a solid shaft and a lead section with single or multiple helical plates (helices). The template connects to and distributes the mooring load to the anchor components. The amount, length, and diameter of helical piles as well as the dimensions of the skirt and template can be scaled to provide a solution for any size MRE technology with any type of mooring system.
Due to all of these variables, the structural design of the template is complicated and requires detailed analysis and engineering evaluation.

The work to be performed in this study will advance floating marine renewable energy technologies such as wave energy converters, floating solar arrays and floating wind farms by providing an economical anchoring solution. Triton has developed a unique concept that shows promise in being a low-cost solution for MRE applications, particularly in the scalability, which makes it easily adaptable for any MRE application. This project will build upon this by utilizing a design space that can be used to generate an optimal design for wide range of environmental and site-specific conditions. In addition, the analysis and optimization performed in this project will result in an understanding of anchor optimization that has been verified for realistic environmental and loading conditions.

6 WORK PLAN

6.1 NUMERICAL MODEL DESCRIPTION

The numerical model used for this study will be a linear-elastic finite element model constructed for the Triton anchor using ANSYS Mechanical version 19.2. The finite element model will have generalized parameterized geometry features for the anchor as well as parameterized material properties for the soil conditions.

A baseline finite element model (FEM) will be generated based on the existing anchor concept in Task 1. This model will most likely include shell elements representative of the skirt and template, solid elements for the pad eye, and beam elements for the helical pile shafts. The static FEA performed in Task 2 will evaluate several different soil modeling methodologies, with one outcome of this task being a decision on the specific soil modeling method to proceed with for the remaining tasks in the project. ANSYS has multiple built-in continuum geomechanical models for modeling soil behavior. When a continuum soil model approach is used, the helical pile plates will be included and modeled as solids or shells. As a simplification, soil will also be modeled using P-Y/T-Z springs. When this soil modeling method is used, the helical pile plates will not be modeled discretely and instead their effect will be captured as additional T-Z resistance. Once a soil model methodology is chosen, multiple soil types will be simulated.

After establishing baseline anchor performance, a computational design of experiments will be conducted by perturbing predetermined geometric and material parameters in the finite element model. The perturbation inputs and measured output responses of interest will be compiled into a table, which will be used for statistical optimization outside of the finite element model. After performing the statistical optimization, the chosen design parameters will be implemented back into the finite element model for a final validation analysis, ensuring the reliability of the optimized Triton anchor configuration.

It should be noted that the optimization for the baseline case is performed within a finite domain (i.e., finite bounds). Different anchor sizes would have a different domain (different bounds); however, the optimization process and design space mapping procedures would be the same, regardless of the scale of the anchor. One key benefit of this work is to develop an understanding of optimization (i.e., the objective function, the parameterization of the design being optimized, constraints, etc.). Once these have been developed and the design space mapping has been defined, developing an optimized design is execution of the process for the specified loading conditions. It is possible that, for significantly larger or smaller anchors, it may be desirable to consider a different configuration for scaled up anchors, and this will be studied in Task 5.

6.2 TEST AND ANALYSIS MATRIX AND SCHEDULE

The table, comprising of geometric inputs for the anchor design as well as soil properties, will be combined with the output responses from the ANSYS mechanical simulations. This integrated data will undergo statistical analysis in MATLAB utilizing the Machine Learning and Statistics toolbox. The analyses in MATLAB will correlate the inputs to the output responses, evaluating the influence of each input on a specific response. Additionally, the statistical analyses will create a general map of the design space, interpolating intermediate cases not directly simulated in ANSYS.

This study requires 5 different tasks:

1. Build the Finite Element Model
2. Perform Static Structural Analyses
3. Perform Fatigue Analyses
4. Improvement Through Optimization
5. Characterization of Load Transfer Between Piles for Larger Anchor Design

Tasks 1 – 3 are intended to be an assessment of the baseline anchor design. In Task 1, the finite element model will be built, and in Task 2 the static FEA will be performed for several soil model types. ANSYS Mechanical includes several geomechanical models that simulate the structure/soil interaction and deformation of the soils under load. These models include:

- Cam-Clay
- Drucker-Prager
- Jointed Rock
- Mohr-Coulomb
- Porous Elasticity
- Menetrey-William

One goal of Task 2 is to identify the appropriate soil modeling technique to proceed with in the optimization and load transfer characterization studies (Tasks 5). The suitability of each model depends on the type of soil being modeled.

For typical offshore anchor installations, the Cam-Clay, Mohr-Coulomb, and Porous Elasticity models are the most applicable and commonly used. Each model has several input parameters that define the structural properties of the soil. These parameters include density, Poisson's ratio, uniaxial/biaxial compressive and tensile strength, shear strength, friction, cohesion, and others. Typical ranges of each of these parameters can often be found in open literature, however, these data may be difficult to locate on a location-specific basis. Should soil suitable data not be available, the P-Y/T-Z soil modeling approach may be selected for the optimization runs. Each of the soil models have benefits and limitations. For example, if the piles are too close together, the P-Y/T-Z model will not capture the grouping effect on pile response. API RP 2GEO and geotechnical references such as "Dynamics of Fixed Marine Structures" by Barltrop and Adams include discussion of the minimum pile spacing for which grouping does not have an effect, typically 8x the pile diameter. The soil modeling approach will be explored in Task 2 with the case matrix shown below for the baseline configuration.

Case #	Soil Model	Soil Type	Soil Stiffness	Sliding Allowed
1	Cam-Clay	Clay	Upper-Bound Stiffness (Stiff)	Yes
2		Clay	Lower-Bound Stiffness (Soft)	Yes
3	Mohr-Coulomb	Clay	Upper-Bound Stiffness (Stiff)	Yes
4		Clay	Lower-Bound Stiffness (Soft)	Yes
5	Porous Elasticity	Clay	Upper-Bound Stiffness (Stiff)	Yes
6		Clay	Lower-Bound Stiffness (Soft)	Yes
7	P-Y/T-Z Springs	Clay	Upper-Bound Stiffness (Stiff)	Yes
8		Clay	Lower-Bound Stiffness (Soft)	Yes

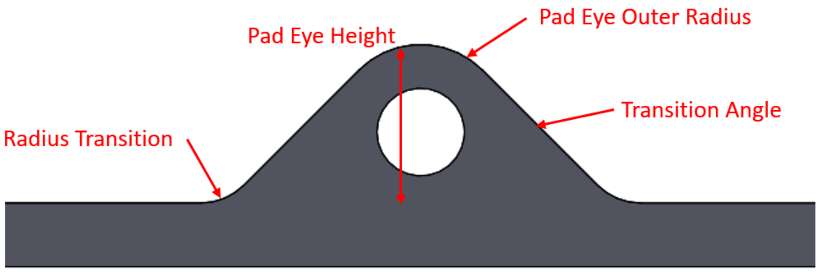
The Fatigue analysis in Task 3 will be performed for the cases with the soil model selected for the optimization. Triton will supply an expected fatigue spectrum (i.e., load magnitude/direction and number of cycles at each load) to be considered.

The anchor optimization will be performed in Task 4. For this task, a methodical approach will be established to validate the optimized Triton anchor configuration using the Box-Behnken experimental design methodology. The statistical experimental design technique systematically explores the effects of multiple variables with fewer experimental runs, optimizing the use of resources. The Box-Behnken design will be employed to conduct a series of finite element analyses. Through this systematic process, geometric features of the Triton anchor will be driven to create ideal or optimized system responses, such as increased strength, reduced peak stresses, and reduced weight. The parameterized inputs that will be analyzed may include, but are not limited to, the following:

- Skirt Thickness
- Skirt Diameter
- Skirt Length
- Top Plate Thickness
- Number of Helical Piles
- Helical Pile Bolt Circle Diameter
- Soil Properties (Up to 3 Sets of Soil Properties)
- Pad Eye Geometry (Optimized Separately from the Other Inputs)

The statistical analyses in MATLAB will involve studying a set of finite element simulation cases. These cases will cover the perturbations of the seven design inputs, including geometric factors and soil properties. By examining this dataset, valuable insight can be gained into how the inputs affect the anchor system's responses. This detailed analysis ensures a comprehensive evaluation of the anchor design and aids in making well-informed decisions for optimal modifications.

The optimization process mentioned above focuses on optimizing the primary structural configuration. However, there is also value in optimizing the pad eye connection separately. Performing a distinct optimization on the anchor pad eye is necessary to distinguish significant geometry changes in the overall anchor design from the relatively smaller geometry changes specific to the pad eye. This separation allows for a more precise and effective optimization approach.



An example of a case matrix used for pad eye design of experiments is shown below:

Case Run	Radius Transition	Transition Angle	Pad Eye Height	Pad Eye Outer Radius
1	Mid	Mid	Mid	Mid
2	Low	Low	Mid	Mid
3	Low	High	Mid	Mid
4	High	Low	Mid	Mid
5	High	High	Mid	Mid
6	Mid	Mid	Low	Low
7	Mid	Mid	Low	High
8	Mid	Mid	High	Low
9	Mid	Mid	High	High
10	Low	Mid	Mid	Low
11	Low	Mid	Mid	High
12	High	Mid	Mid	Low
13	High	Mid	Mid	High
14	Mid	Low	Low	Mid
15	Mid	High	Low	Mid
16	Mid	Low	High	Mid
17	Mid	High	High	Mid
18	Low	Mid	Mid	Low
19	Low	Mid	Mid	High
20	High	Mid	Mid	Low
21	High	Mid	Mid	High
22	Mid	Mid	Low	Low
23	Mid	Mid	Low	High
24	Mid	Mid	High	Low
25	Mid	Mid	High	High

6.3 SAFETY

This project is purely an analysis project. As a result, there are no laboratory or job site hazards that result in significant safety risks for the project. For the office environment it is always good to do the following:

- Take breaks during the workday.
- Be cognizant of surrounds and footings to prevent slips, trips and fall, especially on stairwells.
- Ensure adequate sleep.

Per company HSE requirements, employees shall not

- Work more than 16 hours in a 24-hour period
- Be under the influence of drug or alcohol in the workplace.

6.4 CONTINGENCY PLANS

6.4.1 Adjusted Testing and Schedule

In the event that a portion of the analyses reveal additional required investigation or less, the test plan can be adjusted. This is planned for by allowing for flexibility in the schedule. Additionally, this will be continuously addressed by conducting routine team meetings to discuss findings and determine the best path forward to sufficiently address each technical objective.

6.4.2 Resource Availability

Triton and SES have identified the key personnel that will manage and perform the testing and analyses outlined in this test plan. In the event that a resource is changed or added to the team, the project will continue as planned based on technical objective priorities.

6.4.3 Analysis Methodology Changes

In the event SES encounters analytical challenges with the selected soil modeling method such as converge issues or unrealistic results, the following mitigations will be considered:

- Changing soil modeling methodologies
- Changing mesh or element types

The analyses considered in Task 2 are intended to identify any analysis challenges and address them before moving on to the fatigue analysis and optimization.

6.5 DATA MANAGEMENT, PROCESSING, AND ANALYSIS

6.5.1 Data Management

Simulation data will be generated and stored on the on-premises compute cluster with regular daily backups. Reduced analysis outputs will be transferred to SES's project redundant storage repository for post-processing. Upon completion of and as necessary during the analysis, selected simulation data will be backed up to long-team archive storage. Archived files typically consist of only the files necessary to reproduce the results but not analysis outputs themselves.

Upon completion of the analysis tasks, a summarized final report will be submitted to the Marine Hydrokinetic Data Repository (MHK DR) and Triton. The material in this report can assist others to run similar analyses and optimizations provided they have ANSYS and MATLAB with the Statistics and Machine Learning toolbox. The results will be documented in tables, figures, and graphs, which will be included in the final research report (i.e., the Post Access Report). The data will be made available to other researchers upon request, subject to any restrictions or limitations imposed by confidentiality agreements or other legal considerations. These will be made available to Triton and TEAMER using any mutually agreeable platform.

6.5.2 Data Processing

In a FEA, verifying simulation accuracy is vital. Engineers use different methods like mesh refinement and comparing results to empirical data or analytical solutions. For this finite element analyses used for the anchor optimization, simplified load cases will be used to compare analysis results to empirical data or analytical solutions in order to verify the simulation accuracy.

The main method of correlating the inputs to outputs from the finite element analysis is going to be statistical regression. In statistical regression, modelling errors are assessed by examining residuals, or differences between observed (finite element responses) and predicted values (regression results). Well established metrics such as Coefficient of Determination (R^2), residual p-values, and Root-Mean-Square-Error (RMSE) are often used to evaluate error in a statistical model and verify accuracy.

6.5.3 Data Analysis

There are multiple data analysis and post processing algorithms that will be used for this project. The data generated through analysis in Task 2, which is static structural FEA of the baseline anchor configuration, will be presented graphically to show von Mises stress and strain. Stress utilization will be calculated from the peak stresses and reported in a tabular form. The aforementioned figures, calculations, and tables will be shown for each case in the Task 2 case matrix.

Task 3, the fatigue analysis, will be assessed using the “hot-spot method” per DNV-RP-C203 with the appropriate S-N curve. This method uses FEA to determine stress concentrations due to hot spots (regions of high cyclic stress) and fatigue damage is calculated using the Palmgren-Miner rule.

To summarize this analysis process, an FEA will be performed for a load spectrum provided by Triton Anchor. This spectrum will contain a set of bins with mooring line tension amplitude, direction applied, and the number of cycles expected to occur over a specified time period. A static FEA will be performed for three of the bins and the stresses at each hot-spot will be identified. A stress concentration factor (SCF) for each hot-spot will be calculated based on a reference point (e.g., the base of the top pad eye). The three bins that will be used to determine the stress concentration factors will have sufficiently different loading (i.e., a small load, a high load, and median load).

Note, the use of only three fatigue bins to determine the SCF is assumed to be sufficient since it is not expected that there will be significant variance in SCF from bin to bin. However, if the FEA of the three bins shows a significant variance in the calculated SCF, then it may be required to perform FEA for all bins. Should it be required to analyze each bin, it is not expected to add significant effort, mainly computer time and post processing time. Once the stress spectrum has been assessed the fatigue damage will be calculated using the Palmgren-Miner rule:

$$D = \frac{1}{\bar{a}} \sum_{i=1}^{k} n_i (\Delta\sigma_i * SCF)^m$$

where D is the damage, $\bar{a}$ is the intercept of the S-N curve, m is the slope of the S-N curve, n_i is the number of cycles for a stress bin, $\Delta\sigma_i$ is the stress range, SCF is the stress concentration factor, and k is the number of bins in the spectrum.

Task 4 is the optimization which will utilize the Design of Experiments methodology, as described in Section 6.5.2. The main method of correlating the inputs to outputs from the FEA is going to be statistical regression. In statistical regression, modelling errors are assessed by examining residuals, or differences between observed (finite element responses) and predicted values (regression results). Well established metrics such as Coefficient of Determination (R^2), residual p-values, and Root-Mean-Square-Error (RMSE) are often used to evaluate error in a statistical model and verify accuracy.

For the optimization task, the regression models form the FEA will be used to construct object functions and used to determine inputs that will result in the optimal responses, be it minimized mass or peak stress, or increased anchor strength etc.

7 PROJECT OUTCOMES

Helical pile anchors (Figure 2) are widely used in offshore and subsea applications due to their high holding capacity and ease of installation. These anchors are essential components in mooring systems, renewable energy structures, and offshore oil and gas platforms, where they secure floating structures to the seabed, preventing displacement caused by ocean currents, wind forces, and wave action.

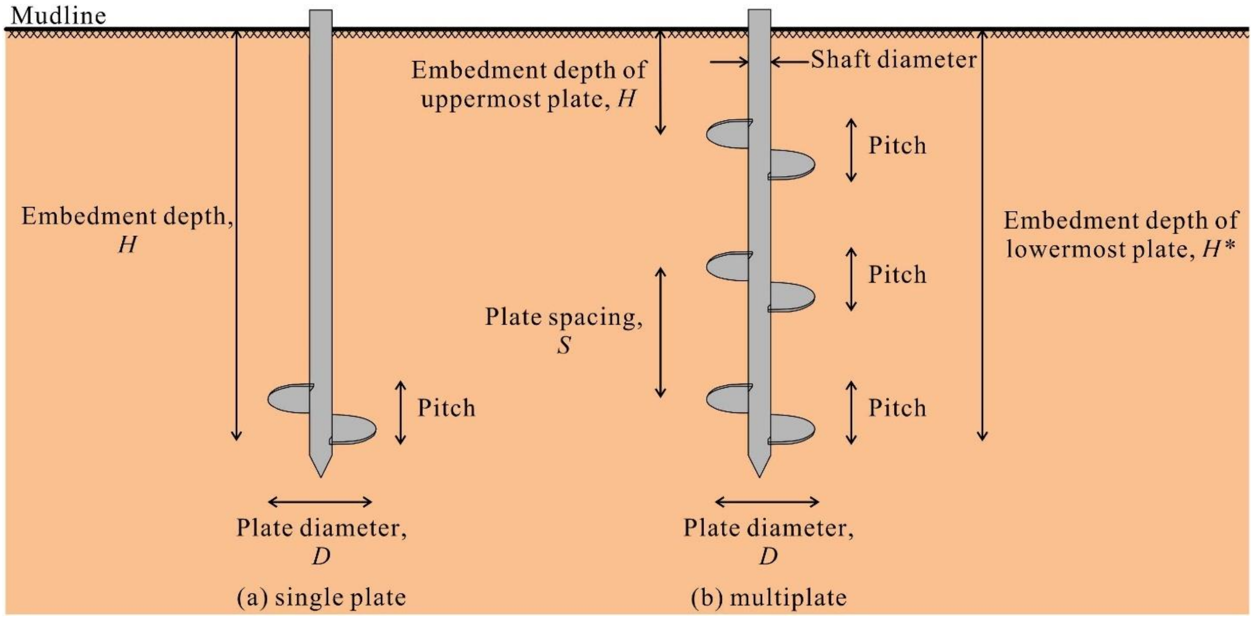


Figure 2: Helical Pile Anchor Example (https://cdnsciencepub.com/doi/10.1139/cgj-2023-0331)

The performance of helical pile anchors depends on several critical factors, including soil conditions, structural integrity, and resistance to cyclic loading. Traditional anchor designs often face challenges such as:

- Excessive stress concentrations can lead to structural failure.
- Complex soil-structure interactions, affecting anchor stability and load distribution.
- Fatigue failures due to high-frequency cyclic loads, which reduce the operational lifespan of the anchor.

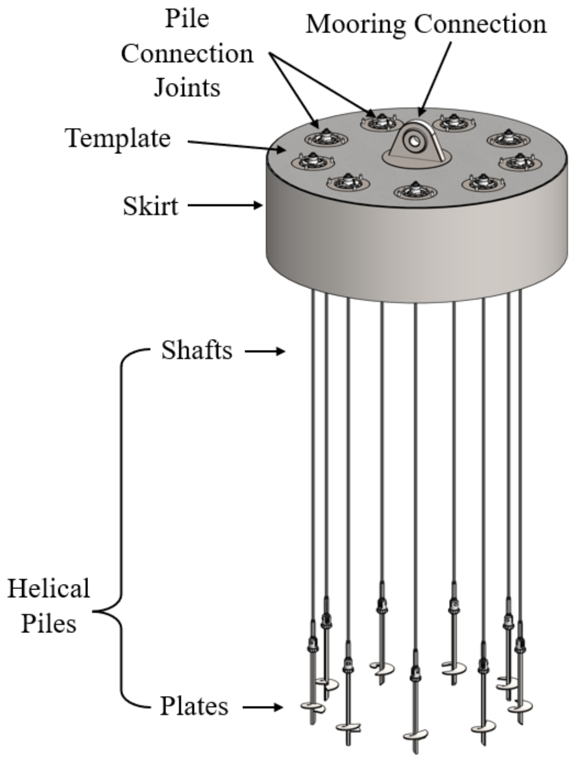


Figure 3: Modular Group Helical Pile Anchor

Given the repeated exposure of these structures to cyclic forces, ensuring long-term durability and reliability is essential. This project was undertaken to evaluate, optimize, and enhance the structural performance of a Modular Group Helical Pile Anchor (see Figure 3). The study focused on four key areas:

- Stress Distribution: Identifying and mitigating peak stress locations to improve overall structural integrity.
- Soil-Structure Interaction: Evaluating different soil modeling techniques to determine the most effective method for anchor-soil engagement.
- Fatigue Resistance: Assessing fatigue performance under cyclic loading to ensure long-term operational reliability.
- Optimization of Anchor Geometry: Adjusting key geometric parameters to enhance anchor performance while maintaining material efficiency.

To address these objectives, the study employed FEA and Fatigue Analysis based on DNV-RP-C203 guidelines to assess and refine anchor performance. Additionally, Design of Experiments (DOE) techniques were used to systematically improve the anchor’s geometry, reducing peak stresses and improving fatigue life.

Helical pile anchors have advantages over traditional anchoring systems, such as driven piles, gravity-based anchors or suction anchors, which include:

- Ease of installation, eliminating the need for heavy offshore construction equipment.
- Less intrusive to the seabed, making them environmentally favorable.
- Less noise that impacts marine life during installation
- Capable of resisting high axial loads, providing high holding capacity in challenging marine conditions.

However, their structural integrity is directly influenced by several factors, including high-frequency cyclic loads, soil variability, and complex stress distributions. Offshore structures are constantly exposed to wave-induced forces, subjecting anchors to cyclic stress and making fatigue life a primary concern, as continuous loading can result in premature failure. Additionally, variations in seabed composition significantly impact anchor behavior, necessitating precise soil modeling techniques to accurately predict load response. Unstable or low-stiffness soils can further reduce anchor efficiency, compromising overall stability. Furthermore, structural components such as pad eyes, gussets, and weld seams often experience localized high-stress concentrations, which, if not properly optimized, can lead to structural failure. Addressing these challenges requires innovative engineering solutions to enhance durability and performance in offshore environments.

To overcome these limitations, this study adopted:

- FEA-based structural analysis to model stress distributions and fatigue performance.
- DNV-RP-C203-based fatigue assessment to evaluate cyclic loading effects on the anchor.
- DOE-driven optimization techniques to refine anchor geometry and improve durability.

The results of this study provide valuable insights into offshore mooring design, anchor fatigue mitigation, and advanced soil-structure modeling techniques.

7.1 TASK 1 FINITE ELEMENT ANALYSIS MODEL

For Task 1, an FEA model was built to assess stress distribution and deformation behavior.

Initial FEA was conducted using ANSYS Workbench, incorporating geometric, material, and loading conditions representative of real-world operational environments. The primary goals of the initial FEA were to:

- Identify stress concentrations in critical regions of the anchor.
- Evaluate load-bearing capacity under static and fatigue conditions.
    - Analyze different soil-structure interaction models to determine the best approach for predicting anchor behavior.

The model was then used in a multi-phase computational study, incorporating tasks 2-4 as described in Section 6.2.

7.1.1 FEA MODEL DEVELOPMENT & ASSUMPTIONS

A STEP file of the baseline anchor design, shown in Figure 4, was provided by Triton Anchor was used to develop the FEA model, incorporating a linear geometry (without non-linear stiffening) and a linear-elastic material model to simulate the structural response.

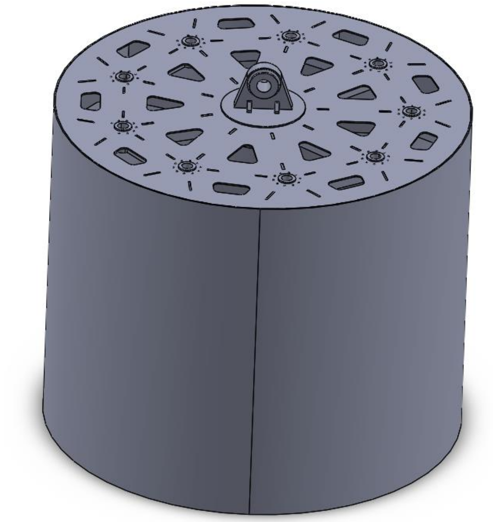


Figure 4: Geometry Provided by Triton Anchor

To ensure computational efficiency while maintaining accuracy, the following assumptions were applied:

- Helical piles were not explicitly modeled – Instead, beam elements with equivalent stiffness were used to simulate their behavior, see Appendix for pile stiffness calculation).
- Boundary conditions – The base of the anchor was assumed to be fully restrained to ensure firm seabed engagement, see Figure 5.
- Load application at the padeye – A vector load was applied as a bearing load to replicate real-world mooring forces, as supplied by Triton Anchor, see Table 1.
- Mesh convergence – A refined mesh was implemented in high-stress regions to ensure accurate results without excessive computational costs.
- Soil-structure interaction modeling (Task 2) – Multiple soil models were evaluated, with an emphasis on selecting a model that balanced accuracy and computational efficiency.

Table 1: Mooring Forces in FEA Model

Description	Angle from Horizontal	Load		
		Total	Horizontal	Vertical
[-]	[deg]	[kN]	[kN]	[kN]
Horizontal Driver	33.7	760	632	422
Vertical Driver	58.8	760	394	650
Max Peak of Both, Unfactored Design Case	45.8	907	632	650

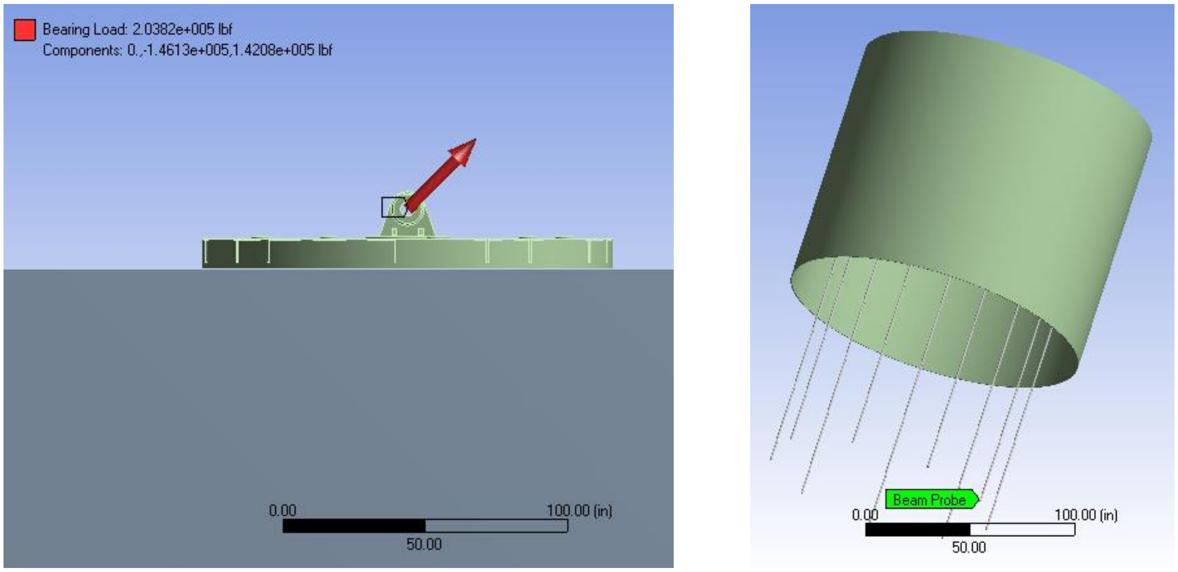


Figure 5: Loading and Beam Elements in FEA Model

7.2 Task 2 Soil-Structure Interaction Modeling

In Task 2, static load conditions were tested across different soil models to evaluate the anchor's structural response. Triton Anchor supplied soil properties for the analysis. The data provided reflects a dry sand, which is typically assumed to be cohesionless. Without the presence of some cohesion, there is little resistance to the applied force, creating significant convergence problems for the FEA solver. Some cohesion was required to achieve a converged solution, as shown in Table 2 below.

Table 2: Soil Properties Provided for Analysis

	Provided Soil Properties		Adjusted Soil Properties	
Unit Weight	109.42	lbf/ft^3	109.42	lbf/ft^3
Initial Inner Friction angle	52.30	deg	52.30	deg
Initial Cohesion	0	psi	1.45	psi
Dilatancy Angle	24.12	deg	24.12	deg
Residual Inner Friction Angle	0	deg	0	deg
Residual Cohesion	0	psi	0.45	psi

Multiple soil modeling techniques were considered in the test plan, including the Cam-Clay continuum model with porous elasticity, the Mohr-Coulomb continuum soil model, and a p-y Spring model. These models were evaluated using the provided soil properties. The Cam-Clay and porous elasticity models were deemed inappropriate due to the high lateral load relative to the skirt depth. The Mohr-Coulomb model initially struggled to support full horizontal (lateral) loads without requiring artificial cohesion adjustments for convergence. While it ultimately handled the loads successfully, it was computationally expensive. The p-y Spring model emerged as the model that most effectively balances computational effort and accuracy, yielding a maximum stress of 31.8 ksi compared to 50 ksi in the Mohr-Coulomb model (see Table 3). Figure 6 shows the equivalent stress contour from the initial FEA used to select the appropriate soil model. Based on these results, the p-y spring model was selected as the most suitable method for fatigue analysis and further optimization.

Table 3: Peak Stress Values for Soil Models

Load Case	Location	Mohr-Coulomb	p-y Springs	Cam-Clay	Porous Elasticity
Horizontal Driver	Top	37.4 ksi	25.5 ksi	N/A	N/A
	Skirt	0.7 ksi	13.9 ksi	N/A	N/A
Vertical Driver	Top	44.6 ksi	27.5 ksi	N/A	N/A
	Skirt	1.2 ksi	8.2 ksi	N/A	N/A
Max Peak of Both, Unfactored Design Case	Top	50 ksi	31.8 ksi	N/A	N/A
	Skirt	1.1 ksi	13.3 ksi	N/A	N/A

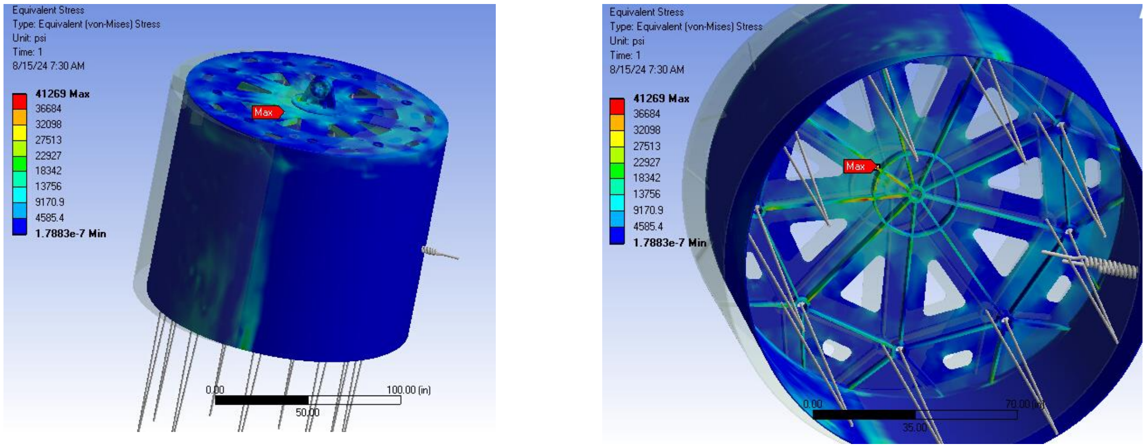


Figure 6: Equivalent Stress Contours from Initial FEA

7.2.1 KEY JUSTIFICATIONS FOR SELECTING THE P-Y SPRING MODEL

A critical aspect of this study was evaluating the effects of soil-structure interaction on anchor performance. The choice of soil model plays a crucial role in accurately predicting load distribution, displacement, and overall structural response. Four soil models were considered for this analysis:

- Mohr-Coulomb Model: Widely used for sandy and clayey soils, but it encountered convergence issues at low cohesion values. It required artificial cohesion adjustments, making it unsuitable for multi-step needed for fatigue analysis and optimization (Task 3 and Task 4).
- Cam-Clay Model: Primarily used for modeling clayey soils under high plastic deformation. However, it was unsuitable for the anchor’s lateral load conditions due to excessive deformation, compromising its reliability.
- Porous Elasticity Model: Designed for porous materials but lacked sufficient lateral stiffness to provide adequate anchor stability. It was not recommended due to its inability to capture realistic soil behavior under high lateral loads.
- p-y Spring Model: Based on API RP 2GEO recommendations for offshore foundation design, this model was the most computationally efficient. It provided realistic soil behavior with minimal convergence issues and allowed for rapid optimization iterations while accurately representing soil-structure interaction.

The p-y Spring Model, shown in FEA in Figure 7, was chosen due to its superior computational efficiency compared to continuum-based soil models. It provided accurate lateral resistance against anchor movement and enabled effective fatigue and optimization studies without excessive computational costs.

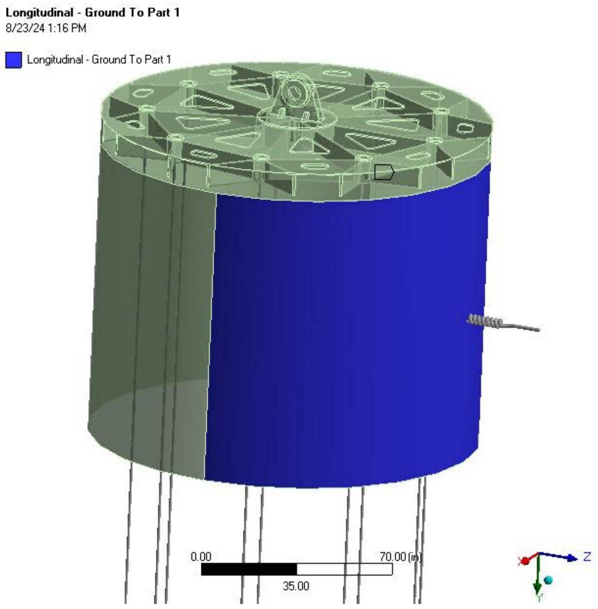


Figure 7: p-y Spring Element in ANSYS Model

7.3 TASK 3 FATIGUE ANALYSIS

The fatigue analysis in Task 3 was conducted using DNV-RP-C203 with the W3 Curve, focusing on stress concentration areas identified through FEA. Stress ranges were evaluated at two critical hotspots under four different loading conditions. Equivalent linearized stress was calculated through the selected hotspot regions, with membrane stress summed with 60% of the maximum bending stress to determine the peak stress value for fatigue calculations, in accordance with the approach described in DNV-RP-C203 for effective hotspot stress from FEA. Figure 8 shows an example of a hot spot linearization path.

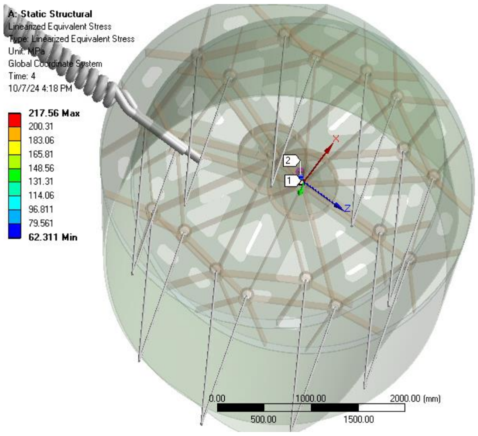


Figure 8: Hot Spot Linearization Path Example

Fatigue failure is a major concern in offshore structures, particularly for helical pile anchors, which experience repeated cyclic loading from ocean currents, wind, and wave action. Over time, these cyclic loads cause progressive material degradation, increasing the risk of structural failure—even when individual load cycles remain below the material's yield strength.

The results indicated significant fatigue failure in the baseline design, with cumulative fatigue damage exceeding 300 times the allowable limit. These findings confirmed that the anchor welds would fail under the given loading conditions, necessitating design modifications to improve fatigue performance.

7.3.1 OBJECTIVES OF THE FATIGUE ANALYSIS

The primary objectives of the fatigue analysis were to:

- Identify regions of high stress concentration that are most susceptible to fatigue failure.
- Evaluate the fatigue life of the anchor using DNV-RP-C203 (W3 Curve) criteria.
- Quantify cumulative fatigue damage and determine whether the current design meets offshore industry fatigue life requirements.
- Propose design modifications to improve fatigue resistance and extend the operational lifespan of the anchor.

7.3.2 FATIGUE ANALYSIS METHODOLOGY

The fatigue analysis was performed using FEA stress results in combination with DNV-RP-C203 fatigue assessment guidelines. The methodology consisted of the following steps:

- Identification of Stress Hotspots: Stress hotspots were identified using von Mises equivalent stress results from static FEA. The highest stress concentrations were observed in the gussets underneath the top plate, where weld seams will be present. These locations were selected for a detailed fatigue life assessment.
- Loading Conditions and Stress Extraction: The anchor was subjected to four different loading conditions: 20 kN, 300 kN, 600 kN, and 1000 kN. These loads were assumed to be at 45 degrees from the horizontal. For each load case, the maximum membrane and bending stress values were extracted from the high-stress regions through stress linearization. These stresses were then combined using the DNV-RP-C203 equation (maximum membrane stress + 60% of maximum bending stress).
- Fatigue Curve Selection: The W3 fatigue curve from DNV-RP-C203 (Figure 9) was selected, as it is suitable for welded joints with limited weld inspections. This approach provides a conservative estimate of fatigue life by accounting for uncertainties in weld quality and load variations.
- Fatigue Damage Calculation: The Palmgren-Miner rule was used to compute cumulative fatigue damage based on the applied load spectrum. The number of allowable cycles at each stress range was determined using the W3 curve, and the total damage from all load cycles was calculated.

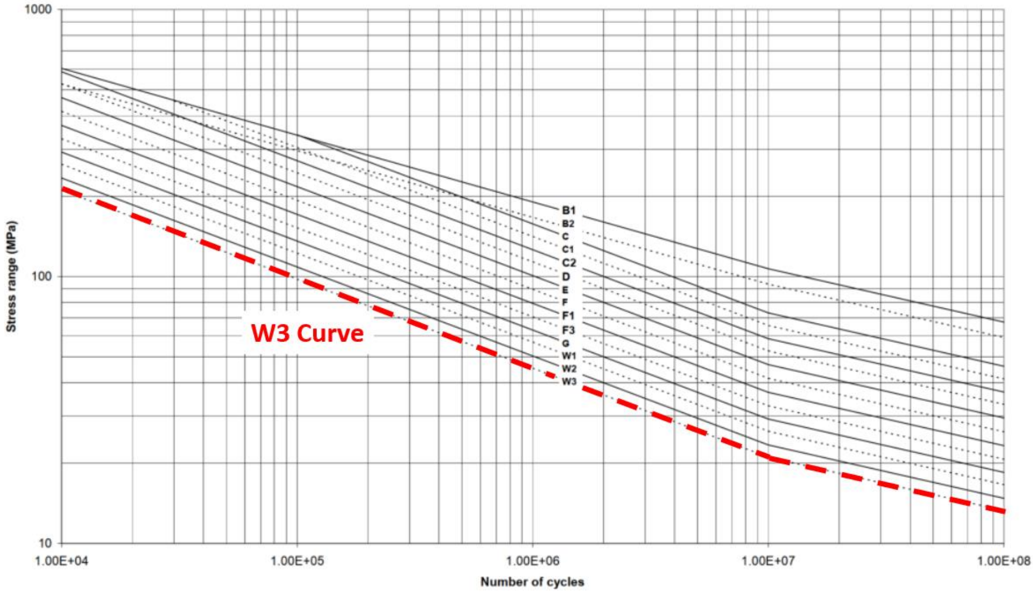


Figure 9: W3 Fatigue Curve from DNV-RP-C203

Note: No factor of safety or stress concentration factors applied to maximum membrane+bending stress. The DNV curve has a stress concentration of 2.50 embedded in the W3 curve.

7.3.3 FATIGUE LOAD SPECTRUM

The fatigue life assessment was based on the provided mooring line load spectrum, which defines the number of cycles at different stress levels. The table below summarizes the key fatigue load cases:

Table 4: Selected Load Amplitude and Cycle Count Provided

Load Amplitude (kN)	Number of Cycles	% Occurrence
20	113,175,120	55.38%
40	8,992,800	4.40%
100	1,779,480	0.87%
300	206,220	1.01%
500	12,912,880	6.32%
600	19,160	0.01%

Note: Selected load amplitudes are shown instead of the full spectrum considered.

The majority of cycles—approximately 55 percent—occur at low loads of around 20 kN, contributing minimally to fatigue damage. In contrast, high-frequency, high-load cycles in the range of 500–600 kN occur less frequently but contribute disproportionately to cumulative fatigue damage.

7.3.4 FATIGUE LIFE RESULTS AND CUMULATIVE DAMAGE

Cumulative fatigue damage was computed for two identified hotspots, revealing severe fatigue failure risks in the initial design. The results are summarized below:

Table 5: Cumulative Fatigue Damage of Initial Anchor Design

Hotspot Location	Cumulative Fatigue Damage (Ratio to Allowable Limit)
Hotspot 1	300x allowable limit
Hotspot 2	250x allowable limit

The initial anchor design is highly susceptible to fatigue failure, particularly at weld locations. Cumulative fatigue damage exceeds allowable limits by a factor of 300, confirming that failure is unavoidable in the current design. High-load cyclic events in the 500 kN range contribute most significantly to fatigue damage, making load spectrum refinement a critical design consideration.

Optimization can significantly improve fatigue performance, but challenges remain, primarily due to high-frequency, high-load cycles that continue to cause excessive fatigue damage. Future work should focus on refining the load spectrum and conducting prototype field testing to validate the improvements.

7.4 TASK 4 OPTIMIZATION OF ANCHOR GEOMETRY

To address fatigue and stress concerns, Task 4 focused on optimizing the anchor geometry. A Design of Experiments (DOE) approach was employed, testing 92 design variations using ANSYS APDL and MATLAB. Several geometric parameters, including plate thickness, gusset height, skirt length, and anchor diameter, were adjusted to identify the optimal configuration.

The optimized design successfully reduced peak stress by 67% and improved fatigue life by 78%. However, cumulative fatigue damage remained 80 times above the allowable DNV limit, indicating that while stress was minimized, fatigue issues persisted. As with the baseline design, analysis revealed that high-frequency, high-load cycles in the load spectrum were the primary contributors to fatigue failure, suggesting that refining the load spectrum could significantly enhance fatigue performance.

7.4.1 DATA COLLECTION FOR OPTIMIZATION

The initial analysis of the Modular Group Helical Pile Anchor revealed significant stress concentrations and fatigue failure risks, particularly in the gussets and associated welds beneath the top plate. To enhance the anchor's performance, an optimization process was conducted using FEA and Design of Experiments (DOE) methodologies.

The primary objectives of the optimization process were to:

- Reduce peak stresses to minimize structural failure risks.
- Improve fatigue performance by reducing cumulative fatigue damage.
- Identify key geometric variables that significantly impact stress and fatigue life.
- Develop an optimized design that maintains strength while minimizing material usage.

A parametric optimization approach was employed to systematically explore the anchor's geometry. Key geometric variables influencing stress and fatigue performance were identified, and nine design parameters were selected for optimization. These variables and their range in the design space considered are shown in Table 6.

Table 6: Optimization Variable Ranges

Variable	Description	Range of Values Tested
Top Plate Thickness	Structural plate thickness at the anchor top	0.5 - 1.25 inches
Skirt Thickness	Thickness of the anchor's skirt section	0.5 - 1.25 inches
Skirt Length	Length of the anchor's lower section	100 - 200 inches
Anchor Casing Diameter	Diameter of the anchor's primary structure	120 - 200 inches
Anchor Bolt Circle Diameter	Distance between anchor bolts	80 - 100 inches
Gusset Height	Height of reinforcing gussets	8 - 16 inches
Gusset Thickness	Thickness of reinforcing gussets	0.5 - 1.25 inches
Number of Anchors	Number of helical piles in the design	8 - 10
Slot Opening Percentage	Percentage of open slots in the structure	10% - 80%

To effectively conduct the analysis, a parametric model was developed in ANSYS APDL to systematically adjust each of the nine design variables. A total of 92 unique design iterations were analyzed using a DOE matrix, exploring how each variable influenced peak stress and fatigue performance. Von Mises stress values were recorded to assess how modifications affected structural behavior.

The parametric ANSYS APDL model consisted of solid elements with linear geometry and linear-elastic material properties, as before. The worst-case load from Table 1 was applied to the top padeye, while beam elements represented the helical pile anchors, and a p-y spring element simulated soil stiffness.

Peak von Mises stresses from the gusset and top plate regions were automatically exported from the ANSYS APDL parametric model. These peak stress values were then compiled along with the corresponding geometric parameters to create a dataset for regression analysis in MATLAB. Figure 10 and Figure 11 show the typical stress distribution from the ADPL parametric analyses.

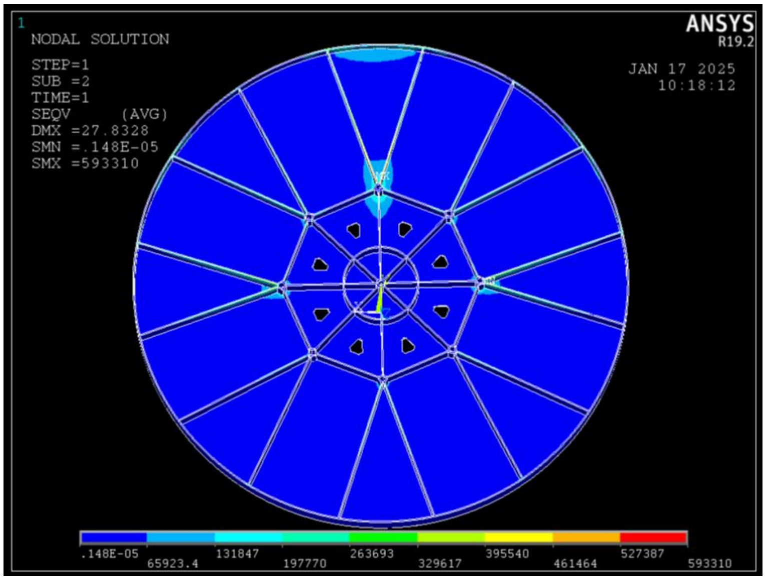


Figure 10: Top Plate and Gussets Stress Contour from ANSYS APDL

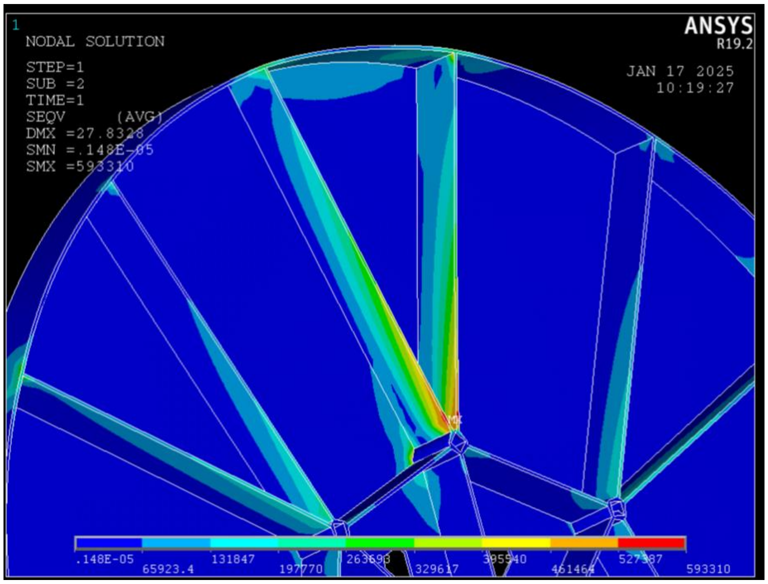


Figure 11: Top Plate and Gussets Stress Concentration from ANSYS APDL

7.4.2 REGRESSION ANALYSIS AND RESPONSE SURFACE MODELING

The peak von Mises stress along the two paths from the parametric FEA were processed in MATLAB to generate a multilinear regression model, which was used to create a response surface plot. This allowed for the visualization of the effects of each geometric parameter on peak stress and thus the fatigue performance. Table 7 shows the optimized parameters. Note, the optimized parameters reflect the best parameter value to minimize stress, considering availability of materials. For example, the top plate thickness of 1.25 in reflects a commercially available size of sheet metal.

Table 7: Optimized Parameters Leading to Minimum Peak Stress

Optimized Parameter	Final Value
Top Plate Thickness	1.25 inches
Skirt Thickness	1.0 inches
Skirt Length	120 inches
Anchor Casing Diameter	120 inches
Anchor Bolt Circle Diameter	100 inches
Gusset Height	16 inches
Gusset Thickness	0.625 (5/8) inches
Number of Anchors	10
Slot Opening Percentage	Max - Free Variable

The Response Surface Analysis provided key insights. Increasing the top plate thickness significantly reduced stress concentrations around the gusset intersection (weld seams). Gusset height and thickness played a crucial role in reinforcing load paths. The slot opening percentage had a minimal impact on peak stress and was treated as a free variable.

After implementing the optimized design, a final FEA analysis was performed to compare stress distributions in the initial and optimized designs as listed in Table 8.

Table 8: Peak Stress and Fatigue Results Comparison After Optimization

Metric	Initial Design	Optimized Design
Peak Stress (ksi)	42 ksi	14 ksi
Cumulative Fatigue Damage (Hotspot 1)	300 times allowable limit	80 times allowable limit
Cumulative Fatigue Damage (Hotspot 2)	250 times allowable limit	60 times allowable limit

Peak stress was reduced by 67%, dropping from 42 ksi to 14 ksi. The calculated stress range was reduced by 40%, and hence the fatigue damage was reduced by 78%. However, cumulative fatigue damage still exceeded allowable limits by a factor of 80. Geometric modifications, including thicker gussets and a reinforced top plate, effectively redistributed stresses. The slot opening percentage had minimal impact on peak stress, allowing for greater design flexibility. While the optimization produced a significant stress reduction, fatigue performance remains a challenge. Even with optimized geometry, high-frequency cyclic loads exceeding 500 kN continue to drive fatigue damage. Further refinement of the load spectrum is essential to meet fatigue life requirements.

Despite the fatigue damage still exceeding the allowable, the Design of Experiments (DOE) and response surface analysis successfully identified key design parameters and produced a significant improvement in the design, demonstrating a valuable and effective design tool for future marine anchor designs.

Reducing high-load cycle occurrences above 500 kN, if operationally feasible, could significantly enhance fatigue life. Implementing this change would require collaboration with mooring system designers to explore alternative loading scenarios. Alternative welding techniques, such as post-weld heat treatment, may also help extend fatigue life. Full-scale offshore testing will be critical to validating these improvements. Additionally, incorporating machine learning techniques with physical test data could accelerate FEA-based optimization.

7.5 TASK 5 DUAL-ANCHOR RING CONCEPT

The final task of this project studied the impact of using multiple anchor rings, specifically the load sharing between them. The dual-anchor ring configuration was introduced as a potential solution to enhance load distribution and improve fatigue performance for the Modular Group Helical Pile Anchor. This design replaces the initial single-ring configuration with two concentric rings of helical piles.

The primary objectives of evaluating the dual-anchor ring system were to:

- Distribute applied loads more evenly across multiple anchor points.
- Reduce stress concentrations in critical regions, particularly at the top plate and gussets.
- Improve overall structural stability by increasing load-bearing capacity.

The larger anchor template, provided by Triton Anchor, featured two concentric helical pile rings—an inner ring positioned closer to the anchor base and an outer ring extending further outward.

7.5.1 EVALUATION METHODOLOGY

To assess load distribution and structural performance, the following approach was applied:

- The optimized plate thickness, gusset height, and anchor diameter skirt thickness from the single-ring study were retained in the dual-ring model.
- Skirt length was increased to accommodate the larger footprint of the new anchor template.
- A finite element model (FEM) was developed to simulate loading conditions for the dual-ring configuration.
- Larger vertical and horizontal loads were supplied by Triton Anchor: 4,760 kN (1.07 million pounds) force upward (vertical), 2,535 kN (0.57 million pounds) force lateral (shear).
- Stress distribution, peak load transfer, and lateral displacement contours were plotted.

This evaluation aimed to determine whether the dual-anchor ring system effectively enhanced load distribution, reduced stress concentrations, and improved fatigue resistance compared to the single-ring design. The dual-ring anchor design concept is shown in Figure 12.

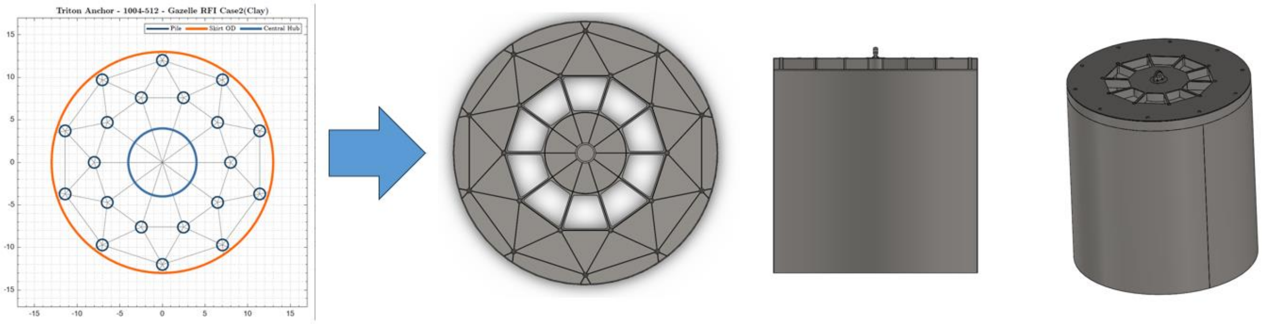


Figure 12: Dual Ring Helical Pile Anchor Concept from Triton Anchor

7.5.2 LOAD DISTRIBUTION RESULTS

FEA of the dual-ring anchor concept, shown in Figure 13, revealed a disproportionate load distribution between the two rings, with the inner ring carrying a significantly larger proportion of the applied load. The dual-ring system successfully increased the load capacity. However, equivalent stress contours indicate that the inner ring carries more load than the outer ring, highlighting a need for further optimization to improve outer-ring engagement.

Lateral displacement, shown in Figure 14, remained nearly unchanged, suggesting that the dual-ring casing diameter provides similar soil resistance to lateral (shear) loads as the single-ring configuration.

The uneven load distribution between the inner and outer rings can be attributed to several factors:

- Proximity to applied load – The inner ring is closer to the primary load application point, leading to greater load resistance, while the outer ring, positioned farther away, is less effective in load transfer.
- Direct force transfer at the padeye – Most of the applied forces are directly absorbed by the inner ring, creating higher load concentrations in this region.
- Load path limitations – The anchor's skirt design favors short, direct load paths to the helical piles, which currently do not extend efficiently to the outer ring.

The optimized gusset configuration from the single-ring design was retained, but its effect on load transfer between the rings was not initially considered. Further adjustments to gusset placement may be necessary to better distribute forces across both rings and improve load sharing efficiency.

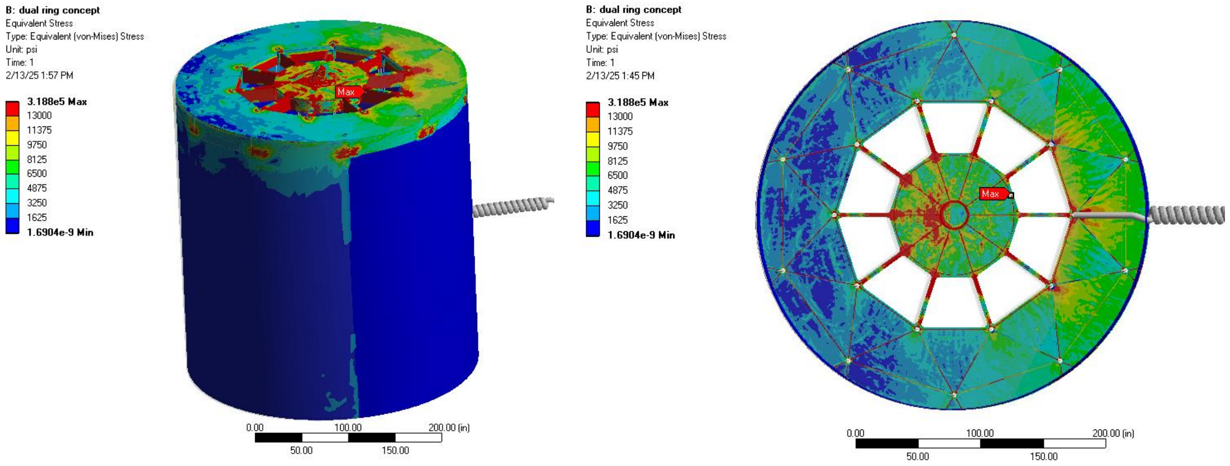


Figure 13: Equivalent Stress Contour for Dual Ring Anchor Concept

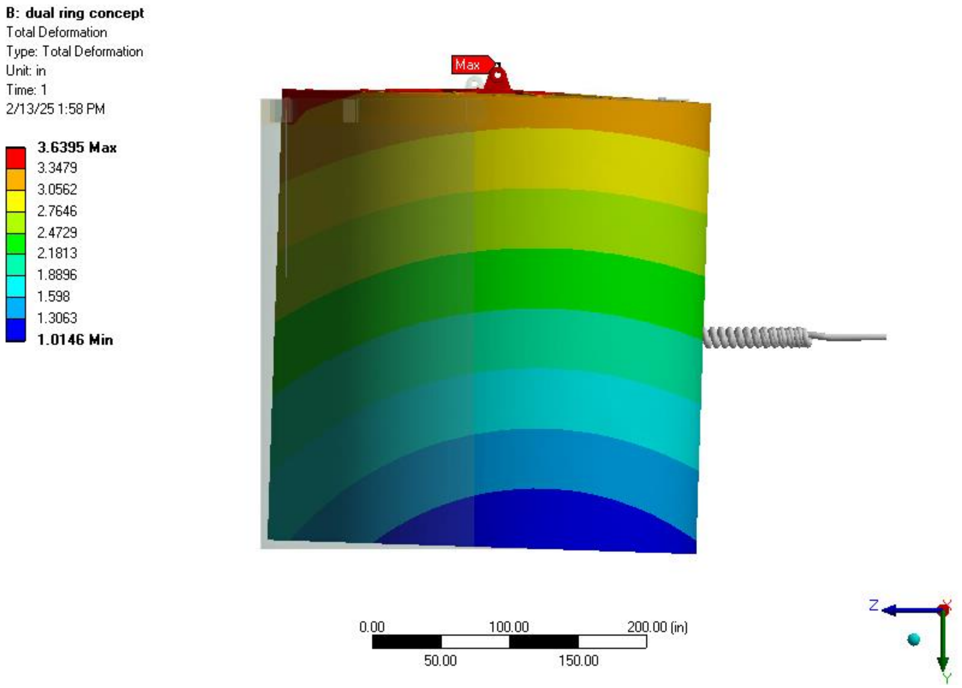


Figure 14: Total Deflection Contour for Dual Ring Anchor Concept

7.5.3 DUAL-RING LOAD DISTRIBUTION FINDINGS AND RECOMMENDATIONS

The dual-ring anchor system demonstrated disproportionate load sharing between the inner and outer rings with the inner ring carrying the majority of the applied forces. This imbalance suggests that further refinement is required to enhance load distribution efficiency before attempting to meet industry fatigue life requirements.

Several design modifications could improve load sharing between the inner and outer rings:

- Increasing skirt thickness and adding more gusseting near the outer ring could enhance load transfer efficiency.
- Adjusting gusset height and placement may help redistribute some of the applied forces to the outer ring, ensuring better utilization of both anchor rings.
- Decreasing the radial distance between the two anchor ring diameters could improve their ability share loading and utilize the soil resistance.
- Incorporating reinforcing struts or stiffeners between the inner and outer rings may enhance load-sharing efficiency.

Furthermore, a more comprehensive DOE optimization process could be employed to improve the design of the dual-ring anchor concept.

7.6 LESSON LEARNED AND TEST PLAN DEVIATION

Several key lessons emerged during the execution of this project that could improve efficiency and effectiveness in future structural and fatigue analysis projects. These lessons span modeling assumptions, computational efficiency, fatigue analysis methodologies, and design optimization strategies.

7.6.1 SOIL MODELING

Initially, multiple soil models were tested, including Mohr-Coulomb, Cam-Clay, Porous Elasticity, and p-y Springs. The Mohr-Coulomb model required unrealistic cohesion adjustments to achieve convergence, while the Cam-Clay and Porous Elasticity models were unsuitable for high lateral loads given the provided soil characteristics. While the planned approach intended to use a continuum soil model, the p-y Spring model ultimately proved to be the most effective, delivering accurate stress distribution with computational efficiency. To optimize future projects, preliminary modeling studies should be conducted early in the design phase to assess soil behavior and minimize time spent on unsuitable models.

The primary reason for this deviation was due to early attempts to model soil behavior using continuum methods leading to long computation times and convergence issues. Switching to the p-y Spring model significantly reduced computational costs, enabling more iterations and refinements in the optimization process. Furthermore, this project was focused on the anchor structure rather than the soil itself and the load carrying capacity of the soil. The soil model served only to generate the appropriate applied load on the anchor. Moreover, it was assumed for all analyses that the anchor does not exceed the soil capacity. One aspect that the p-y model did not capture is any localized changes in soil loads, and their impact on the anchor structure, due to the interaction of the helical piles with each other as well as the skirt. While the p-y method cannot capture this, these effects are expected to be negligible. Future projects should prioritize computational efficiency from the outset, selecting models that balance accuracy with processing efficiency.

7.6.2 FATIGUE LIFE AND LOAD SPECTRUM INFLUENCE

The high-frequency, high-load cyclic events in the given load spectrum were identified as the primary driver of fatigue failure. Even after extensive optimization, fatigue damage remained 80 times above the allowable limit. This does not reflect poorly on the research done on this project; rather, it provides insight into future anchor design improvements. The load spectrum considered for this project includes a high number of bins with high occurrence and high amplitude. Despite being a small percentage of the total number of fatigue bins in the spectrum, they account for a significant portion of the damage. Despite the fatigue life not being met, the significant reduction in fatigue damage demonstrates the success of the optimization process. Future projects should involve earlier collaboration with load definition teams to assess whether the loading spectrum is overly conservative or can be adjusted without compromising safety.

7.6.3 OPTIMIZATION PROCESS IMPROVEMENTS

The Design of Experiments (DOE) approach with 92 simulations successfully reduced peak stress by 67%, but some parameters had minimal impact. Future projects should conduct sensitivity studies early to eliminate low-impact variables, reducing unnecessary simulations and improving efficiency.

7.6.4 LOAD DISTRIBUTION IN DUAL-RING ANCHOR DESIGN

The dual-anchor ring concept revealed inefficiencies in load sharing, with the inner ring carrying most of the load. Future projects should explore design variations earlier to ensure balanced load distribution before committing to a specific configuration.

8 CONCLUSIONS AND RECOMMENDATIONS

This project provided valuable insights into the structural performance, fatigue resistance, and optimization of modular group helical pile anchors. The findings have significant implications for future research and development.

8.1 MAJOR CONCLUSIONS

There are several key learnings taken from this project, which are summarized below.

1. For structural design optimization, p-y spring modeling for the soil-structure interaction is adequate and desired for computational efficiency.
    - Continuum soil models can be useful in geotechnical design, but for anchor structural design, p-y springs provide sufficiently accurate soil loads at a lower computational effort.
    - The Mohr-Coulomb model required artificial cohesion adjustments, making it less suitable for fatigue analysis.
    - This project focused on a sandy soil and, as a result, other continuum models (i.e., cam-clay, etc.) were not applicable.
2. The structural performance was within allowable values for strength criteria, but not for fatigue criteria.
    - Stress hot spots exist in the gussets near the helical pile ring.
    - Peak stress was successfully reduced by 67% (from 42 ksi to 14 ksi) through design optimization.
    - Fatigue damage was reduced by 78% through design optimization, but fatigue damage remained 80x above the allowable limit. Again, one of the primary goals for this project was to demonstrate the optimization process and its benefits in design. With this consideration, the project was successful.
3. Fatigue and loading spectrum influenced the high fatigue damage.
    - High amplitude, high-cycle loads were the primary driver of fatigue failure. Typically, it is expected that higher loads tend to occur at a lower frequency. The fatigue load spectra was provided to SES by Triton Anchor, and the authors are unclear if these high-amplitude, high-cycle loads are realistic. The assumption was made that they are for this work.

   - Refining the load spectrum is necessary to improve fatigue performance.

4. The optimization methodology employed in this project successfully optimized the anchor design.
   - The DOE optimization methodology utilized 92 simulation cases to map the design space, providing the data to optimize the structure.
   - In addition to converging to the optimal component dimensions, optimization resulted in several key findings, including:
     - The optimal helical pile anchor ring diameter was pushed away from the center, toward the skirt.
     - The slot opening percentage in the template had minimal impact on peak stress and could be eliminated in future analyses.

8.2 RECOMMENDATIONS FOR FOLLOW ON WORK

The conclusions from the project lead to several recommendations for continuing research. These include:

1. The fatigue load spectrum considered in this study should be verified to ensure the significant contribution of high cyclic load bins is as expected and realistic for the use case considered (floating wave energy converter). If it is, design refinements should be considered to significantly decrease stress in hot spots.
2. Perform an additional optimization study which considers two rings of helical pile anchors. This optimization would evaluate the diameters of the helical pile rings and optimize the load sharing between them.
3. Perform laboratory and field testing of a full-scale prototype to validate the anchor performance.
4. Consider computational efficiency improvements to automate the optimization processes and explore machine learning approaches.

8.3 FINAL ASSESSMENT

Overall, this project successfully achieved the goal of utilizing the DOE optimization process to improve the design of a helical pile anchor. To summarize:

- The peak stress was successfully reduced.
- The fatigue life was significantly improved, although fatigue damage remains excessive for the load spectrum considered.
- Field validation is recommended for real-world performance verification.

Although the final, optimized anchor design did not meet the fatigue requirements for the load spectrum considered, the project successfully demonstrated that the DOE optimization process is a valuable tool that will allow designers to design efficient structures in a reliable and efficient way. This project has generated a roadmap for designers of marine renewable energy assets to optimally design their systems, reducing CAPEX and thus LCOE.

For Triton Anchor's current design, further work is required to fully meet fatigue requirements including load spectrum refinement, improved fatigue modeling, and physical validation testing.

9 REFERENCES

[1] DNV (2010). DNV-RP-C203 Fatigue Design of Offshore Steel Structures 2010 Edition.

[2] Wiley (2016). Response Surface Methodology, 4th Edition.

[3] Butterworth-Heinemann (2017). ANSYS Mechanical APDL for Finite Element Analysis.

[4] API (2011). API RP 2GEO: Geotechnical and Foundation Design Considerations.

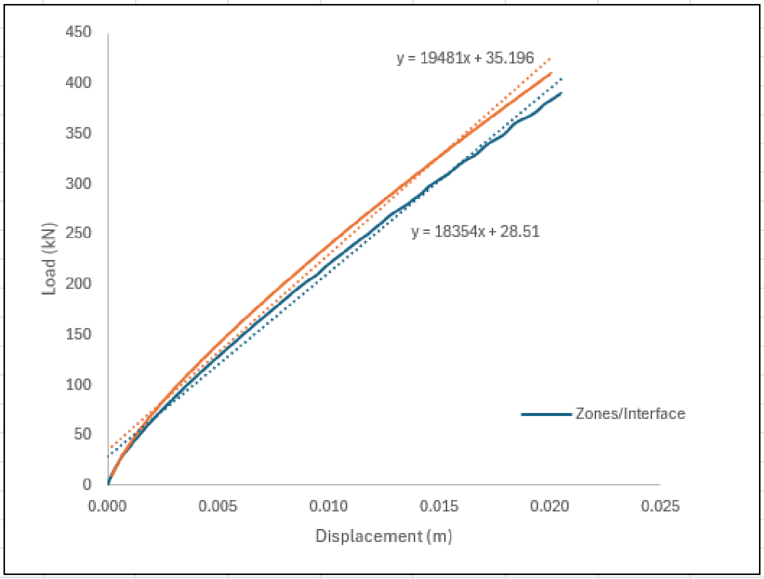
10 ACKNOWLEDGEMENTS

The authors of this report wish to acknowledge the contributions of Alwin Jose from Stress Engineering Services, Inc. who supported this fatigue analysis in this project.

11 APPENDIX

11.1 HELICAL PILE STIFFNESS CALCULATION

Pile Stiffness provided by Triton Anchor



Anchor Vertical Stiffness:

$$k_{anchor} := 19000 \frac{kN}{m} = 108.493 \cdot \frac{kip}{in}$$

Modulus of Steel:

$$E := 29 \cdot 10^6 psi$$

Proposed Model Anchor Diameter / Radius:

$$d := .9882in \qquad r := 0.5 \cdot d = 0.4941\,in$$

Cross-sectional Area of Anchor Rod:

$$a := .25 \cdot \pi \cdot d^2$$

Equivalent Length of Model Anchor Required to Match Vertical Stiffness:

$$L_{eq} := \frac{E \cdot a}{k_{anchor}} = 205.011 \cdot in$$

11.2 P-Y SPRING MODELING CALCULATIONS

- Modulus of Subgrade Reaction is a function of internal friction angle, per API RP 2GEO.
  - Data is provided for internal friction angles between 25 deg and 40 deg.
  - API RP 2GEO data is extrapolated to assess the modulus of subgrade reaction of an internal friction angle of 52.3 deg.

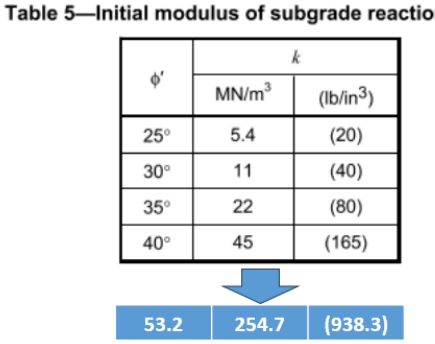
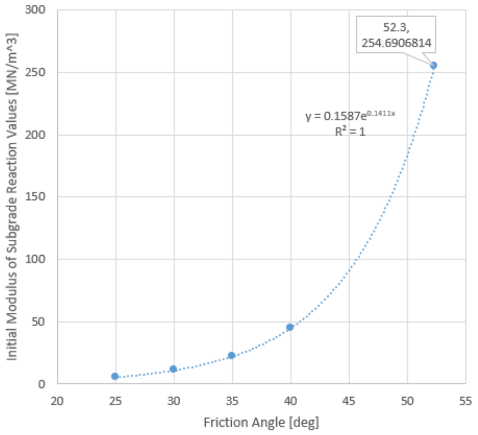


Table 5—Initial modulus of subgrade reaction values

ϕ'	k	
	MN/m^3	(lb/in^3)
25°	5.4	(20)
30°	11	(40)
35°	22	(80)
40°	45	(165)
53.2	**254.7**	**(938.3)**



Diameter of Pile (Anchor Diameter):

$$d_{pile} = 144 \cdot in$$

Depth of Pile (90% of Anchor Height):

$$z := 0.9 \cdot h_{pile} = 108 \cdot in$$

Submerged Soil Weight:

$$\gamma := 109.4 \frac{lbf}{ft^3}$$

Soil Friction Angle:

$$\phi := 52.3deg$$

Modulus of Subgrade Reaction Value (Extrapolated):

$$k := 254.7 \cdot \frac{MN}{m^3} = 938.304 \cdot \frac{lbf}{in^3}$$

Calculation of Constants:

$$\alpha := \frac{\phi}{2} = 0.456 \qquad \beta := 45deg + \frac{\phi}{2} = 1.242 \qquad K_o := 0.4 \qquad K_a := \frac{1 - \sin(\phi)}{1 + \sin(\phi)} = 0.117$$

$$C_1 := \frac{(\tan(\beta))^2 \cdot \tan(\alpha)}{\tan(\beta - \phi)} + K_o \cdot \left[\frac{\tan(\phi) \cdot \sin(\beta)}{\cos(\alpha) \cdot \tan(\beta - \phi)} + \tan(\beta) \cdot (\tan(\phi) \cdot \sin(\beta) - \tan(\alpha)) \right] = 14.796$$

$$C_2 := \frac{\tan(\beta)}{\tan(\beta - \phi)} - K_a = 8.463$$

Lateral Bearing Capacity of Shallow Soil on Anchor:

$$p_{us} := \left(C_1 \cdot z + C_2 \cdot d_{pile}\right) \cdot \gamma \cdot z = 19.259 \cdot \frac{kip}{in}$$

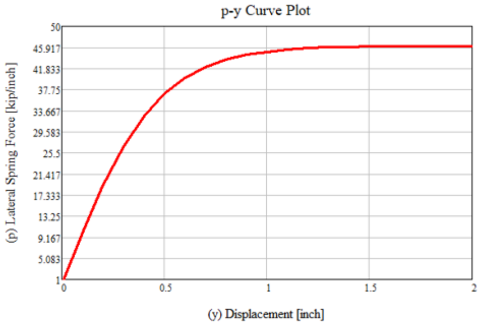
Loading Factor:

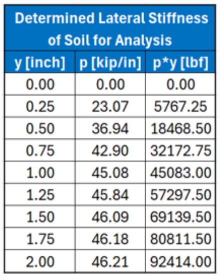
$$A := \left(3 - 0.8 \cdot \frac{z}{d_{pile}}\right) = 2.4$$

Lateral Soil Resistance (p-y) Curve; (p as a function of y):

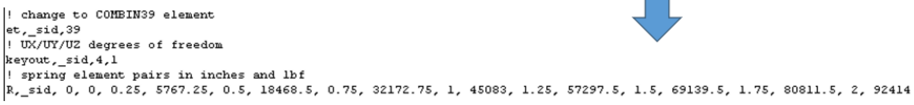
$$\boxed{p(y) := A \cdot p_{us} \cdot \tanh\left(\frac{k \cdot z}{A \cdot p_{us}} \cdot y\right)}$$

- A nonlinear stiffness representing the lateral stiffness of the sand was determined, and a representative spring was modeled in ANSYS using a COMBIN39 nonlinear spring element, with displacement versus load values derived from the API 2GEO calculations.





Determined Lateral Stiffness of Soil for Analysis		
y [inch]	p [kip/in]	p*y [lbf]
0.00	0.00	0.00
0.25	23.07	5767.25
0.50	36.94	18468.50
0.75	42.90	32172.75
1.00	45.08	45083.00
1.25	45.84	57297.50
1.50	46.09	69139.50
1.75	46.18	80811.50
2.00	46.21	92414.00



```
! change to COMBIN39 element
et,_sid,39
! UX/UY/UZ degrees of freedom
keyout,_sid,4,1
! spring element pairs in inches and lbf
R,_sid, 0, 0, 0.25, 5767.25, 0.5, 18468.5, 0.75, 32172.75, 1, 45083, 1.25, 57297.5, 1.5, 69139.5, 1.75, 80811.5, 2, 92414
```

TRESS