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An analytical approach for offshore structures considering soil-structure interaction

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Abstract. This paper presents an advanced analytical approach for the design and analysis of fixed offshore structures with soil structure interaction considered. The proposed methodology involves conducting case studies to illustrate and assess the structural response of a structure considering seven different earthquakes, with the primary goal of ensuring there is no global collapse in the structures. The case studies focus on developing a model for structural analysis and its topside, incorporating nonlinear axial and lateral springs to capture soil-pile interaction. Additionally, mass and damping ratios are considered through the use of dashpots in the analyses. Finite Element Software was employed for structural analyses with detailed modeling, with soil spring nodes applied in the entire structure across various depths. After the finite element analysis was carried out, a sensitivity analysis was conducted to quantify and report the effects of different parameters.

Keywords: finite elements; offshore structures; soil-structure interaction; structural response

1. Introduction

Offshore structures are mostly used as petroleum structures today. It is deployed on platforms in open seas anywhere in the world. The design, construction, and operation of offshore structures require a sophisticated understanding of engineering principles, environmental factors, and safety considerations. Today, the offshore building industry has become one of the most evolving industries. While evaluating these developments, the risks of structural damage that may arise should also be taken into consideration (Qasim and Hasan 2020). Since they can be designed as very costly and bulky structures, their analysis must be done very carefully. Especially in seismically risky areas, these structures should be determined well, and their earthquake resistance should be fully determined (Joao and Hao 2014). With the increasing demand for energy, oil and natural gas exploration and extraction activities are not limited to only lands, but many searches are made for this purpose in the seas (Storheim *et al*. 2018, Billingham *et al*. 2003, Anis and Kadim 2017). For the structural evaluation processes, the development and evolution of the structural modeling of offshore structures have been driven by the constant quest and constraints based on the structural and soil interaction. From fixed platforms anchored to the seabed to floating production systems that navigate the waves, the design of these structures has evolved to

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meet the demands of deeper waters and determined conditions. Limitations should be defined with the given conditions.

In offshore structures, the design of each platform and floating offshore structures for floating production storage and transportation differ in line with the requirements of the special operations applied. It differs depending on the activities of the structure and whether the substance produced is gas or oil (APIRP 2005, EN ISO 2000). Offshore structures consist of many different structural elements. They are quite complex and complex structures. These structures are the transmission area where the pipelines carrying liquids, hydrocarbon gases or water used for production purposes, hydrocarbon processing elements, production separators, and gases coming from the separators are compressed, liquefied, and purified; Consists of areas such as power stations for power generation, helicopter platform, administrative buildings and living spaces for personnel (Zarrin *et al*. 2018, Sharifian *et al*. 2015, Jahanitaba and Bargi 2018). Offshore structures are designed according to the rules to be followed in various regulations in order to display acceptable structural behavior and stay on the safe side. In the design of such structures, solutions are made by using single and multi-degree freedom systems, such as dynamic analysis in a time domain and structural analysis. The offshore oil structures supported by the sea are modeled using Finite Element Analysis (Tremayne and Kelly 2005, Ali 2007).

2. Literature review

There are many studies related to offshore structures, which have attracted the attention of researchers, especially because of their economic and functional values. In some of these studies, the earthquake behaviors of offshore structures were discussed (Mohamed and Kadim 2015, Dong *et al*. 2018). Asgarian *et al*. (2012) investigated the Soil-Pile-Structure Interaction (SPSI) on the dynamic characteristics of the offshore platform through experimental and numerical analyses. In the study, it was found that the dynamic properties of the system have changed significantly with the effect of SPSI. In a study by Rosyth (2004), it was determined that the behavior of the flooring of the building platform with finite elements in its research on the superstructures of floating structures for the purpose of storage, transport, and transportation. In his analysis with ABAQUS, he determined the mod shapes of the building, and the floor displacements were calculated. Ali conducted a detailed study on performance-related design in offshore structures. Jahanitabar and Bargi (2017) carried out dynamic analyses and evaluated fragility curves capturing the effects of seismic fragility, aging, and corrosion deterioration of the newly designed Jacket type coastal platform for offshore structures. Izzuddin and Smith (1997) examined the damage situations that would occur in offshore structures and conducted analyzes using the finite element method. Banda and colleagues (2003) have similarly studied floating systems Sari *et al*. (2016) studied the effect of soil radiation damping, soil-pile, and multi-level excitation and seismic loading with inelastic behavior of the fixed offshore structure, and they achieved remarkable results on that subject. Cortijo *et al*. (2003) Detailed the design criteria and demonstrated the applicability of these criteria for offshore structures through dynamic analysis.

3. Finite element analysis of off-shore structures

Finite Element Analysis begins with the creation of a detailed computerized model representing the geometry and material properties of the offshore structure. This model is then divided into

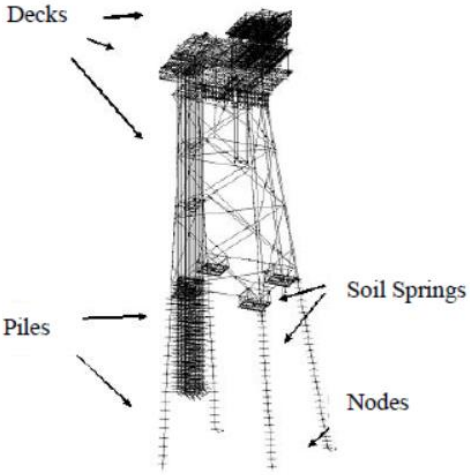


Fig. 1 Finite element model of off-shore structure

finite elements, each with defined properties and connectivity. Structural evaluation for the offshore structure was handled through the finite element model established (England 2015). Modeling plays a crucial role in the accurate evaluation and optimization of offshore structures. Modeling with sophisticated conditions and limitations means to predict their behavior under diverse and challenging conditions. As the boundary conditions in the analysis, as seen in Fig. 1, the free end definition was made at the lower end (Polatov *et al*. 2020). To express the soil-pile interaction, non-linear springs with free retention have been identified (Baker 2015, Ajamy *et al*. 2018). Offshore structures, including platforms, jackets, and subsea systems, must effectively transfer loads to and interact with the underlying soil to ensure structural integrity and stability in varying environmental conditions. Earthquake data is defined as displacement at the involvement points of these springs. In addition, earthquake data was also affected on the platform at each location. Ground-pile elements have been used to define ground-pile interaction. These ground-pile interaction elements were also used to connect the free end with the pile element defined in the analysis. Ground-pile interaction elements are expressed with P-Y, T-Z, and Q-Z spring properties (Lyu *et al*. 2021). Finite Element analysis employed with consideration of soil-structure interaction is defined with the structural definition ability and realistic soil conditions for offshore structures. The structural model is coupled with a soil model, allowing engineers to study the dynamic behavior of the entire system. This comprehensive analysis helps in predicting the response of the structure to environmental loads, including waves, wind, and seismic events, while accounting for the influence of the soil conditions.

With developments and improvements in technology and software in structural computation with supercomputers, complex structures such as offshore structures can be accurately and easily analyzed with FE approaches. Even soil-structure interaction is a complex condition to define. It is a detailed investigation of the design and analysis of offshore structures. Proper modeling and understanding of this interaction contribute to the development of robust and resilient offshore installations capable of withstanding the challenges posed by the marine environment. They can be evaluated using their dynamic behavior considering soil-structure interaction via computer-based simulations. This approach would allow the accurate creation of a design for all types of soil-structure interaction for offshore structures. Additionally, if it is applied to the in-situ fitting of a tower crane mast, it will provide us with a structural system and design method that is safe, cost-efficient, and workable. This forms the basis of the proposed new design method.

Five wave directions were selected based on initial results from the simplified model in SACS. 100-year waves associated with these directions were considered in extreme and fatigue analyses. Strength analysis response for the caisson system was seen to be worse for wave loading from the South and North. A maximum displacement of around 78 mm was seen in the south caisson between the mid-guide and subsea guide. Deadweight support connection to the platform column was seen to have maximum von-mises stress of around 33 MPa. Von-mises stress contours of dead weight support lug slot show stress concentration near the region where the caisson trunnion lug structure sits. Maximum von-mises stress in this region was around 85 MPa. Maximum von-mises stress of around 137 MPa was seen in connection of mid guide to platform column. Subsea guide shear key connection was seen to have maximum von-mises stress of around 276 MPa. Maximum von-mises stress of 175 MPa was seen on the south caisson near the subsea guide clamp region.

In the Finite Element Analysis, when examining the interaction between the trunnion lug and the dead weight support lug slot, the analysis indicates that the maximum von-Mises stresses are concentrated between the center and the right end of the lug slot. Importantly, these stresses remain within the elastic range, ensuring structural integrity and avoiding plastic deformation. In the broader aspects, sensitivity analyses on both grout material and rubber bag material reveal that stress contributions exhibit minimal variation, indicating that softer grout and rubber do not significantly impact the overall stress levels. Based on this simplified and conservative approach, all the selected hot spots, except the shear keys at the subsea guide, would have more than 10 years of fatigue life (Mohammadreza *et al*. 2018, Maedeh *et al*. 2018, Ghanshyam 2018).

Anchor bolts would have more than 10 years of fatigue life. Tensile stress and axial tensile force of anchor bolts for the worst wave load were acceptable, as the capacity of bolts was higher than preload and applied external load. In-line wave-induced vortex shedding was observed. The amplitude of in-line wave oscillation derived from the DNV approach was too conservative. For the “modified approach”, using the combination of wave velocity and stability parameters, the amplitude of in-line excitation was more reasonable (Yu and Amdahl 2018a, b, Cai *et al*. 2018, Jeong and Ko 2020).

Structural variability in defining the characteristics contributes to a dynamic and less predictable environment, affecting the structural response. Additionally, considering the variation of wave velocity with depth becomes crucial in understanding the complex nature of wave dynamics. First, a comprehensive analysis of wave kinematics variations is run for assessing and mitigating the effects of wave-induced vibrations on structures. For structural modeling, wave kinematics, both spatially and temporally, within full-scale multi-directional random waves can potentially alleviate the impact of wave-induced vibrations. In characteristics of the structures, platforms should be considered as the main analysis part of the modelling. As a part of the modeling, effective mass of the caisson structure and damping ratio of the system are taken into account.

The orbital nature of wave-particle velocity with the passage of the wave, together with the variable length would result in the excitation of frequencies of adjacent spans which would lead to effective damping and negligible structural response. The maximum amplitude of in-line motion calculated from the “Modified approach” for the first mode of vibration was calculated to be approximately 15 mm for the worst extreme wave loading. FE analysis for maximum amplitude in-line wave vibration resulted in a maximum von-mises stress of around 84 MPa. The following recommendations are suggested from the VIV analysis:

- If the response is a problem, then the caisson system should be redesigned to eliminate the motion by increasing,
- Natural frequency of the caisson system diameter of the caissons,
- Effective mass of the caisson structure,
- Damping ratio of the system,
- If the redesign is impossible, consider devices to prevent vortex-induced oscillation such as strakes, fairings, etc.,
- Use advanced VIV analysis using Shear to remove conservatism and capture more,
- accurate VIV response.

The following recommendations are suggested from fatigue response analyses:

- Shear key thicknesses can be increased to improve the fatigue life of shear connection,
- Weld locations on caissons may be changed,
- Stress concentration may be reduced by changing geometry detail at hot spot locations.

The assessment focuses on evaluating the service water caisson system during its operational phase, encompassing the installation and full functionality of all system components. The primary load cases under consideration are the self-weight of the structure and the environmental loading on the caissons. Velocity enhancement factors are introduced to accommodate the acceleration of water around the legs of the substructure. This comprehensive analysis aims to ensure the structural integrity and performance of the caisson system under the influence of its own weight and external environmental forces, taking into account the dynamic effects associated with water flow around the substructure legs. The following approach is adopted in the study:

- Static environmental wave, wind, and current loads are calculated using SACS,
- Static SACS analyses are performed to determine the most onerous load conditions,
- A detailed three-dimensional FE model of the Service Water Caisson System was developed in ABAQUS and then utilized to assess the strength and fatigue performance of the design. Equivalent static analysis was utilized in the design of the caissons.

The dynamic amplification factor (DAF) was calculated and applied to the static environmental load based on the natural period of the caissons. There are several benefits to utilizing a detailed three-dimensional ABAQUS model to verify the design against the design load cases:

- The design was checked against accurate guide reaction forces due to the explicit representation of the guide and clamp stiffness in the structural analysis,
- Increased confidence in calculated bolt forces and stresses than with approximate hand calculations due to the complex geometry of the system,
- The analysis result indicated the magnitude and location of peak stresses so that high or low-cycle fatigue failure can be prevented.

3.1 SACS Model

To analyze the caisson's response, it was discretized into 1-meter-long members, enabling the calculation of nodal forces per meter along the caisson's height. The boundary conditions for the Dead Weight Support were assumed to be pinned. Additionally, roller-type boundary conditions were assigned to the Mid Guide and Subsea Guide, allowing axial motion of the mid-guide and subsea guide clamps. This detailed modeling approach using SACS facilitated a thorough assessment of wave loading and dynamic characteristics, enhancing the accuracy of the analysis for the caissons.

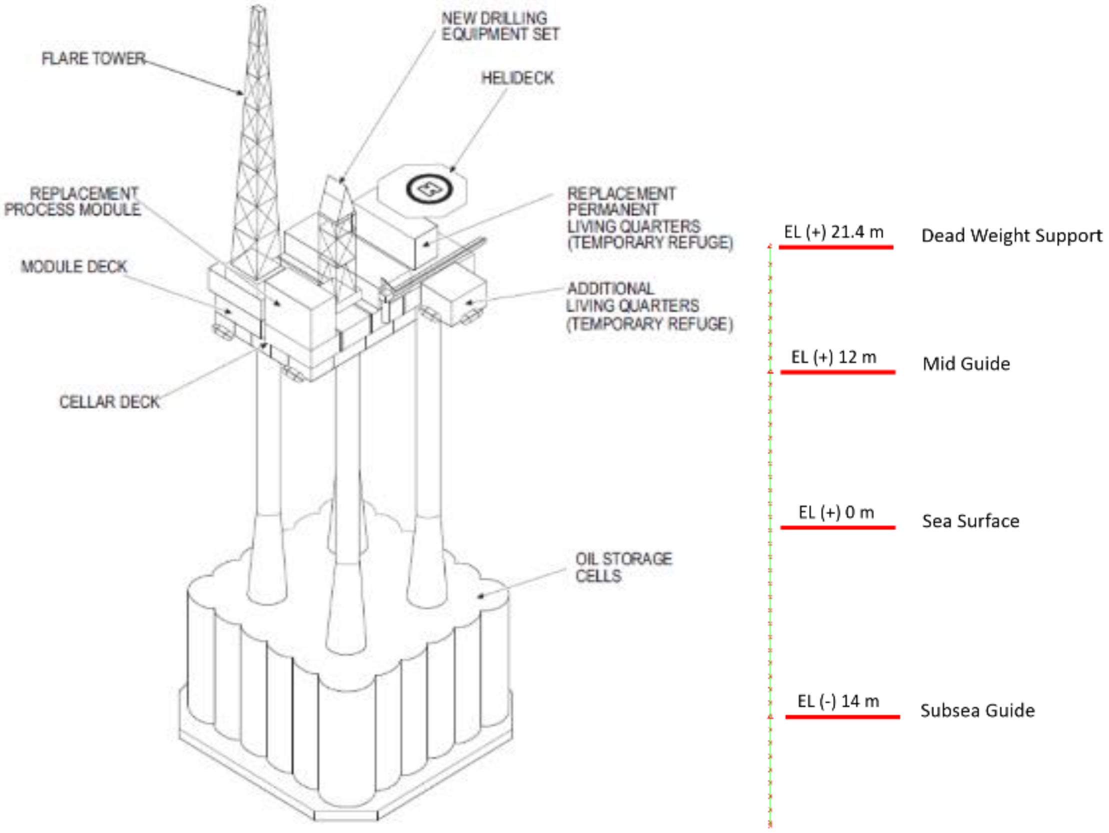


Fig. 2 Topside facilities layout and SACS model

SACS was utilized to generate wave loading profiles on caissons for loading Finite Element (FE) models. Within the SACS model, the natural period of the caisson was calculated, serving as a key parameter for estimating the dynamic amplification factor. Fig. 2 illustrates the SACS model used for environmental loading profiles and the determination of the natural period.

3.2 ABAQUS Model

The partial length of the caissons, near the guide and dead weight support region, was modeled in ABAQUS using shell elements. The remaining length of the caissons was modeled using beam elements (Azqandi *et al*. 2019). The dead weight support, mid guide, and subsea guide are modeled in detail using shell elements. Fig. 3 shows the caisson system ABAQUS FE model. The interaction between the caisson shell elements and the beam element model is modeled by kinematic coupling. Fig. 3 shows the kinematic coupling between the caisson shell model and the beam model. The interaction between the dead weight support and the caissons is modeled by contact algorithms. The interaction between the caisson, grouted guide, mid guide, and sub-sea guide are modeled by tie algorithms. Cartesian connector elements were used to model the bolt fasteners with realistic stiffness defined according to the bolt properties. Effects of grout on caissons and guides were taken into account by detailed grout and guide FE modeling.

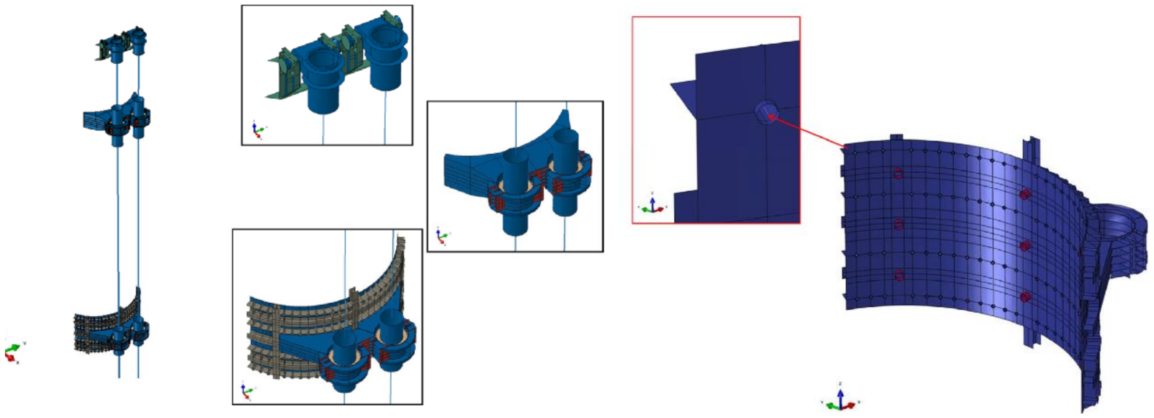


Fig. 3 ABAQUS FE model of the system

4. Analysis results

In this study, an advanced analytical approach was employed to assess offshore structures, utilizing a sophisticated numerical calculation based on the finite element method (FEM). The primary focus of the analysis was to understand the behavior of offshore structures, taking into account the crucial aspect of soil-structure interaction.

The finite element method involves dividing complex structures into smaller, more manageable elements to simulate their behavior under various conditions. This method allows for a detailed examination of structural responses to external forces, such as waves, wind, and seismic events, while considering the interaction with the underlying soil.

To carry out this advanced assessment, supercomputer systems were employed. These high-performance computing systems enable complex and computationally intensive simulations that are beyond the capacity of traditional computing resources. In this case, the analysis was conducted within the SACS (Structural Analysis Computer System) framework, which is a software suite designed for structural analysis and design in the offshore and maritime industry.

SACS provides a Finite Element Environment, a powerful tool that facilitates the modeling and analysis of complex structures, especially those in the offshore domain. This environment allows engineers to simulate the intricate interplay between the structure and the soil, providing a more realistic representation of the structural response.

By utilizing supercomputers and the advanced capabilities of SACS in a Finite Element Environment, the study aimed to enhance the accuracy and reliability of the assessment for offshore structures. This approach allows for a more comprehensive understanding of the dynamic behavior of the structures under various environmental conditions, ultimately contributing to improved design, safety, and performance of offshore installations.

In the research, static structural analysis was performed using SACS to compute the reaction forces at guide locations including dead weight support, mid guide, and subsea Guide for 100 years of Extreme load cases (England, 2015). The wave analysis included marine growth, wave shielding, and wave enhancement effects. Five extreme load cases with a 100-year return period were chosen to capture the strength assessment on the guides and caissons.

Reaction forces per meter length from SACS simulation for these five cases provided the load profiles on the caissons. The stress-strain relationship for various loadings is shown in Fig. 4. It

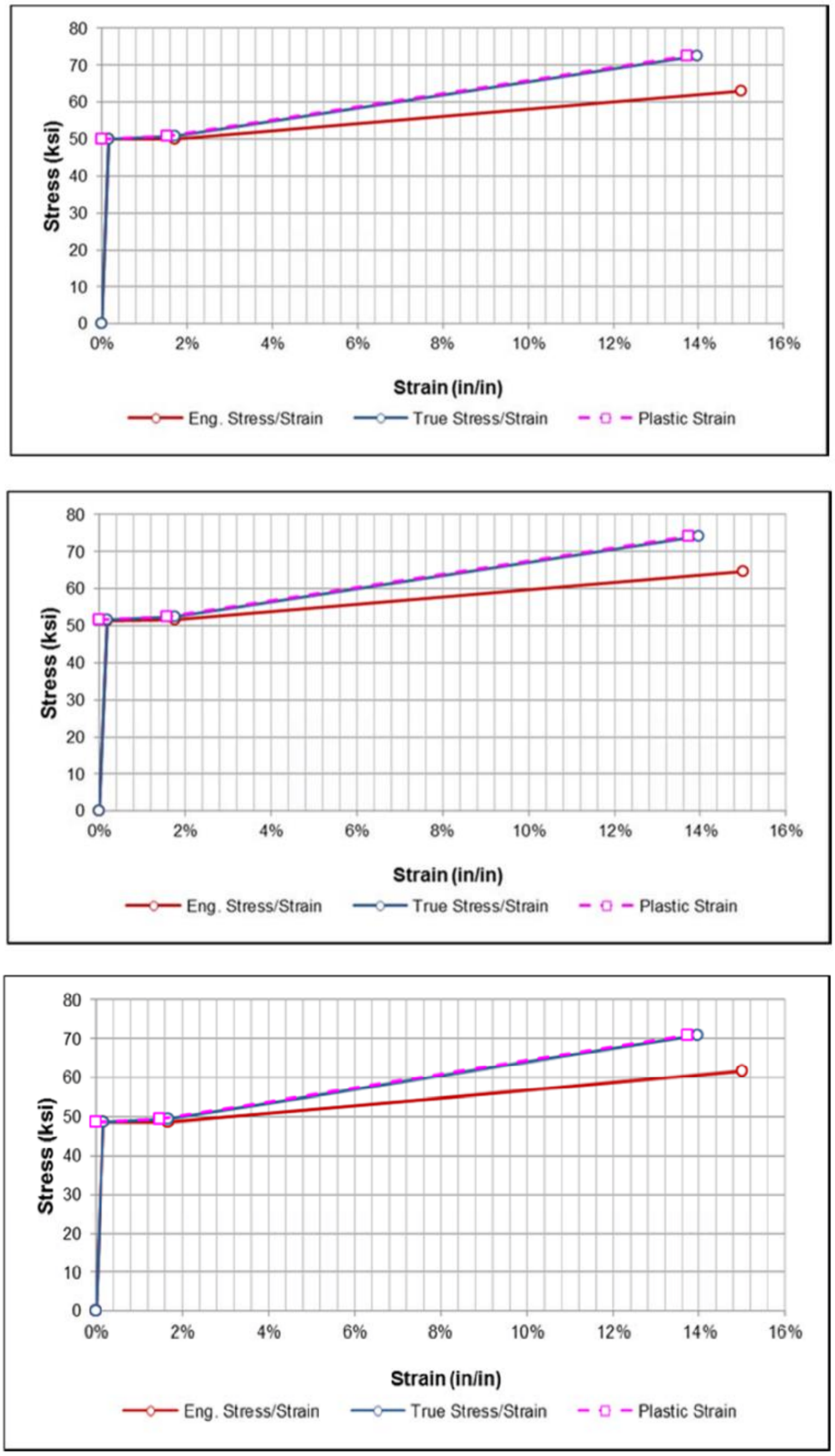
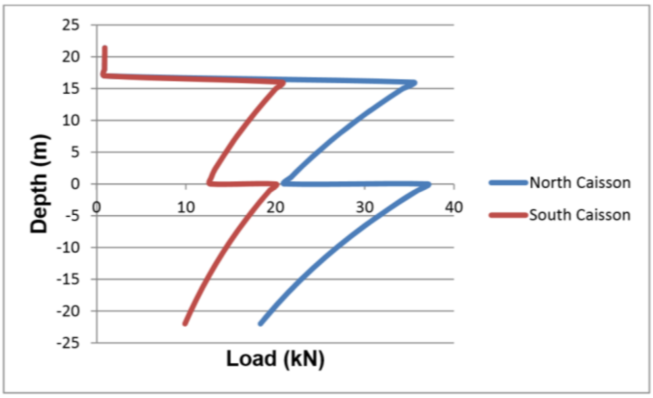
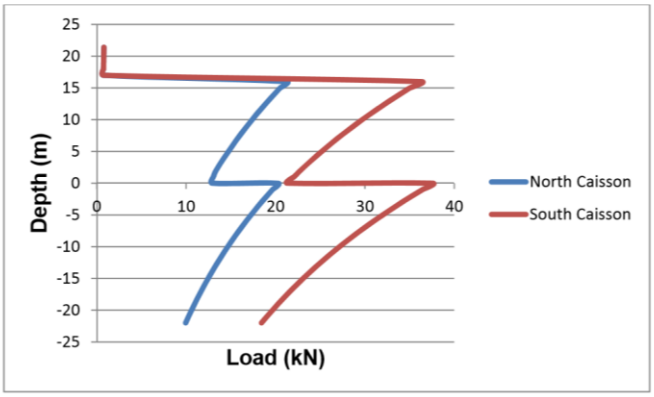


Fig. 4 Stress-Strain Relationship



100-year Extreme Load Profile over height of caisson for loads from North



100-year Extreme Load Profile over height of caisson for loads from South

Fig. 5 Load Profiles for North and South Walls

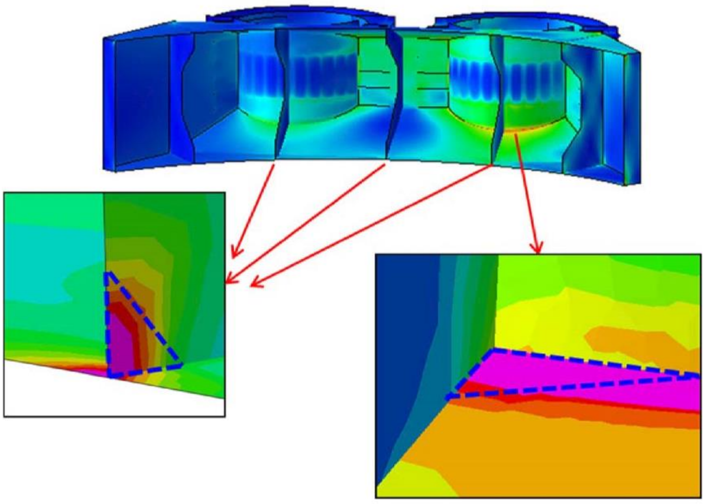


Fig. 6 Sample hot spot stress locations in the system

was observed that with no marine growth above means sea level (MSL) the wave loading decreased above MSL. Wave load was the dominant load for the service water caisson system. Fig. 5 shows Load Profiles for the North and South Walls. Wave shielding effect on the north caisson for waves from the South was seen in Fig. 5. Fig. 6 shows sample hot spot stress.

5. Conclusions

The strength analysis response for the caisson system revealed a less favorable outcome when subjected to wave loading from both the South and North directions. Notably, the maximum displacement observed was approximately 78 mm in the south caisson, specifically between the mid-guide and subsea guide. This indicates a significant deformation in the structure under the influence of wave forces, particularly in the specified region. Further investigation and potential modifications for detailed analysis may be necessary to enhance the structural integrity and address the observed displacement in the caisson system during wave loading from these directions.

Deadweight support connection to the platform column was seen to have maximum von mises stress of around 33 MPa. Von-mises stress contours of dead weight support lug slot show stress concentration near the region where the caisson trunnion lug structure sits. Maximum von-mises stress in this region was around 85 MPa. Maximum von-mises stress of around 137 MPa was seen in connection of mid guide to platform column. Subsea guide shear key connection was seen to have maximum von-mises stress of around 276 MPa. Maximum von-mises stress of 175 MPa was seen on the south caisson near the subsea guide clamp region. Material sensitivity of grout and grout rubber bag show that stress contribution does not show significant variation due to softer grout and rubber.

The analysis of the interaction between the trunnion lug and the dead weight support lug slot revealed that the maximum Von-Mises stresses are concentrated between the lug slot center and the right end. Importantly, these stresses remain within the elastic range which is critical for the structural investigation. Applying a simplified yet conservative approach and its all investigations, it was found that, except for the shear keys at the subsea guide, all selected hot spots would have more than 10 years of fatigue life.

The anchor bolts, crucial components in the system, were also examined, indicating a fatigue life exceeding 10 years. Tensile stress and axial tensile force for the anchor bolts under the worst wave load were deemed acceptable, as the bolt capacity exceeded the preload and applied external load.

Additionally, the analysis identified in-line wave-induced vortex shedding, highlighting a dynamic phenomenon in the system. This comprehensive assessment provides insights into the structural performance and fatigue life of critical components, allowing for informed decisions and potential optimizations in the design and operation of the system.

Tables 1 present the reaction forces at the guide and support locations resulting from environmental loading on the offshore structure. These reaction forces serve as crucial data for further analysis. For the comprehensive assessment of the structural integrity and fatigue life, five specific wave directions were chosen for in-depth evaluation. These directions include South, North, South East, North East, and North West, representing various scenarios that can impact the offshore structure.

Strength and fatigue assessments were conducted based on the reaction forces associated with

Table 1 Reaction at dead weight support

Wave Direction	Caisson	Force X, N	Force Y, N	Resultant	Force Z, N
South	SC	65,791	0	65,791	227,680 (Same as the weight of the system)
South*	SC	152,190	0	152,190	
North	NC	-62,850	0	62,850	
North*	NC	-146,240	0	146,240	
South East	SC	51,682	51,675	73,084	
North East	NC	-42,696	42,690	60,377	
South East	NC	28,319	51,663	58,915	
North West	NC	-46,930	-17,142	49,963	
South West	SC	46,127	-16,348	48,938	
North East	SC	-23,437	42,681	48,693	
East	NC	0	46,238	46,238	
East	SC	0	46,238	46,238	
South	NC	35,622	0	35,622	
South*	NC	84,180	0	84,180	
North	SC	-33,760	0	33,760	
North*	SC	-80,250	0	80,250	
North West	SC	-25,623	-17,142	30,828	
South West	NC	24,802	-16,348	29,705	
West	NC	0	-24,262	24,262	
West	SC	0	-24,262	24,262	

*Including force enhancement effect

these selected wave directions. This approach allows for a detailed understanding of how the structure responds to environmental loads from different angles. By considering these specific wave directions, engineers can gain valuable insights into potential vulnerabilities, load distributions, and areas of concern within the structure.

The decision to analyze specific wave directions is a strategic choice, aiming to capture a range of loading conditions that the offshore structure may encounter in its operational environment. This targeted approach enhances the precision of the assessments and aids in identifying critical areas that may require design modifications or reinforcement. Overall, the comprehensive analysis of reaction forces and subsequent assessments based on selected wave directions contribute to a thorough evaluation of the structure's performance under varying environmental conditions.

As a result of the VIV Analysis, some recommendations can be suggested as follow. If the response of the caisson system poses a challenge, a viable solution involves redesigning the system to mitigate motion-related issues. This can be achieved through strategic adjustments, including increasing the natural frequency of the caisson system, modifying the diameter of the caissons, optimizing the effective mass of the caisson structure, and adjusting the damping ratio of the system. These design considerations aim to enhance the system's stability and resilience. In cases where a complete redesign is impractical, alternative measures can be explored. Implementing devices like strakes and fairings can effectively counter vortex-induced oscillations.

Moreover, an advanced Vortex-Induced Vibration (VIV) analysis, employing Shear to eliminate conservatism and capture a more precise VIV response, can offer valuable insights. In the context of fatigue response analyses, specific recommendations include increasing shear key thicknesses to improve fatigue life in shear key connections. Additionally, mitigating stress concentration can be achieved by modifying the geometry details at identified hot spot locations. These recommendations collectively contribute to a comprehensive strategy for optimizing the caisson system's performance and addressing potential challenges.

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