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A comparison between spudcan and caisson foundations of jack up platforms subjected to cyclic loading

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ABSTRACT

The design, construction and installation of a mobile jack up drilling unit is considered to be a highly demanding task for the geotechnical engineer. The difficulties and extreme conditions that prevail offshore lead to the demand of resilient and at the same time economical solutions for the foundation of these systems. This paper conducts a comparison between two alternative foundations for a three legged jack up platform under wind and wave cyclic loading. The selected foundation types are a suction caisson with a skirt length to diameter ratio (L/D) equal to 0.5 and a spudcan, typically a shallow inverted cone which constitutes the most common solution for this type of offshore platforms, with an embedment ratio (W/D) equal to 1. Three-dimensional numerical analyses were conducted with the use of full platform-foundation models taking into consideration the soil-structure interaction and were compared with corresponding simplified decoupled models of the two alternative foundations. Finally, the role of non-linear interface, materialized through sliding between the foundation and the soil, was investigated under combined vertical and static cyclic loading.

Keywords: spudcan, suction caisson, offshore geotechnical engineering, 3D finite element modeling, soil-structure interaction, jack up platform

INTRODUCTION-SCOPE OF THE STUDY

In the offshore industry, most of the drilling activities in shallow to moderate water depths (up to 180m) are performed by self-elevating mobile jack-up drilling units due to their proven mobility and cost-effectiveness. Typically, these units consist of a triangular deck resting on three similar truss legs as the weight of the platform is more or less equally distributed. The foundation that is most commonly used for this type of platforms is a circular inverted conical footing known as spudcan with diameter that can exceed 20 m depending on the size of the rig and the soil bearing capacity of the operation area. These platforms are hauled to the drilling site floating on the hull with the legs elevated outside the water level. Once they arrive at the final location, the legs are lowered to the seabed. At this point, seawater is pumped into the ballast tanks of the platform and the foundations are pre-loaded, penetrating the soil until adequate bearing capacity is achieved. The ballast tanks are then emptied before operations on the jack up can begin.

The ultimate design criterion for any jack up rig is that once jacked up it must remain stable under most severe environmental conditions. Design of the platform must ensure that the rig can withstand the horizontal forces of wind, waves and ocean currents as well as the dead loads of the platform. Before a jack-up is installed engineers must ensure its stability in large storms (with the 50-year return period used in current industry guidelines SNAME) that could lead to wind speed exceeding 100 knots and wave height up to 15 m. This requires understanding of the bearing capacity of each footing under combined vertical (V), horizontal (H) and moment (M) loading, as well as their interaction with the above platform structure.

To this end, alternative foundation solutions are being considered by researchers that could achieve a both reliable and economical solution. The alternative investigated in this study is the suction caisson that is a foundation similar to an 'upturned bucket': it consists of a circular shallow footing whose capacity is enhanced by peripheral embedded skirts that confine the internal soil. Thus, it is believed that skirts of the periphery could improve the moment bearing capacity of the foundation and its rotational stiffness making it a considerable alternative against the commonly used spudcan.

Scope of this paper is to:
(i) compare the response of the spudcan and caisson foundations under static cyclic loading due to extreme weather events (wind and wave)
(ii) make a comparison between full platform-foundation 3D finite element models and the corresponding simplified decoupled models, as well as understand the importance of soil-structure interaction
(iii) introduce non-linear interfaces between the soil and the footing and observe their role to the system's response

PROBLEM STATEMENT

The problem under research refers to a typical jack up rig that has similar dimensions and characteristics with Trident IX, a platform spudded off the coast of Angola for Chevron Corp. (Fig. 1). For the purpose of this study, the platform is founded on a homogenous clay deposit with assumed undrained shear strength S_u=45 kPa and modulus of elasticity E=45000 kPa. The foundations examined are a spudcan with diameter D=18 m and a suction caisson with diameter D=20 m with embedment-diameter ratio W/D=1 and skirts length-diameter ratio L/D=0.5 respectively for each footing. The selection of the dimensions of the spudcan was made with reference to the footing of Trident IX whereas dimensions of the caisson were chosen so that the bearing capacity of the foundation is equal to that of the original footing (Fig. 2). The truss legs of the platform are modeled as pipe sections with stiffness corresponding to the real stiffness of the columns (Fig. 1). All dimensions and properties of the jack up and the two foundations are summarized in Table 1.

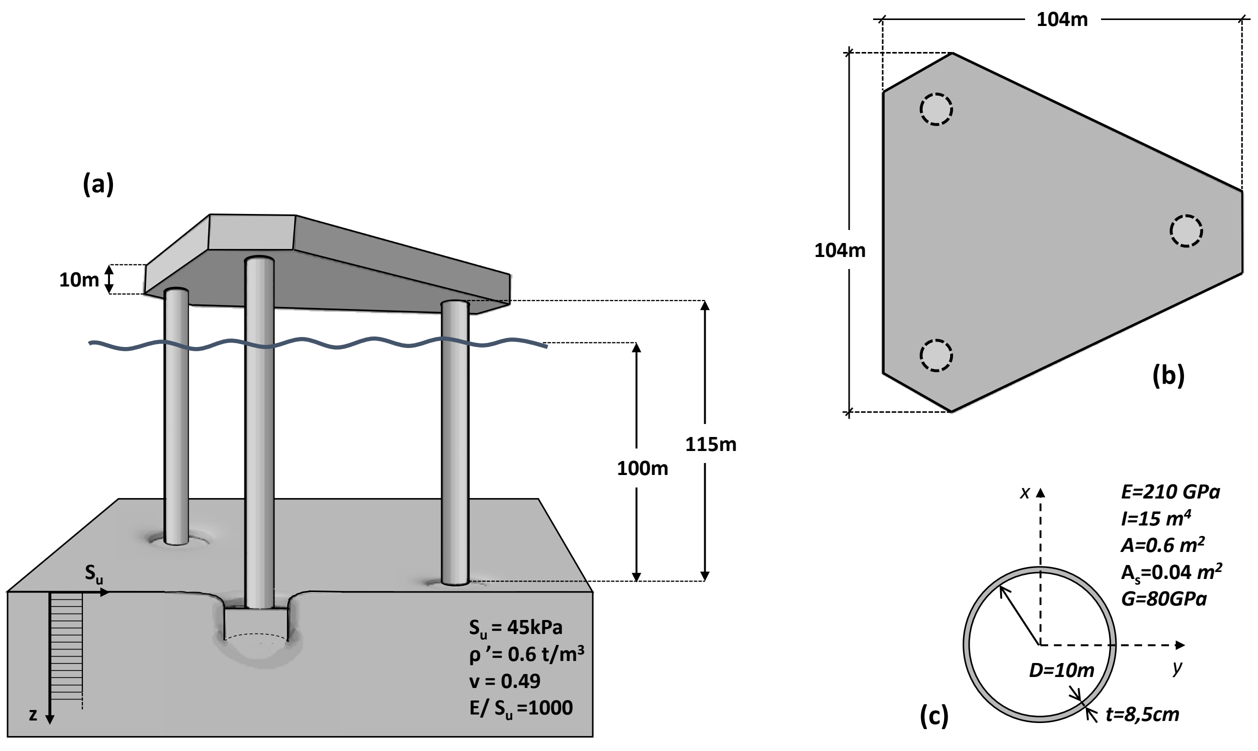

Figure 1. (a) Lateral aspect of the selected platform, (b) Vertical plot of the platform with its typical dimensions and (c) Cross section of the pipe equivalent to the truss legs with its mechanical properties.

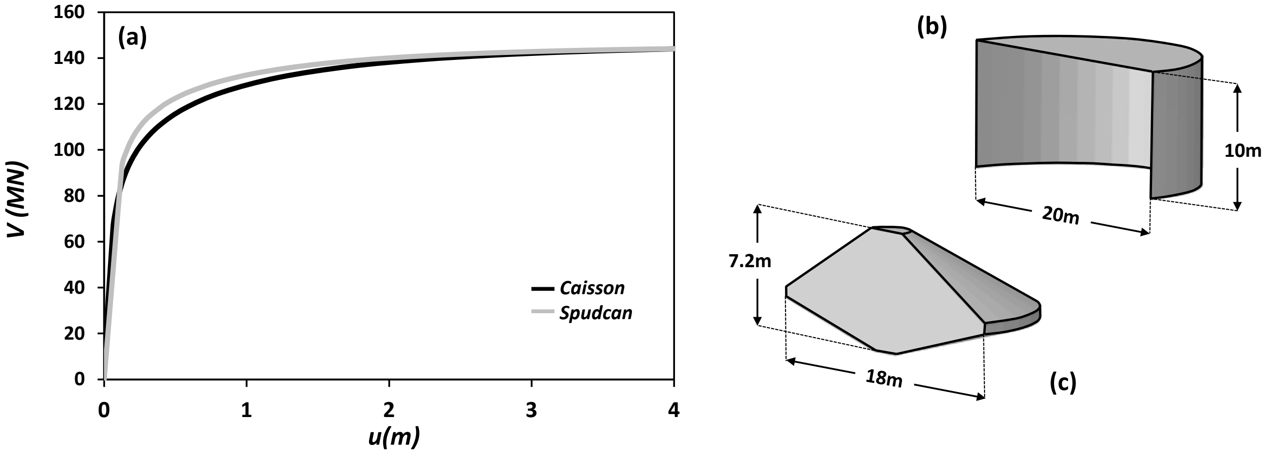

Figure 2. (a) Vertical Force-Vertical Displacement curves produced during monotonic vertical loading of the selected foundations (b) Dimensions of the suction caisson (c) Dimensions of the spudcan foundation.

Jack-Up Rig Specifications			
Dimensions	Hull	Length	104m
		Width	104m
		Depth	10m
	Diameter of Foundation	Spudcan	18m
		Caisson	20m
Design Criteria	Weather Conditions	Wave Height	12m
		Wind Speed	120 knots
	Water Depth		100 m
	Total Mass		10200tn

Table 1. Dimensions and design criteria of the selected jack up rig.

NUMERICAL METHODOLOGY

For the purposes of the current study, two different model variations are considered: a full model of the platform-footings and soil as well as a simplified decoupled model of the system, corresponding to both the spudcan and suction caisson alternative solutions.

The analyses for the investigation of the problem were conducted in three-dimensional space using the finite element code ABAQUS. The developed 3D meshes, taking advantage of the symmetry of the geometry and the one directional loading applied to the analysis, are displayed in Figure 3. The soil body is modeled using 8-node hexahedral continuum elements (C3D8) with nonlinear behavior following a kinematic hardening constitutive model with Von Mises failure criterion [Anastasopoulos et al, (2012)]. The ratio of Eo/Su where Eo the elastic modulus for zero plastic strain was assumed equal to 1000.

The platform of the simplified model is constructed as one leg with distributed mass and a concentrated mass on the top that represents the deck of the rig. Its leg is modeled using linear elastic beam elements while the foundation is modeled using linear elastic shell elements for the caisson and hexahedral continuum elements for the spudcan footing respectively (Fig. 4). The rotation at the top of the beam is restrained in order to realistically simulate the fixed conditions at the junction of the leg and the rigid hull. The deck of the full modelis simulated as a rigid part using 3D solid elements with appropriate material density so that its total mass is 10200 tn. The legs are again modeled using linear elastic beam elements.

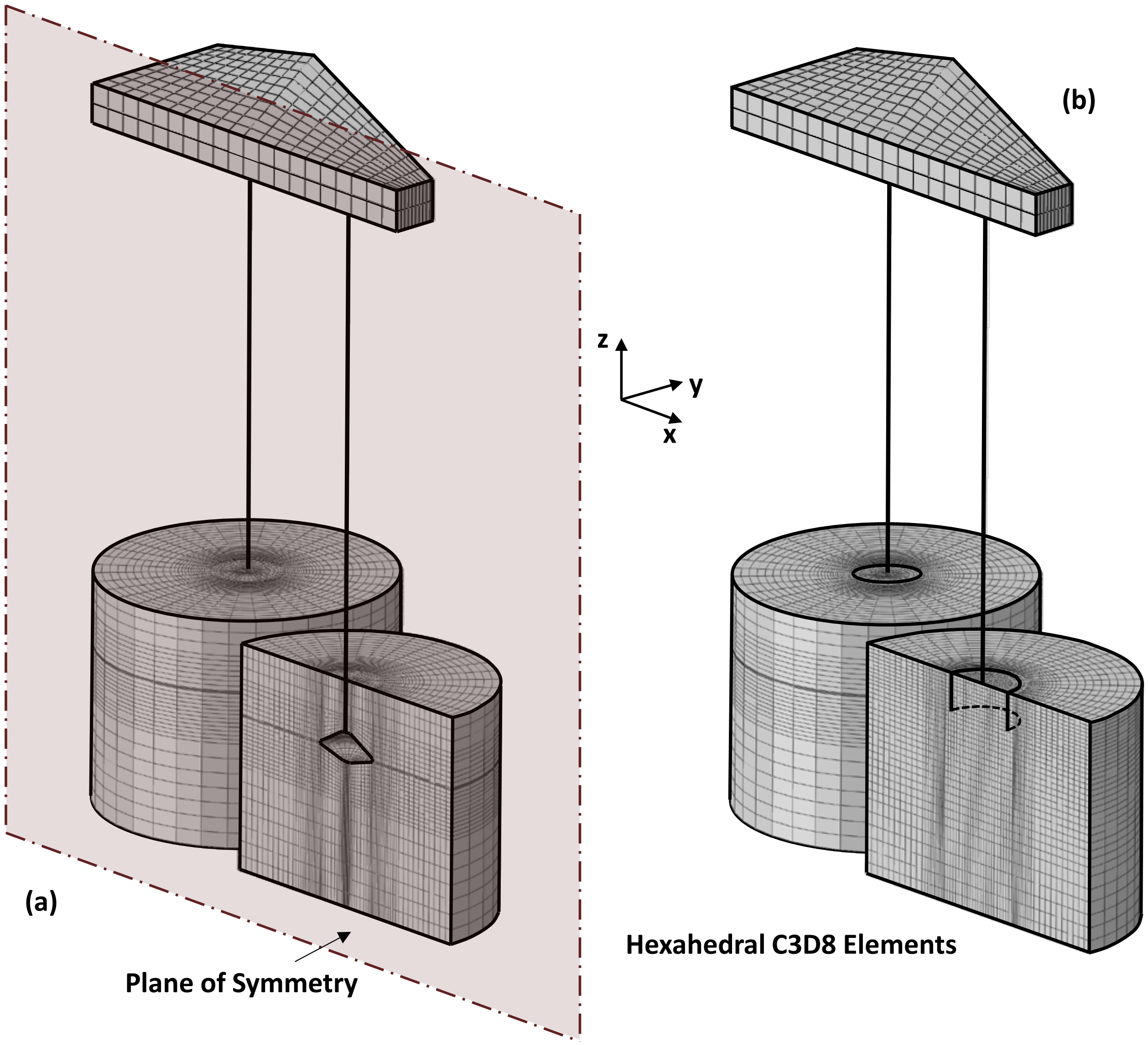

Figure 3. The developed 3D meshes of the platform with the two types of foundation: (a) spudcan (b) suction caisson.

It is generally accepted that due to several factors, some of which are related with the installation process, interfaces between the suction caisson or the spudcan and the surrounding soil may not always be considered as fully bonded. Thus, in order to model as realistically as possible the interface conditions between the foundations and the surrounding soil, contact elements are introduced with appropriately adjusted characteristics so as to simulate two different conditions:

- Perfect interface conditions, where the full shear strength of the model may be mobilized and full tensile strength can be developed
- Imperfect interface conditions, where reduced shear strength is considered to be a fraction (α) of the undrained shear strength and detachment between the soil and the foundation is possible. Factor α has been assumed equal to 0.5

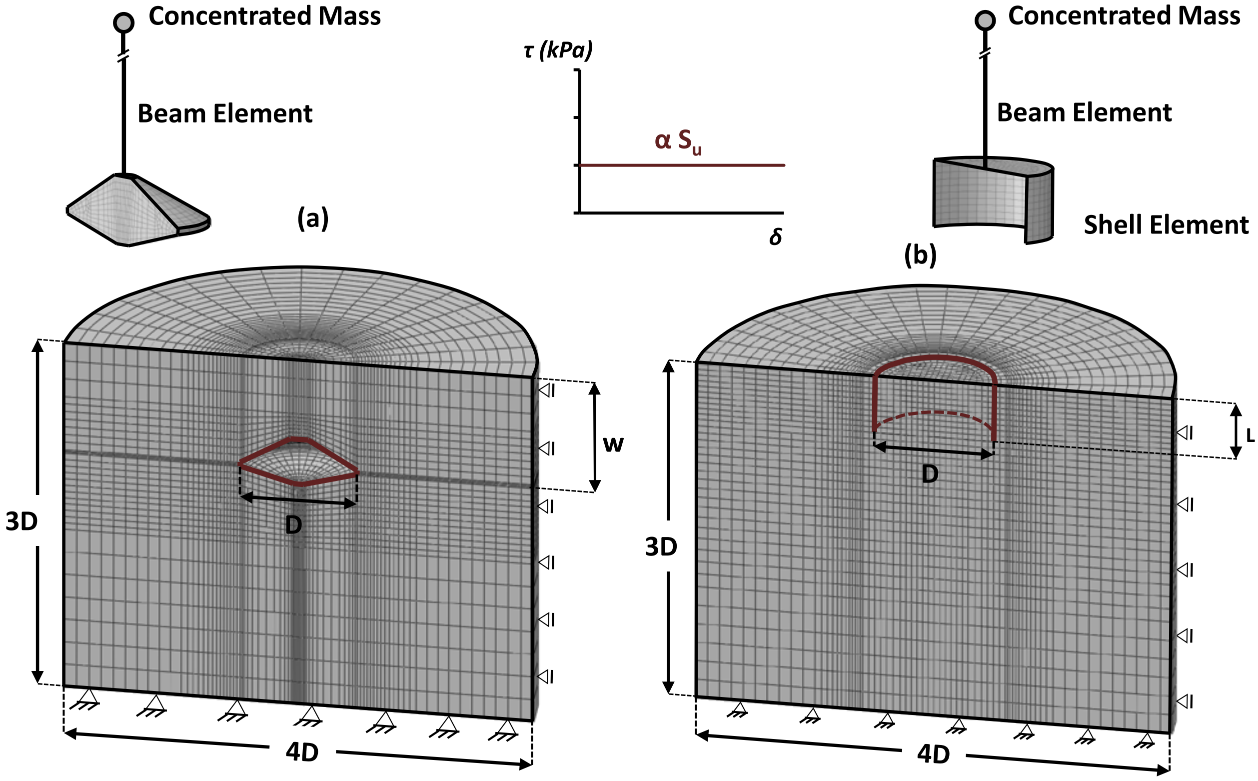

Figure 4. The developed 3D meshes of the simplified model of the platform with the two types of foundation: (a) spudcan (b) suction caisson.

RESPONSE UNDER CYCLIC LOADING

Offshore jack up rigs are exposed to environmental loading comprising wind, waves and current forces that impose horizontal loads and moments on the foundations thereby altering the vertical load between them. These loads are not applied monotonically; instead they switch direction constantly resulting in a continuous cyclic loading of the construction. The platform selected for the current study is designed to overtake 120 knots wind speed and wave height up to 12 m leading to a total overturning moment of 110 MNm.

The main object of this research is to preliminarily compare the response of the examined foundations in terms of settlement and rotation accumulation due to weather events. To this end, a scenario of ten cycles of 10 MN (5 MN for the half models used) horizontal force (Fig. 4) is applied to the middle of the hull in order to simulate the environmental loading, as illustrated in Figure 5. The adopted assumption regarding the positive direction of the horizontal displacement and rotation can also be observed in Figure 5.

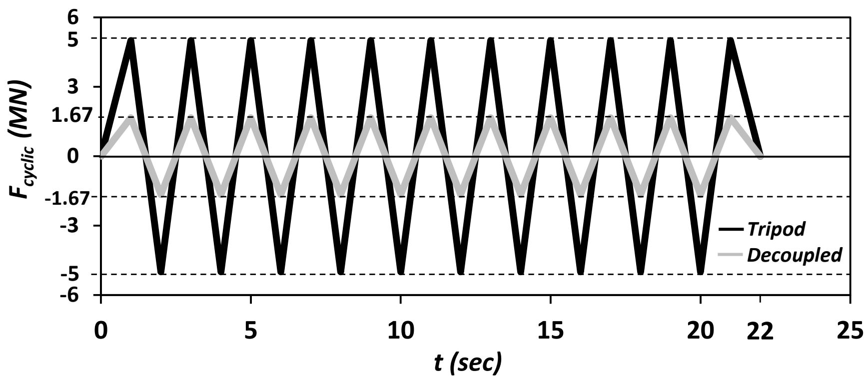

Figure 4. Applied cyclic horizontal forces for the full and the simplified model.

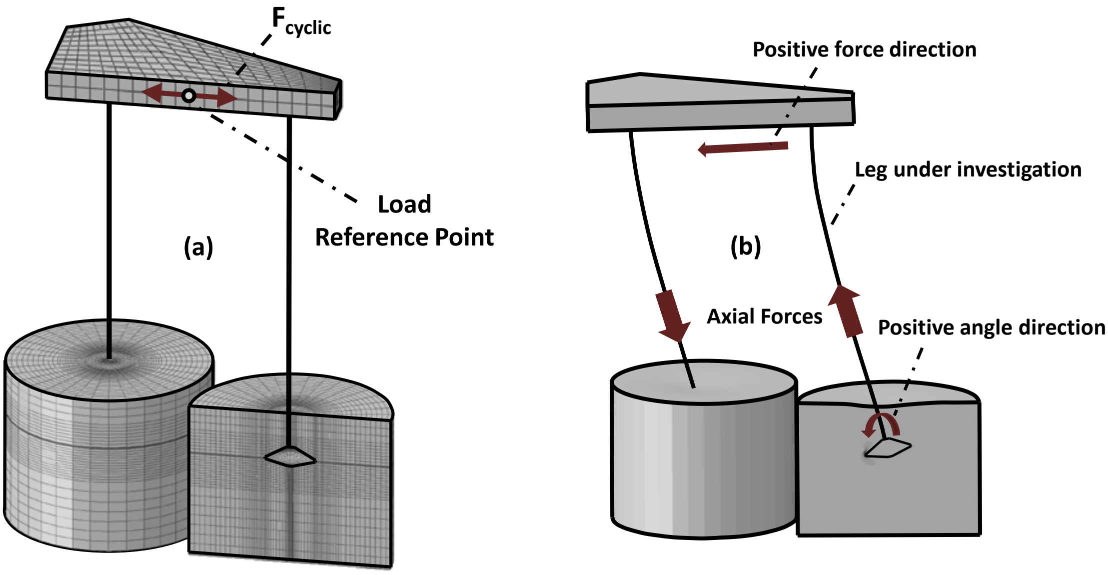

Figure 5. (a) Schematic definition of the load reference point (b) Definition of the positive horizontal force and angle direction as well as illustration of the axial forces developed during the horizontal loading.

The investigation has been repeated for both foundation alternatives: the suction caisson and the spudcan. Figure 6 portrays the results for the cases analyzed plotted in terms of vertical displacement of the footing (W)-rotation of the footing (θ) and moment at the bottom of the leg (M)-rotation of the footing (θ).

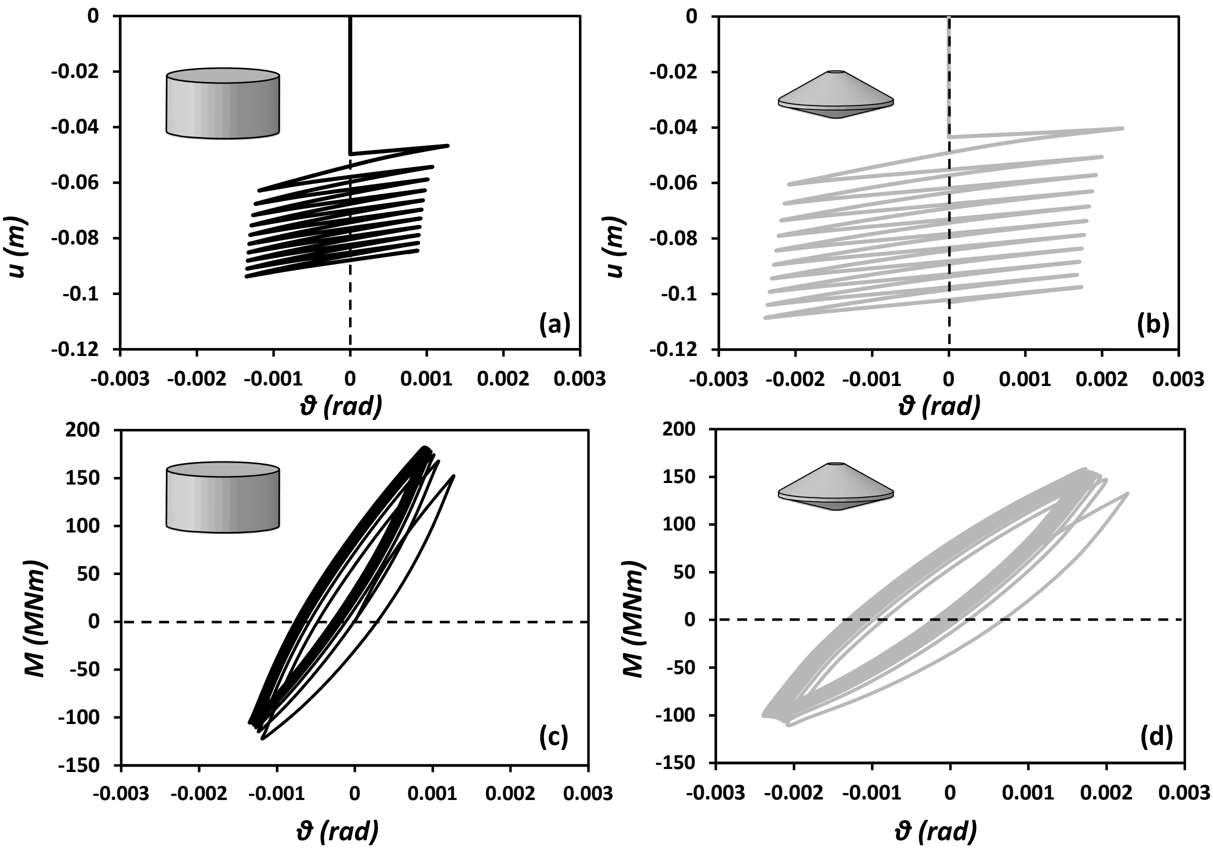

Figure 6. (a), (b) Vertical displacement-Rotation curves and (c), (d) Moment-Rotation curves of the suction caisson and spudcan foundations corresponding to the front leg of the full model with assumption of perfect interface conditions.

A general look at the displacement graphs (W-θ) (Fig. 6) shows that, for both systems, when the horizontal load is applied to the positive direction there is a simultaneous reduction of the vertical force of the foundation, leading to foundation uplifting. On the contrary, when the load is applied to the opposite direction, the vertical force of the foundation increases and, as a result, the footing settles. As the cyclic loading proceeds, the ratio of vertical displacement per cycle diminishes. By comparing the two foundations we can easily observe the dominance of the suction caisson in terms of vertical displacement. The rotation of the spudcan is almost twice as high the rotation of the suction caisson and thus, the settlement of this footing is greater. Although the gravity loads of the platform lead to a displacement of 4.9 and 4.6 cm for the caisson and the spudcan respectively, the total vertical displacement of the caisson is 8.5 cm whereas the displacement of the spudcan reaches the number of 10.5 cm. As a consequence, it may be concluded that the shape of the suction caisson and the embedded skirts enhance the rotational stiffness of the footing making it a more rigid solution.

As regards the moment-rotation (M-θ) graphs, observe that both solutions present greater moment and reduced rotation when the horizontal load is positive (positive rotation) and the vertical load of the footing decreases. When the load switches direction and the vertical load increases however, the moment is diminished and the rotation increases. This observation leads to the assumption that the leg axial force augmentation reduces the stiffness of the soil-foundation system and in this way, the rotation rises with a simultaneous reduction of the moment of the leg. The opposite phenomenon occurs when the vertical load decreases and the system becomes stiffer. Additionally, at the end of the first loading cycle, the moment of the leg presents a significant increase with a simultaneous reduction of the rotation due to the fact that the stiffness increases as the cyclic turning movement of the foundation confines the soil below. It is a process of loading, unloading and reloading of the soil elements that leads to this response of the system and that continues to happen during the next cycles with diminishing ratio of stiffness increase. Again, the caisson appears to be more robust leading to a system developing lower rotation values but increased moment at the base of the leg.

ALLOWING SEPARATION OF THE FOUNDATION AND THE SURROUNDING SOIL

As already stated in previous chapters, the full shear strength between the foundation and the soil may not always be available and detachment of the footing and the surrounding soil could occur during loading of the structure. Therefore, imperfect interface conditions are introduced to realistically simulate the response of the platform. Figure 8 displays the results of the 10 MN cyclic loading imposed on the platform in terms of vertical displacement-rotation (W/θ) and moment-rotation (M-θ) for the two types of foundation. Contact elements were introduced as implied by the previous discussion.

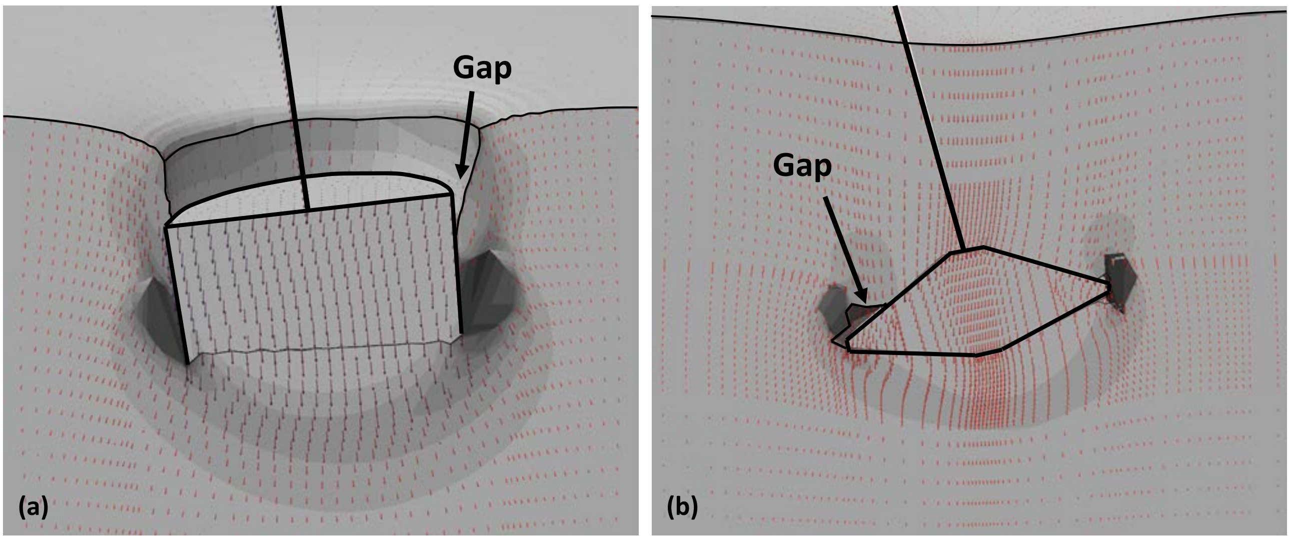

Figure 7. Deformed mesh presenting the separation of the foundation from the soil after the introduction of imperfect interface conditions to the model for: (a) suction caisson and (b) spudcan foundations.

A first comparison with the fully bonded foundation models shows that the existence of interfaces has a great influence on the response of the models, especially as regards the caisson foundation. Displacement (W-θ) graphs present a significant increase of the total vertical displacements of the caisson and a small increase of the rotations. This vertical and rotational stiffness reduction is a result of the shear strength degradation between the skirts and the soil and of the detachment which is allowed to occur while the horizontal load is applied on the structure. (Fig. 7). On the contrary, the loading of the spudcan results in the generation of mainly normal stresses on the interface of the footing and the soil. Hence, this type of foundation presents little sensitivity to the existence of imperfect interfaces and it appears that there are not substantial differences between the response of the tied assumption and the one investigated in this chapter. This is the reason why the two foundation solutions present a small difference in terms of total settlements whereas the suction caisson appeared to be much more efficient when the footings were fully bonded with the soil.

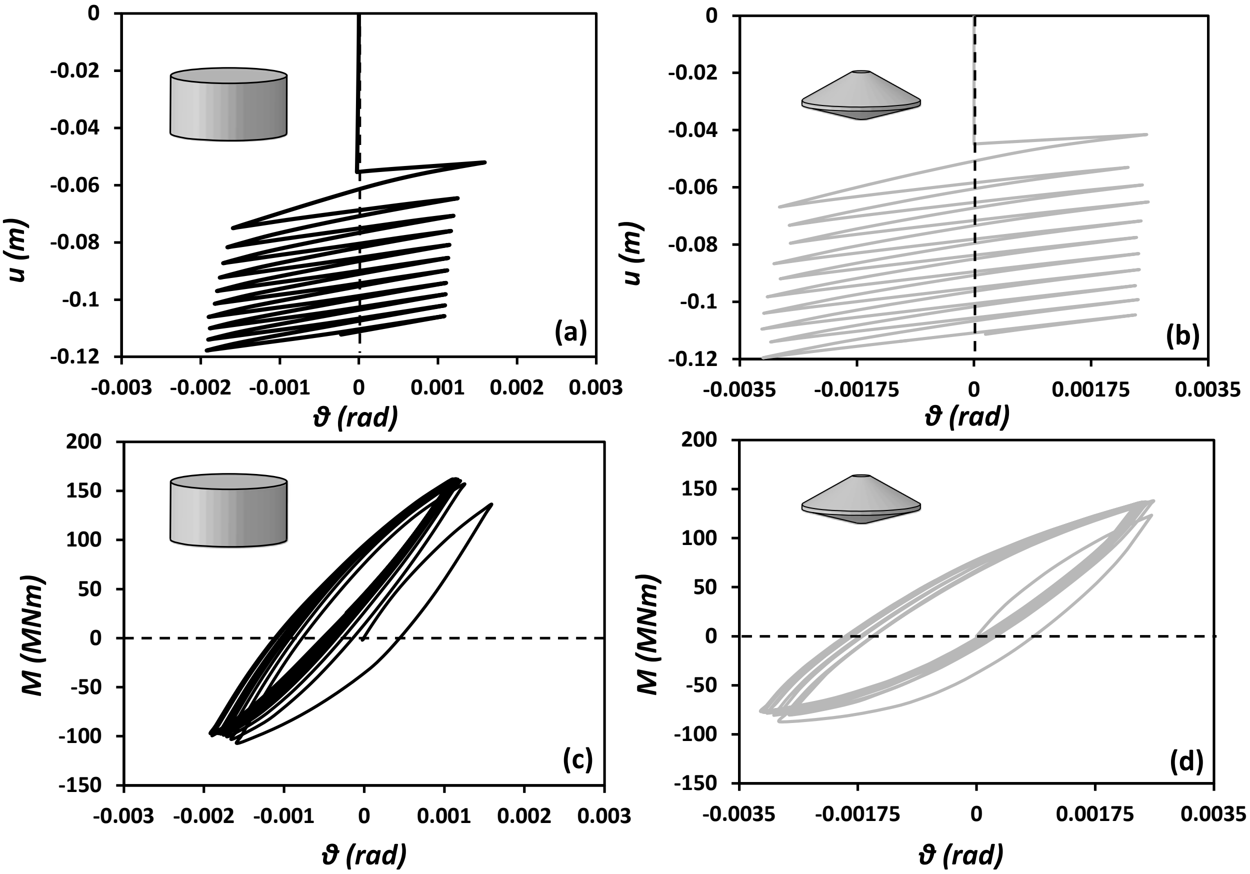

Figure 8. (a), (b) Vertical displacement-Rotation curves and (c), (d) Moment-Rotation curves of the suction caisson and spudcan foundations corresponding to the front leg of the full model with assumption of imperfect interface conditions.

RESPONSE OF THE SIMPLIFIED MODEL

At this part of the study, an investigation of the response of a simplified decoupled model that consists of the foundation, the one leg of the platform and a concentrated mass is attempted. The purpose of this simplified solution is to examine whether it is possible to use this cost-effective model, in terms of analysis time, in order to simulate the response of the foundation of the jack up platform under cyclic horizontal loading. Perfect interface conditions between the footings and the soil were assumed. Results for the two foundations are illustrated in Figure 9. We observe that the graphs at this occasion reflect a ly symmetrical shape as opposed to the graphs of the full model with perfect interface conditions. This difference is a consequence of the fixed vertical force that is imposed on the foundations during the cyclic loading that leads to a uniform settlement of the footings. Instead, the cyclic loading of the full model results in variations of the axial force conducing to the uplifting of the footings when the force is reduced and to the settlement of the footings when the vertical force increases. The total vertical displacement of the simplified caisson model, however, reaches the value of 8.4 cm, being very close to the value of the full model (8.5 cm). The same rule applies to the spudcan solution. On the other hand, this intense loading and reloading that results to the confinement of the soil, is not materialized. Hence, the response of the model in terms of rotations and moments is not the same; the total moments of the leg differ from the moments of the full model.

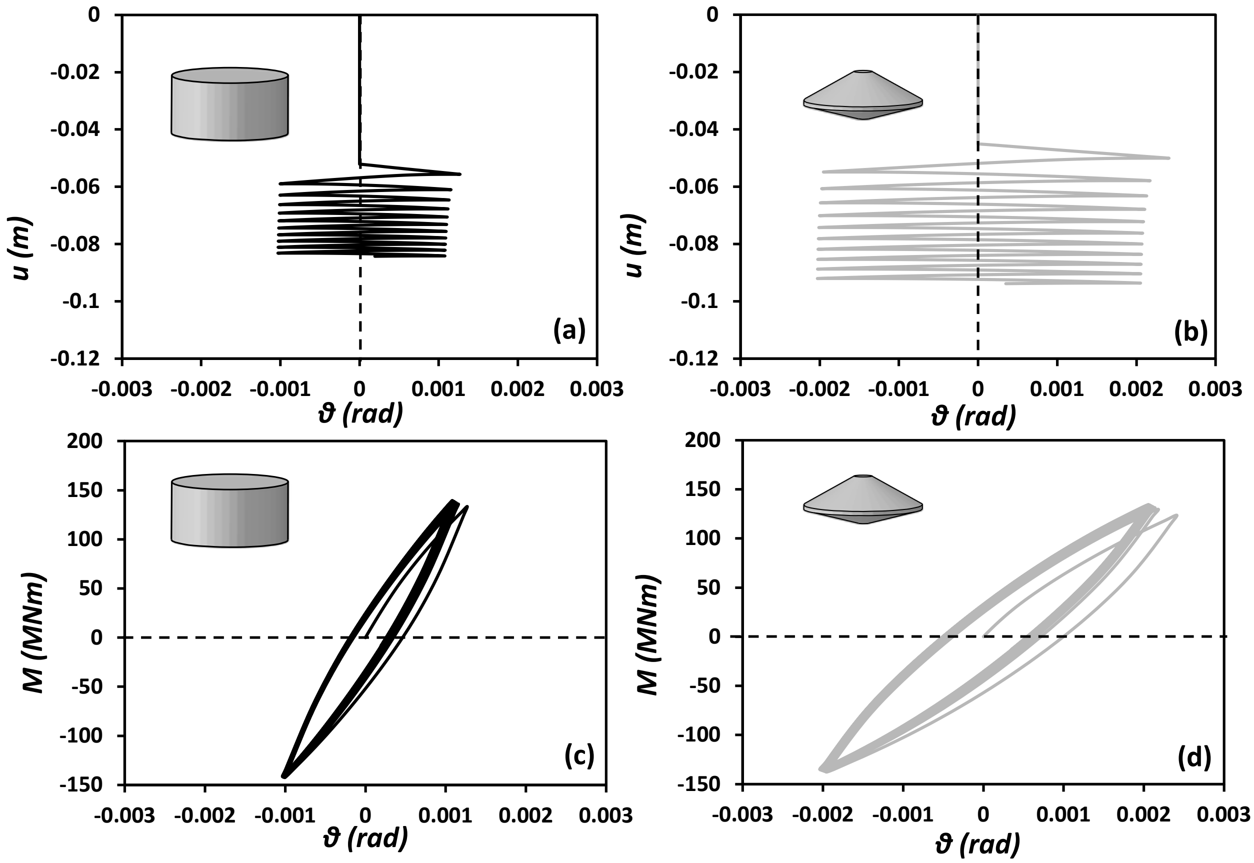

Figure 9. (a), (b) Vertical displacement-Rotation curves and (c), (d) Moment-Rotation curves of the suction caisson and spudcan foundations corresponding to the leg of the simplified model with assumption of perfect interface conditions.

CONCLUSIONS

In this paper two alternative foundation solutions for a jack up unit subjected to cyclic horizontal loading due to weather events are investigated; a spudcan and a suction caisson. The study utilizes 3D non-linear finite element analyses in order to make a preliminary comparison between the two footings and understand the behavior of the system platform-foundations under exposure to this environmental loading. Introduction of imperfect interface conditions between the soil and the foundations was made in order to realistically simulate the conditions after the installation of the two footings. In addition, simplified decoupled models of the platform were constructed and compared with the full models. The analysis has highlighted some interesting issues summarized below:

(i) the suction caisson appears to be a more robust solution for the foundation of the platform since the embedded skirts enhance its rotational stiffness

(ii) introduction of imperfect interface conditions leads to a substantial different response of the suction caisson but to small changes of the spudcan behavior

(iii) simplified models seem to work adequately in terms of total vertical displacements but not in terms of moment and rotation of the foundations as the effect of the structure is significant

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