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Effect of Soil-Pile-Structure Interaction on Behaviour of Offshore Jacket Structure

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Abstract

Offshore jacket structures are generally supported on pile foundations. Studies have evaluated the effect of soil-pile interaction on design of foundation; however, effect of soil-pile-structure interaction on behaviour of jacket structure has received little attention. Hence, present study focuses on understanding the influence of soil conditions, soil-pile interaction and foundation modeling approach on deformation characteristics and member forces of jacket structure. Linear static analysis on a typical 4-legged battered jacket structure is performed using STAAD Pro., subjected to dead/live loads and environmental loads. The water depth of 120 m and wave heights of 5 m, 10 m and 15 m are considered for this study. Morison's equation considering Stokes 5th order wave theory is used for calculation of wave forces on jacket structure. The supports are modelled as skirted pile groups. The piles are represented by springs, with stiffness calculated using soil-pile interaction analysis. The soil conditions used in the study are varied for different compaction states of sand and different consistency states of clay and various parameters such as lateral/vertical deflection, support reactions, forces in leg, beams and bracings have been compared. It is concluded that ignoring soil-pile-structure interaction during analysis of jacket structure would underestimate the lateral/vertical deflections, support reactions, shear force and bending moment for leg, and axial forces in beam and plan bracing of the structure. No substantial impact of the interaction on other member forces is observed. Jacket structure founded on clayey soil exhibits higher deformation and member forces as compared to sand in general. The study is expected to help structural engineers in adopting an appropriate modelling approach, considering soil-pile-structure interaction, to obtain more realistic response for jacket structures.

Keywords: Jacket Structure, Wave Load, Sand, Clay, Soil-Pile-Structure Interaction, Pile Stiffness, Structural Response

1. Introduction

The offshore jacket structures, used widely in oil and gas industry for exploration activities in oceans, can be located in different soil conditions encountered at the site of their placement. The response of the jacket structures depends on the behaviour of its supporting pile foundation and interaction of piles and soil below seabed. The interaction between piles and soil depends on the properties of both pile and soil. Researchers have investigated the response of the offshore jacket structures to the lateral soil movement and noted that the response of the pile to soil movement depends upon the axial load and fixity conditions at the pile head, while the effect of extreme environmental loading conditions were predominant on the structure [1]. Another study concluded that while performing analysis, soil-pile-structure interaction should be taken into consideration for the design of offshore jacket structure, as it was observed that natural frequency of the jacket structure decreases due to the soil-pile-structure interaction in sand, consequently increasing the relative displacement and equivalent modal damping of the structure [2]. The study on soil-pile modelling parameters in clay by El-Din and Kim revealed that variability in skin friction parameters has higher impact on maximum top displacement followed by maximum inter-story drift ratio, but the end bearing parameters have little effect on the response of the jacket structure [3]. The results of analysis performed in another study considering soil-structure interaction revealed that the topside drift and the natural time period of the jacket structure increases significantly with the consideration of marine growth. This is attributed to the increase in mass of the jacket structure without any contribution towards its stiffness due to the marine growth. It has also been observed that the wave direction has considerable influence on the response of jacket structural members in terms of axial force, shear force and bending moment [4]. Karimi et al. carried out the push over analysis on damaged offshore jacket structures to study the sensitivity of the structure to failure and found that damage to the upper portion of the jacket renders it to be un-operational, while damage to the legs/braces makes the structure most vulnerable to failure [5]. Studies on the

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response of various structures viz. reinforced concrete chimney, wind turbine tower and tall building, in terms of displacement and acceleration when subjected to wind forces considering soil structure interaction revealed that response of the structures considered and design parameters of dampers provided to control their response are affected considerably by the type of soil. Moreover, distributed multiple tuned mass dampers have been found to be more efficient in controlling multi-mode response compared to single tuned mass damper [6, 7, 8]. The study of literature reveals that the effect of pile-soil interaction (including the effect of varying soil conditions) on the response of jacket structure has not been studied much. Hence, the present study focuses on understanding the influence of different soil conditions on the deflection, member forces and support forces for jacket structure. This is achieved by modelling the jacket structure supports in STAAD Pro. model with pile spring stiffness (corresponding to different soil conditions), viz., considering the soil-pile-structure interaction, and comparing the response of the jacket structure among the different cases. It is opined that such studies would help the structural engineers in adopting an appropriate modelling approach for the jacket structure considering soil-pile-structure interaction to obtain realistic response and reliable design of the jacket structure members and their connections.

2. Methodology

To achieve the objectives of the study, a 4-legged, 7° battered jacket structure has been considered in the study. The base is square shaped and the structure is provided with X-pattern of bracing. The structure has been statically analyzed for vertical and lateral environmental loading conditions, considering that fundamental time period of the structure is away from the time period of the wave action. The top dimensions of the jacket structure are 10m x 10m. For the study, the height of jacket structure is considered as 135m corresponding to the water depth of 120m and the wave height has been varied as 5m, 10m and 15m. All members of the jacket structure are tubular members; wherein, the leg member has outer diameter of 2m and thickness of 0.06m, while beam members have outer diameter of 1.1m and thickness of 0.03m. The vertical and plan bracing have outer diameter of 0.9m and thickness of 0.02m.

2.1 Details of load application on the Jacket Structure

The jacket structure is supporting both vertical and environmental lateral loads. The vertical load includes dead load due to the self weight of the jacket structure and other miscellaneous loading (viz., conductors and other utilities) supported on it as well as live load. A deck area of about 25m x 25m (not modeled) is considered to be supported on the jacket structure at top with a loading as 32 kN/m^2. The point load due the deck loading on each leg of jacket structure is 5000 kN. The environmental lateral loads are caused by wind, wave and current loading and are applied in both diagonal and orthogonal directions on the jacket structure. The application of conductor load on the horizontal beams of jacket structure in STAAD model is shown in figure 1.

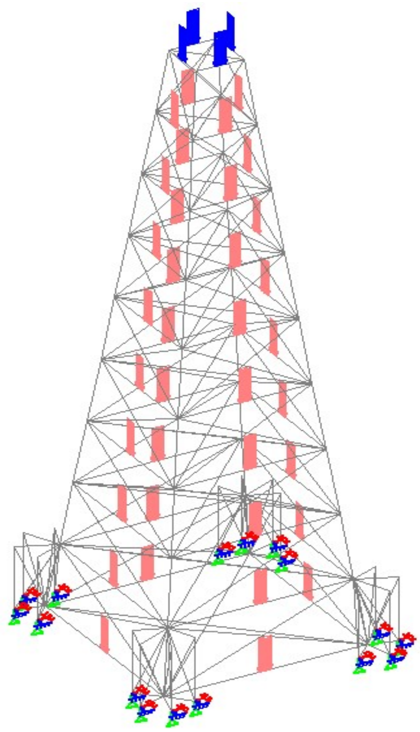


Fig. 1 Typical application of conductor loads on horizontal beams of jacket structure

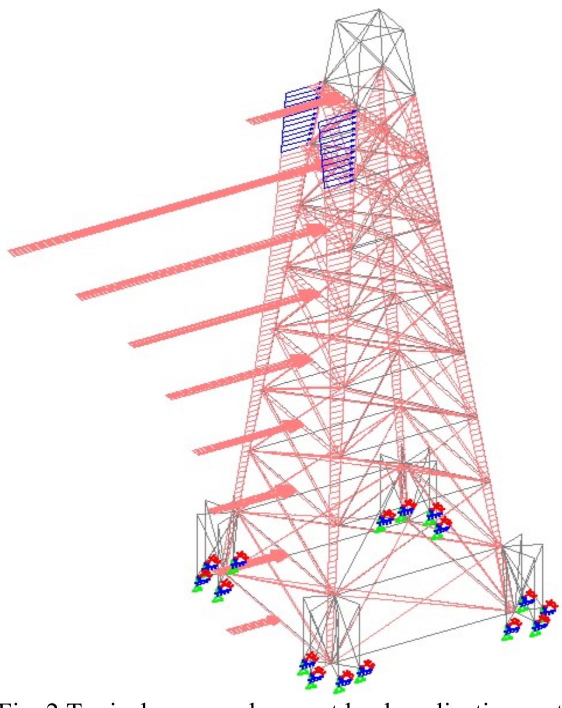


Fig. 2 Typical wave and current load application on the members of jacket structure

For computation of the wave and current load on the jacket structure, the Morison's equation has been utilized. The Stokes 5th order wave theory has been employed for calculating the velocities and acceleration for wave and current effects. The inline velocity of current at the mean sea level is considered as 2 m/s. Figure 2 shows the typical wave and current load application on the members of the jacket structure in STAAD model. For application of wind load, a wind speed of 30 m/s (over one hour time period) has been considered. The wind load is applied on the top members of jacket structure above the mean sea level, as shown in the

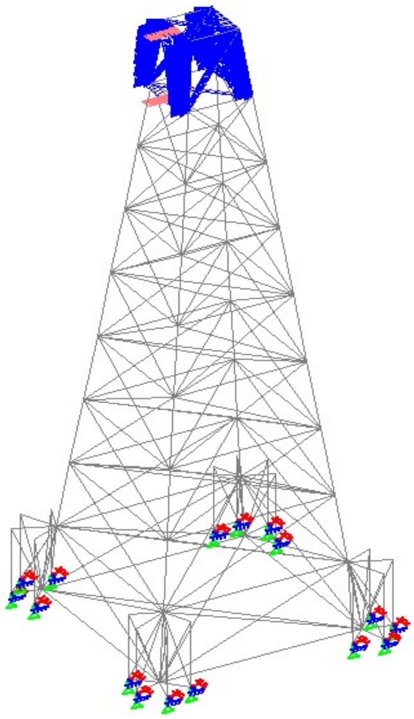


Fig. 3 Typical wind load application on the members of jacket structure

figure 3. The parameters kept constant in the study includes the deck loading, the current velocity and the wind load. The load combinations as per recommendations of API RP 2A - WSD have been considered in the study [9].

The support provided by the soil-pile system to the legs of the jacket structure is considered as springs having stiffness based on the soil-pile interactions, allowing displacement and rotation of support. The pile stiffness has been computed as the ratio of design load and the corresponding displacement for vertical and horizontal stiffness of pile (K_V and K_H respectively). For computing the rotational stiffness (K_θ), the design moment has been divided with the corresponding rotation of pile. For three states of compaction of sandy soil (loose, medium dense and dense) and three different consistency states of clayey soil (soft, medium stiff and hard), the pile stiffnesses (in case of sandy soils) and pile cluster stiffnesses (in case of clayey soils) have been computed and applied in the respective STAAD models. The vertical and horizontal displacement as well as pile rotation; have been computed considering the group interaction effects from other piles in the group for sandy soil, and other piles in the cluster as well as between the clusters for clayey soil as per recommendations in the literature [10, 11]. The plan view of the pile foundation in sand and clay are presented in figures 4 and 5, while the details and their stiffness values are presented in tables 1 and 2.

2.2 Support conditions for the Jacket Structure

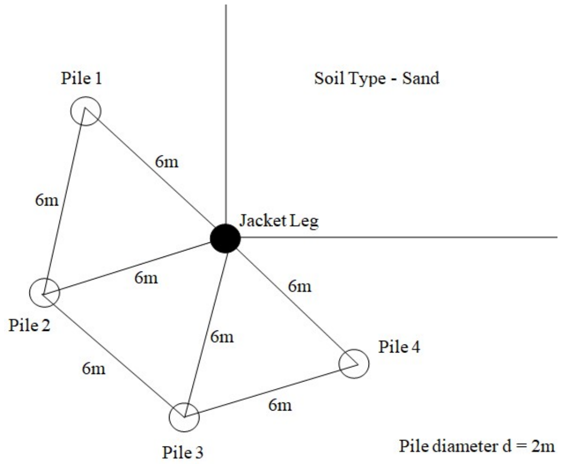


Fig. 4 Plan view of skirt piles configuration at base of jacket structure in sand

Table-1 Details of the pile foundation in sand

Parameters \ Soil type	**Sand (4 piles for each leg)**		
Factor of safety (FOS)	2		
Vertical design load on pile, P (kN)	9502		
Horizontal design load on pile, H (kN)	2397		
Design moment on pile, M (kNm)	2247		
Pile material	Structural steel		
Elastic modulus of pile, E_p (kN/m^2)	2×10^8		
No. of piles under a leg, n	4		
Outer diameter of pile, d (m)	2		
Thickness of pile section, t (mm)	60		
Length of pile, L (m)	35		
Pile spacing (m), centre to centre	6		
Soil state	Loose	Medium	Dense
Friction angle, ϕ (degree)	30	35	40
Poisson's ratio, ν_s	0.30	0.30	0.30
Elastic modulus of soil, E_s (kN/m^2)	27500	55000	80000
Vertical stiffness of a pile, K_V (kN/m)	249669	435890	613058
Horizontal stiffness of a pile, K_H (kN/m)	88537	163169	227098
Rotational stiffness of a pile, K_θ (kNm/degree)	207998	262151	296517

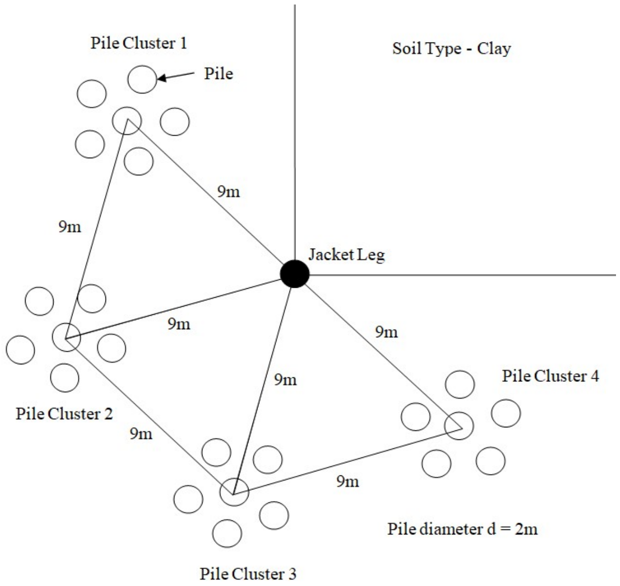


Fig. 5 Plan view of skirt piles configuration at base of jacket structure in clay

Table-2 Details of the pile foundation in clay

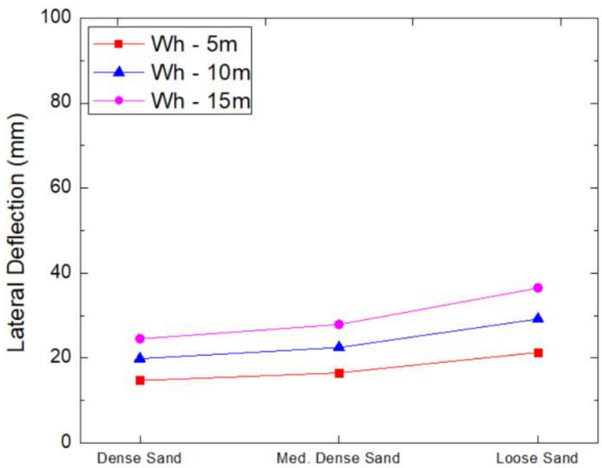
Soil type / Parameters	Clay (4 clusters of 6 piles in a cluster, for each leg)		
Factor of safety (FOS)	2		
Vertical design load on a pile cluster, P (kN)	44366		
Horizontal design load on a pile cluster, H (kN)	2786		
Design moment on a pile cluster, M (kNm)	3300		
Pile material	Structural steel		
Elastic modulus of pile, E_p (kN/m^2)	2 x 10^8		
No. of pile clusters under a leg, n	4 clusters of 6 piles in a cluster per leg (24 piles per leg)		
Diameter of pile, d (m)	2		
Thickness of pile section, t (mm)	60		
Length of pile, L (m)	100		
Pile cluster spacing s (m), centre to centre	9		
Soil state	Soft	Medium	Hard
Cohesion, c (kN/m^2)	25	50	100
Poisson's ratio, ν_s	0.45	0.35	0.30
Elastic modulus of soil, E_s (kN/m^2)	8270	15550	46150
Vertical stiffness of a pile cluster, K_V (kN/m)	151059	262956	581994
Horizontal stiffness of a pile cluster, K_H (kN/m)	36924	63966	167488
Rotational stiffness of a pile cluster, K_θ (kNm/degree)	166566	202894	285480

It may be noted that the vertical load for pile group in clay (refer table 2) is significantly larger than that in sand (refer table 1) as weight of soil plug within the tubular pile and self-weight of pile is higher in clay due to long and higher number of piles.

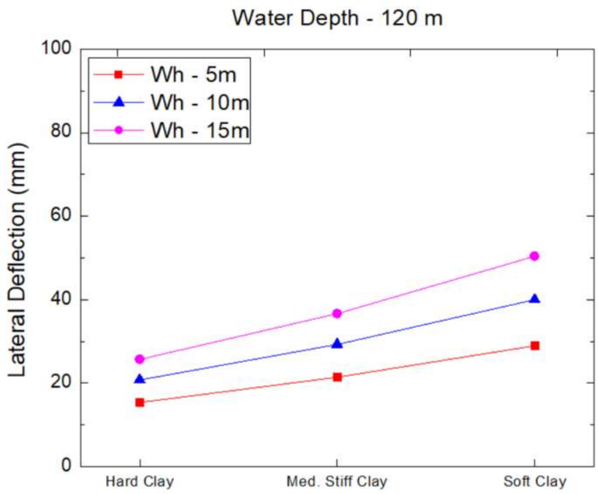
3. Results from Numerical Study

The maximum lateral and vertical deflection, support reactions and moments, and member forces are considered as the response of the jacket and are discussed below for all the cases studied viz., water depth of 120m and wave heights of 5m, 10m and 15m for pile foundation in varying compaction/consistency states for sand and clay.

The maximum lateral deflection as shown in figure 6 increases in an approximately linear manner with variation in soil state (dense to loose for sand and hard to soft for clay) and wave height, and greater effects are observed for pile foundation in clay as compared to that in sand. Similar trend is observed for vertical deflections in both sand and clay, but values remains constant with change in wave height as illustrated in figure 7.



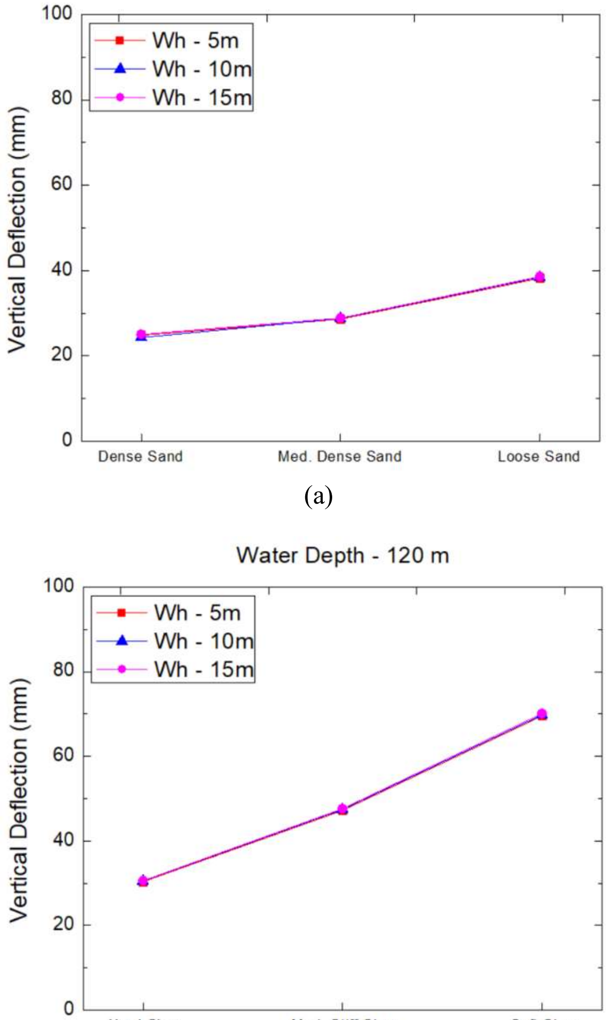
(a)



(b)

Fig. 6 Maximum lateral deflection of jacket structure supported on pile foundation in (a) sand and (b) clay

The maximum vertical support reactions values remain nearly constant with change in soil state, besides the effect of increase in wave height being insignificant for all cases. Further, vertical support reactions are higher for pile foundations in clay compared to that in sand. The maximum horizontal support reactions appear to be decreasing linearly with reduction in the stiffness of soil (change of soil state from dense to loose for sand and hard to soft for clay). The results in both sand and clay are comparable. The maximum support moments similar to vertical reactions, remain nearly constant for different state of compaction/consistency of soil, the values being higher for pile foundations in clay compared to that in sand. Additionally, it has been observed that the change in wave height has visibly small influence on support moment for all cases, except loose sand and soft clay. This may be attributed to relatively larger sway of jacket structure with foundation in loose sand/soft clay leading to additional moment.

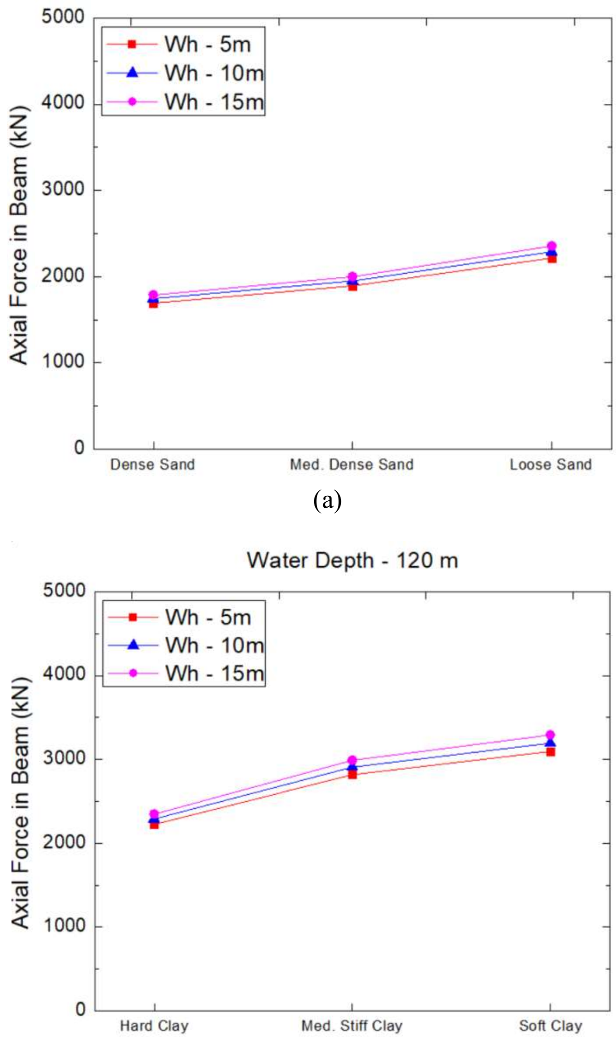


(a)

(b)

Fig. 7 Maximum vertical deflection of jacket structure supported on pile foundation in (a) sand and (b) clay

The maximum axial force in legs follows the trend for maximum vertical support reaction and remains nearly constant with change in soil compaction state, with insignificant variation with increase in wave height. Also, they appear to be independent of soil type being sand or clay. The maximum axial forces in beams illustrated in figure 8 increases more or less in a linear manner with reduction in stiffness of the base of jacket structure (based on change in soil compaction state from dense to loose sand or hard clay to soft clay). The increase is more prominent for foundation in clay as compared to sand, while experiencing insignificant effects due to change in wave height. It is also noted that with reduction in stiffness of jacket base support, the horizontal support reactions reduce, while axial force in beam increases. This indicates that reduction in stiffness of foundation system (due to pile-soil interaction) would increase the lateral movement and local forces in the horizontal members, while the horizontal reactions transferred to the foundation system would reduce.



(a)

(b)

Fig. 8 Maximum axial force in beams of jacket structure supported on pile foundation in (a) sand and (b) clay

The maximum bending moment and shear force in the legs, as depicted in figure 9, are observed to be increasing linearly as the soil states change from dense/hard to loose/soft and are affected slightly due to wave height. However, the effect of variation in soil state and wave height on the bending moment and shear force in beams is not observed. Also, bending moment and shear force get enhanced for leg members with for pile foundation in clay as compared to sand, but for beam members these values remain unaffected by type of soil.

Foundation soil compaction states and soil types both have no influence on the maximum values of minor axis bending moment and shear force for beams (lateral effect on beams) of jacket structure, but the increase in wave height increases these values quite significantly. This can be reasoned by the

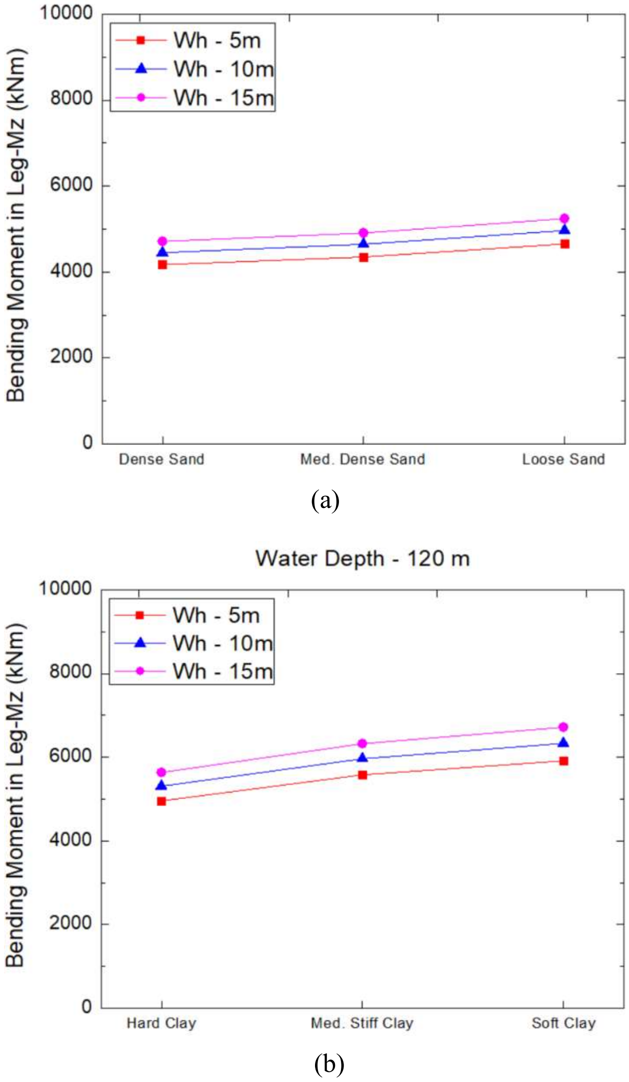


Fig. 9 Maximum bending moment in legs of jacket structure supported on pile foundation in (a) sand and (b) clay

fact that as the local action of wave forces acts on the beams, their effect is prominent on the beams near the mean sea levels or above that, where the wave forces are at their maximum. Hence the foundation soil type or state has no influence on this localized action.

The maximum axial forces in the vertical bracing remain unaffected with change of soil compaction state and soil type as the distribution of force to vertical bracing is more sensitive to the jacket structure geometry such as spacing between legs, angle and number of vertical bracings sharing the load, etc. There is visible increase in the axial forces of the vertical bracing with increase in wave height. The effect of wave height on maximum axial force in plan bracing is not evident, but they exhibit increased axial forces with change in the soil type, with the values being higher for the pile foundation in clay as compared to sand.

Maximum bending moment and shear force in bracings are observed to be independent of all the varying factors considered in this study.

The summary of percentage variation in the values of different response parameters of jacket structure, when the soil supporting the pile foundation changes from sand to clay; has been presented in table-3.

Table-3 Change in response of jacket structure considering soil-pile-structure interaction with change in soil type from sand to clay

Particulars of structural response for jacket structure		**Change in response (%) when foundation soil type changed from sand to clay**		
		Loose sand to soft clay	**Med. dense sand to med. clay**	**Dense sand to hard clay**
Deflection	Lateral	38.2	31.47	4.61
	Vertical	81.6	64.86	22.27
Reaction force, Reaction moment	Horizontal	-13.54*	-15.915*	1.6
	Vertical	36.08	36.4	39.42
	Moment	19.17	17.34	26.68
Axial force	Leg	0	0	0
	Beam	39.85	49.5	31.34
	Vertical bracing	4.84	4.93	3.82
	Plan bracing	44.02	43	35.44
Major bending moment	Leg	28.04	28.86	19.56
	Beam	0	0	0
	Vertical bracing	0	0	0
	Plan bracing	0	0	0
Vertical shear force	Leg	22.23	22.51	15.258
	Beam	0	0	0
	Vertical bracing	0	0	0
	Plan bracing	0	0	0
Minor bending moment	Beam	0	0	0
Horizontal shear force	Beam	0	0	0

*negative value of parameter indicates reduction in values when foundation soil type is changed from sand to clay

Percentage variation in values of different response parameters of jacket structure with variation in the soil compaction/consistency state and wave height has been presented in table-4 below.

Table-4 Change in response of jacket structure considering soil-pile-structure interaction with change in compaction/consistency state of soil and wave height

Particulars of structural response for jacket structure		**% variation in parameter when soil state changes from: (with 120m water depth and 15m wave height)**		**% variation in parameter when wave height changes from: (with 120m water depth)**	
		Dense to loose sand state	**Hard to soft clay state**	**5m to 15m wave height (loose sand)**	**5m to 15m wave height (soft clay)**
Deflection	Lateral	48.75	96.53	71.17	74.09
	Vertical	54.3	129.16	0	0
Reaction force, Reaction moment	Horizontal	-24.36*	-35.64*	45.92	54.76
	Vertical	-2.6*	-4.96*	6.95	4.74
	Moment	7.07	0	15.02	15.65

Axial force	Leg	0	0	11.65	11.64
	Beam	31.68	40.22	6.18	6.35
	Vertical bracing	0	0	19.33	35.77
	Plan bracing	5.92	12.64	0	0
Major bending moment	Leg	11.32	19.22	12.65	13.55
	Beam	0	0	0	0
	Vertical bracing	0	0	0	2.36
	Plan bracing	0	0	0	0
Vertical shear force	Leg	8.48	15.05	7.4	8.84
	Beam	0	0	0	0
	Vertical bracing	0	0	0	0
	Plan bracing	0	0	0	0
Minor bending moment	Beam	0	0	60.34	60.35
Horizontal shear force	Beam	0	0	34.2	58.59

*negative value of parameter indicates reduction in values; when compaction / consistency state of foundation soil is changed from dense to loose sand/hard to soft clay; when wave height changes from 5m to 15m

4. Conclusions

From the comparative study of maximum values of deflection, support reactions and member forces when soil type is changed from sand to clay and when compaction/consistency states of sand/clay are changed from loose/soft to dense/hard (considering soil-pile-structure interaction for different soil conditions) for different wave heights, following conclusions can be obtained:

- The effect of soil-pile-structure interaction is more observed to be more prominent for jacket structure on clay as compared to sand.
- Flexure design of legs and axial design of beams and plan bracings along with the serviceability requirements can be expected to be significantly affected because of the soil-pile-structure interaction.
- Although foundations pile spring stiffness values are comparable when soil type is sand or clay, to achieve this comparable stiffness the number of piles and length of piles required in clay are significantly higher and the piles have to be provided in clusters in clay. Based on this, it can be opined that pile foundations for offshore jackets in clay might be more expensive and hence consideration of soil-pile-structure interaction would be important in such cases.
- Influence of change in compaction or consistency states of a soil type is limited to deflection of the jacket structure and axial design of the beams.
- While designing for extreme wave conditions, design of the jacket structure members needs to carefully ensure the flexural strength of beams in the local lateral direction, axial capacity of vertical bracing, as well meet the serviceability requirements, in both sand and clay soil.

Disclosures

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