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A Parametric Study on Effect of Wave Height, Water Depth and Support Conditions on Behaviour of Offshore Jacket Structure

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Abstract

Fixed offshore jacket structures are constructed for facilitating oil/gas exploration and production. These structures and their foundations are designed to resist large vertical and lateral loads. Various factors including water depth, wave height and support conditions would affect the response of jacket structures. However, few studies have focused on understanding the response of offshore jacket structure due to variation in these factors. In this context, the present work evaluates response of typical X-braced, square base, 4-legged battered jacket structure using STAAD Pro. under combined vertical and lateral environmental loading. The variables included are water depth (60 m, 90 m and 120 m), wave height (5 m, 10 m and 15 m) and two foundation modelling approaches (viz., fixed at pile location and with defined pile stiffness). The connection between structure leg and pile location is modelled to simulate realistic connection. Deck loads, wind forces and current velocities are considered constant for this study. The wind and wave loads have been applied in parallel, perpendicular and diagonal directions with respect to jacket structure. The wave forces are calculated by Morrison's equation. For obtaining pile stiffness, medium dense sand layer is considered as foundation soil. The increase in water depth and wave height results in corresponding linear increase in lateral deflection and support reactions, the effect of water depth being more prominent. Moreover, lateral and vertical deflection, shear force and bending moment in the legs, the axial forces in the lower tie beams and plan bracings, and support moments are observed to increase when pile locations are modelled with appropriate vertical, lateral and rotational stiffness instead of fixed support. The effect of water depth on member forces is higher as compared to wave height. The present work deliberates on the mechanisms/reasons to explain the observed results and contributes in direction of framing decision matrix for design optimization of jacket structures.

Keywords: Jacket Structure, Wave Load, Water Depth, Wave Height, Pile Stiffness, Structural Behavior

1. Introduction

Fixed offshore jacket are used extensively in the oil and gas industry and are usually tubular space frame structures with welded connections. These structures may be subjected to large lateral loads, especially wave and current loads depending on the environmental conditions and water depths encountered at locations of their placement. Hence, understanding of the extent to which water depth, wave height and support conditions would affect the response of jacket structures is deemed important in this study. Offshore structures generally have natural period varying between 1 to 4 seconds, and as wave periods are generally higher than this range, the assumption of static analysis has been reported to be acceptable, and an equivalent static wave analysis using dynamic amplification factor can be performed for offshore jacket structures [1]. The static and dynamic analysis performed by the researchers on offshore jacket to study the effect of foundation flexibility and pile-soil-pile interaction suggested that the overall response increases along the height of the jacket structure [2]. Offshore structures have to be designed for its safety and operational performance under both operating and extreme conditions throughout its lifespan. Owing to huge investment in oil and gas exploration activities, the safety and operational performance of offshore jacket structures becomes very important. The response of various bracing configurations to the lateral loading under the application of pushover and cyclic loading conditions was evaluated in an earlier study and it was noted that X-bracing offers superior lateral resistance [3]. Another study conducted linear static analysis on an existing offshore jacket structure located in Persian Gulf under extreme wave load conditions. Unity ratio of members and joints were found to be exceeding the limit, especially for those located in wave splash zones, while the topside drift of jacket was observed to be exceeding the limit of H/200 (where H is the height of the jacket) as stated in AISC-2005. Based on the results of in-place strength evaluating parameters (viz., unity ratio and displacement), it was observed that the jacket structure is

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unfit for its required performance [4, 5]. The peak drift was termed as the most important and suitable response parameter in a research study, as it can represent both pile and structural failure together [6]. Another recent research work performed the pushover analysis on a newly designed offshore jacket structure to study its failure modes under different wave heights, weak and strong soil profiles and varying pile stiffness and concluded that it is desirable to design the piles with lower utility ratio values than that of the brace elements, as the pile stiffness is the governing factor in determination of the failure mode of jacket structure and its foundation [7]. Thus from the literature review on existing studies on offshore jacket structure, the response of offshore jacket structures is regarded to be significantly dependent on the behaviour of foundation system. An important fact to be considered for understanding the foundation response is the nonlinear soil behaviour and the pile-soil interaction. This interaction would further affect the pile-jacket structure interaction. Hence an effort is made to understand this pile-structure interaction in order to predict the behaviour of jacket structures in a more realistic manner. Further, the effect of variation in water depth and wave height on response of jacket structure has also been studied.

2. Methodology

The variations in the response of jacket structure with and without pile-structure interaction for offshore jacket structures is assessed, establishing the importance of its consideration in the static analysis of offshore jacket structure. To achieve this, static analysis on a typical X-braced, square base, 4-legged battered jacket structure has been performed using STAAD Pro. under the combined effect of gravity and lateral environmental loading conditions. Plan dimensions at the top of the jacket are 10m x 10m and that at the bottom are calculated correspondingly by considering the batter angle of leg as 7°. The jacket structure's height is varied as 75m, 105m and 135m corresponding to the varying water depths of 60m, 90m and 120m in which they are placed, while the wave height (which affects the wave force) experienced by the structure is varied as 5m, 10m and 15m. Details of section dimensions of various members of jacket used are given below in the table-1.

2.1 Loads Applied on Jacket Structure

The jacket structure is subjected to a combination of gravity and lateral environmental loads. Weight of jacket structure and various facilities, fluid and live loads are considered under gravity load, while environmental load acting on the jacket structure are considered to be caused by wind, wave and associated current effects. Deck load of 32kN/m^2 for a deck area of 25m x 25m, has been considered to be supported by the legs of jacket structure. The deck structure is not modelled as they do not provide significant

Table-1 Dimensions of jacket member's section

Member	Outer diameter (m)	Thickness (mm)
Leg	2	60
Beam	1.1	30
Braces	0.9	20

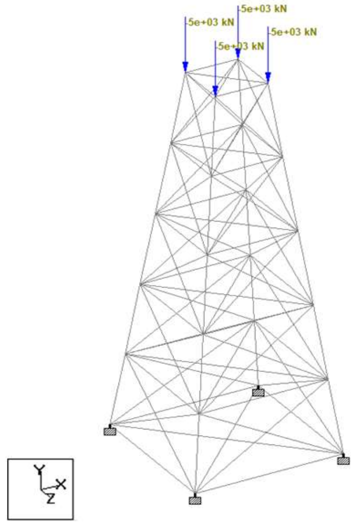


Figure 1 Deck loads transferred on the top of the legs

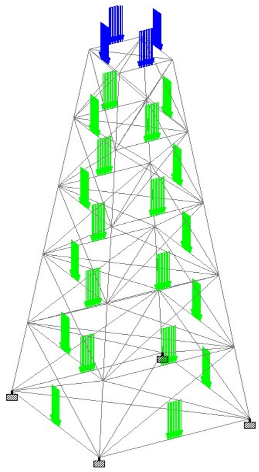


Figure 2 Conductor loads transferred on horizontal beams

stiffness to the offshore platform and 5000 kN is applied as point load corresponding to weight of deck structure acting directly on each of the four legs of the jacket in STAAD Pro. model as shown in figure 1. Conductor pipes are assumed to be supported from the deck to the sea bed level by the horizontal beams over a width of 2.5m, at every 15m (bay height), and dead weight and fluid load of 2 kN/m each is applied on the horizontal beams in STAAD Pro. model as shown in figure 2.

Sustained wind speed of 30 m/s taken over duration of the order of an hour, is used to calculate global wind loads on jacket members/conductors using equations of wind force calculation as recommended by API [8], and is applied on the jacket structure in STAAD Pro. model as shown in the figure 3.

The Morison's equation is used for calculation of combined wave and current forces on the members of the jacket structure. Wave and current induced velocities and accelerations have been calculated considering the Stokes 5th order wave theory, with the inline current velocity considered as 2 m/s at mean sea level. Global wave and current forces are applied on the jacket structure in STAAD Pro. as shown in figure 4. The environmental loadings viz. wind, wave and current forces are considered in orthogonal and diagonal directions viz. 0°, 45° and 90°, with respect to

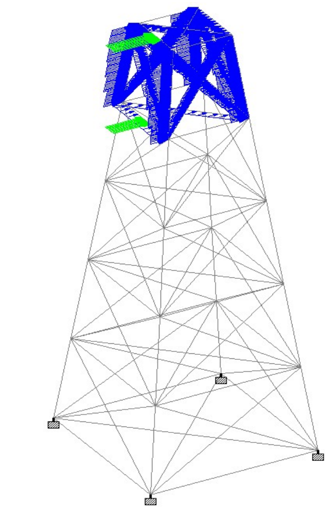


Figure 3 Wind loads applied on jacket structure members

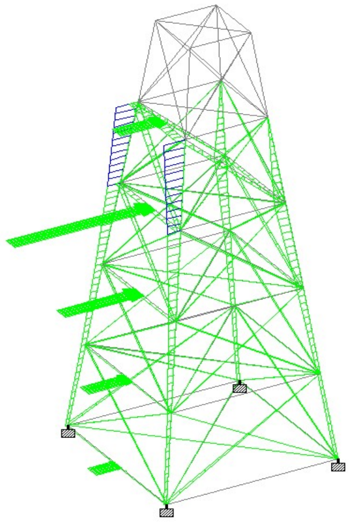


Figure 4 Wave and current loads applied on jacket structure members

jacket structure. The values of deck load, wind force and current velocity have been considered same for different cases studied. The load combinations used for the analysis of offshore jacket structure are according to API [8].

2.2 Jacket Support Condition

The support provided by the soil-pile system to the legs of the jacket structure at the sea bed level is considered either as fixed without allowing any displacement and rotation at support, or as springs having stiffness based on the soil-pile interaction. For obtaining pile stiffness, taken as ratio of design load or moment on pile and corresponding displacement or rotation of pile, respectively; medium dense sand layer is considered as foundation soil. Considering the effect of interaction from other piles in the group, vertical settlement of pile is calculated using settlement formula given in literature [9], while horizontal displacement and rotations are calculated using the equations given by Pender [10]. The details of the pile foundation (skirt piles arrangement around the jacket leg) and their stiffness values are presented in table-2 and in figure 5. It may be noted that the vertical loading stated in table-2 for evaluation of pile stiffness includes the self-weight of pile and soil plug inside the tubular steel pile sections.

Table-2 Details of pile foundation in medium dense sand

Soil type / **Parameters**	**Sand (4 piles for each leg)**
Factor of safety (FOS)	2
Vertical design load, P (kN)	9502
Horizontal design load, H (kN)	2397
Design pile moment, M (kNm)	2247
Pile material	Structural steel
Pile modulus, E_p (kN/m^2)	2 x 10^8
No. of piles in a group, n	4
Pile diameter, d (m)	2
Pile thickness, t (mm)	60
Pile length, L (m)	35
Pile spacing, s (m)	6
Soil state	Medium dense sand
Angle of friction, ϕ (degree)	35
Poisons ratio, ν_s	0.30
Soil modulus, E_s (kN/m^2)	55000
Vertical pile stiffness, K_V (kN/m)	435890
Horizontal pile stiffness, K_H (kN/m)	163169
Rotational pile stiffness, K_θ (kNm/degree)	262151

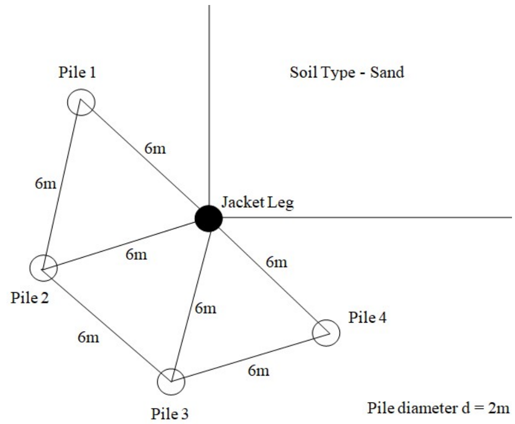


Figure 5 Plan view of skirt piles configuration at base of jacket structure in medium dense sand

3. Numerical Study

The response of the jacket structure in terms of maximum lateral and vertical deflection, support reactions and member forces for all the cases studied, viz., water depths of 60m, 90m and 120m and wave heights of 5m, 10m and 15m for both fixed base and with pile spring supports are discussed below.

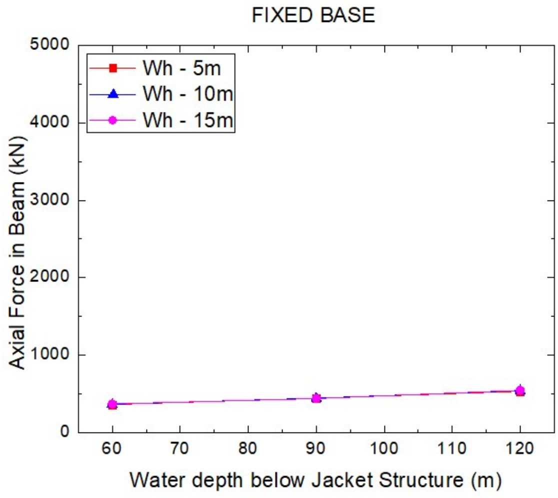
For both fixed base case and with pile springs, an almost linear increase is observed in the maximum lateral deflection of the jacket structure with increase in water depth and wave height, but the effects are magnified for the latter. The maximum vertical deflection increases linearly with increase in water depth without experiencing any influence due to change in wave height, and similar to lateral deflection, the effect of water depth is higher for case with pile springs as compared to fixed base. For the case of 120m water depth and 15m wave height, with the change in support condition from fixed to pile spring the lateral deflections increase from 16 mm to 28 mm, while the vertical deflections increase from 15 mm to 29 mm.

The maximum vertical support reaction also increases linearly, with increase in water depth as anticipated; while on the contrary, the impact of increase in wave height on the vertical support reaction is insignificant for both the support conditions. Moreover the effect of the modelling pile springs is found to reduce the vertical support reactions compared to the fixed support. With the change in support condition from fixed to pile spring, the vertical support reactions decrease from 7526 kN to 6580 kN for the case of 120m water depth and 15m wave height.

It is also observed that the maximum horizontal support reactions increase linearly with water depth as well as wave height for fixed support, whereas only minor increase is visible on the jacket horizontal support reaction modelled with pile springs. Also the horizontal support reaction decreases from 2397 kN to 664 kN (for the case of 120m water depth and 15m wave height) with change of foundation support conditions from fixed to pile springs, which indicates that defining pile spring introduces some flexibility to the supports as compared to fixed support, which results in higher support displacement and lower support reactions for case with pile springs.

The maximum support moment, similar to vertical reaction, increases linearly with water depth for the cases with fixed support as well as pile springs. However, the effect of change in wave height for fixed based foundation is negligible, while some increase in support moments is visible for the case with pile springs.

The maximum axial forces in legs similar to the maximum vertical support reactions increase linearly with increase in water depth while appearing to be independent of change in wave height and foundation support condition. The maximum axial forces in beams, shown in figure 6, seems to be free of any influence due to the variation of wave height and exhibit some effect of water depth for fixed support and this may be attributed to predominant contribution of vertical and plan bracing in distributing the lateral loads. However, in the case of jacket structure modelled with pile springs, axial force in beams increases with increase in water depth with no visible effect of wave height. The axial forces in beam are higher, when pile springs are modelled instead of fixed support, probably due to the higher distribution of lateral forces to beam at the joints due to joint flexibility (introduced by flexible pile springs as compared to fixed support) and higher sway of structure. The variation in maximum bending moment and shear force in legs appear to be following the same trend of increasing linearly with increase in water depth (refer to figure 7). Whereas, effect of increase in wave height on the change in bending moment and shear force is insignificant. This is due to the fact that the increase in wave loads, corresponding to the increase of wave height, is not very significant considering the large height of structure below water. Here, the values of bending moment and shear forces get enhanced for leg members, when the supports are modelled with pile springs instead of fixed supports, and this effect is observed to be higher at higher water depths. The modelling approach for support does not seem to have any influence on the maximum major axis bending moment and shear force in beams.



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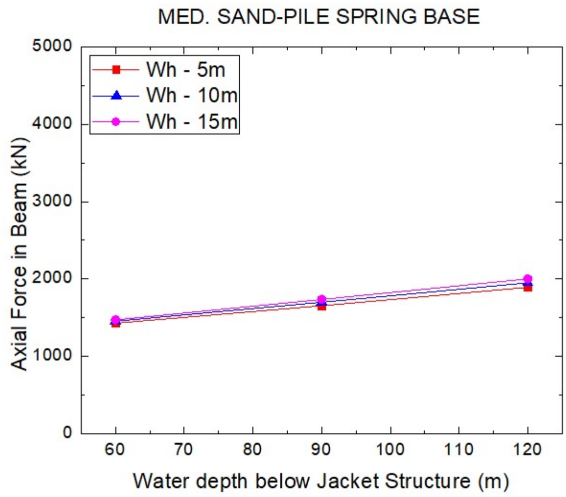

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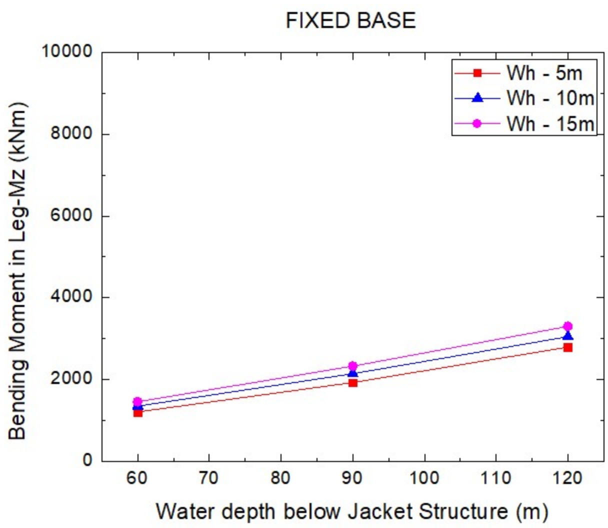
Figure 6 Maximum axial force in beams of jacket structure



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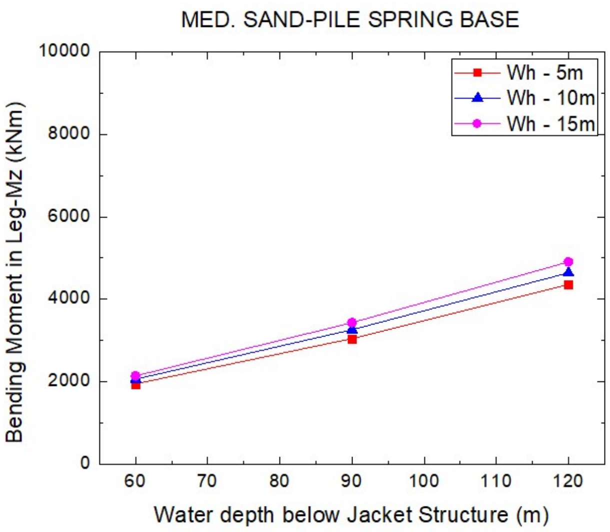

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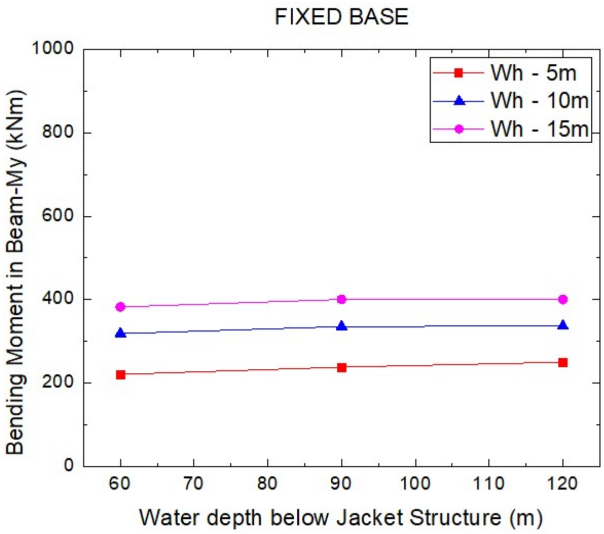
Figure 7 Maximum bending moment in legs of jacket structure

Figure 8 illustrates the influence of increase in water depth and wave height on the maximum minor axis (local lateral direction) bending moment and thus on corresponding shear force for beams, from which it is evident that the water depth has insignificant effect but the increase in wave height almost doubles the values of maximum minor axis bending moment and hence the shear force. This happens, as the wave forces acting on the beams, cause local lateral bending and shear in the beams, and this effect is especially experienced by the beam members in the vicinity of the mean sea level and above this level wherein the wave rises. It can also be noted from the figure 8 that the foundation support modelling approach does not have visible impact on this localized action on the beams.

The axial forces in the vertical bracing exhibit no effect of water depth, but visible increase in axial force is noticed with increase in wave height. This might be reasoned as increase in number of vertical bracings and plan bracings with increase in the height of structure and increase in the spacing of legs at base, which leads to the better distribution of forces/moment. Besides, these values remain unaffected with the change in foundation modelling approach. Maximum axial force in plan bracings is shown in figure 9. For plan bracing, the axial force increases with increase in water depth with the values being higher for support modelled with pile spring as compared to the fixed support, while the effect of wave height on axial force in plan bracing is not evident for both support modelling approaches.

Maximum bending moment and shear force increases almost linearly for both vertical and plan bracing, with increase in water depth but remain unaffected with change in wave height and support modelling approach. Implication of this observation is that the bracing member needs to be treated as flexural member rather than a pure truss member since they experience significant flexural forces besides axial forces (especially in welded tubular jacket structures). Further, it can be inferred that the effect of water depth on bending moment in bracings is higher than shear force.



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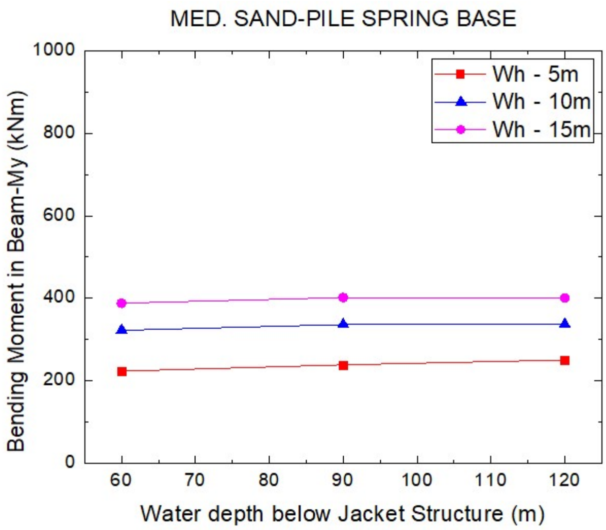

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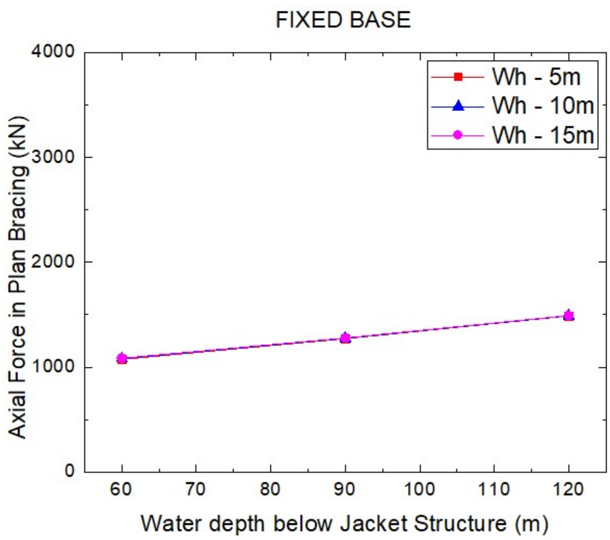
Figure 8 Maximum minor axis bending moment (in lateral direction) in beams of jacket structure



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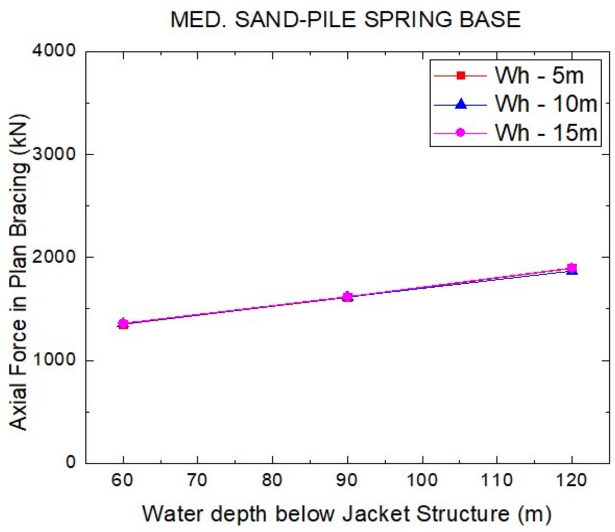

(b)

Figure 9 Maximum axial force in plan bracings of jacket structure

A summary of percentage variation (for jacket structure in 120m water depth and subjected to 15m wave rise) in values of different parameters such as lateral and vertical deflection, support reactions and member forces, when the foundation support condition is changed from fixed to support defined with pile spring stiffness, has been presented in table-3 below.

Table-3 Response of jacket structure with pile-soil interaction as compared to fixed support

Particulars of structural response for jacket structure for 120m water depth and 15m wave height		**Change in response when support condition is changed from fixed to pile spring support (%)**
Deflection (mm)	Lateral	74.63
	Vertical	92.17
Reaction force (kN), Reaction moment (kNm)	Horizontal	-72.28*
	Vertical	-12.56*
	Moment	20
Axial force (kN)	Leg	-3.24*
	Beam	267.61
	Vertical bracing	5
	Plan bracing	27.24
Major bending moment (kNm)	Leg	48.71
	Beam	0
	Vertical bracing	0
	Plan bracing	0
Vertical shear force (kN)	Leg	33.27
	Beam	0
	Vertical bracing	0
	Plan bracing	0
Minor bending moment (kNm)	Beam	0
Horizontal shear force (kN)	Beam	0

*negative value of parameter indicates reduction in values when support type is changed from fixed to pile spring support

4. Conclusions

From the comparative study of maximum values of deflections, support reactions and member forces when support conditions are changed from fixed support to pile spring support (considering pile-structure interaction with soil as medium dense sand) for offshore jacket structure, along with consideration of the effects of increase in wave height and water depth, following important conclusions have been made.

Effect of increase in water depth is found to be greater than that of increase in wave height on all the parameters studied, viz., deflections, support reactions and member forces, except for flexure in the local lateral direction (minor direction) of the beams and axial force in vertical bracings wherein, the effect of wave height is governing. This is mainly due to the higher moments experienced from the lateral environmental loads with increasing structure height corresponding to the increase in water depth. Since there is significant influence on the deflections of jacket structure due to increase in water depth and wave height, meeting the serviceability requirements should be given due consideration.

Foundation modelling with the consideration of pile spring stiffness at supports has major effect on deflection, axial force in beams and plan bracings, and flexure design of legs as compared to the fixed support condition. Therefore, considering fixed support for modelling of jacket structure foundation may lead to unconservative design because of underestimation of deflection and member forces (bending moment and shear force in legs and axial force in beams and plan bracings).

Due to the flexibility induced by defining support with pile spring stiffness, the jacket structure exhibits higher deflection, and large amount of flexural force is transferred to the legs, which they are unable to fully transfer to other members since they undergo large deformations themselves. High axial forces experienced by the beams and plan bracings with flexible foundation support (with defined pile spring stiffness) can also be attributed to the sway experienced by the jacket structure and related secondary effects, especially due to lateral forces getting transferred to beam members as thrust from the legs at the beam-column joints.

The present work contributes in the direction of understanding the effect of water depth, wave height and foundation modelling approach on the response of jacket structure, with relevant discussions on possible mechanisms/reasons for the response. It is opined that such studies would be a useful contribution in the direction of framing decision matrix for design optimization of jacket structures.

Disclosures

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