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NONLINEAR DYNAMIC ANALYSIS OF JACKUP PLATFORMS CONSIDERING SOIL STRUCTURE INTERACTION

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ABSTRACT

In this paper nonlinear dynamic analysis of a sample jack-up platform in Persian Gulf subjected to wave and current loading is conducted using both deterministic and stochastic methods. Various foundation models including hinged and fixed bases, linear and nonlinear spring models, hinged with rotational linear spring are considered in finite element model of structure and sensitivity of structural responses are studied.

The main object of this paper is to assess level of influence of different parameters in nonlinear dynamic responses of the sample Jack-up in Persian Gulf. It is observed that with the assumed soil properties, the results of fixed foundation model are closer to more advanced soil structure interaction model in both approaches; this implies that starting with a preliminary deterministic analysis is a practical approach to recognize the closest simplified foundation model for implementation in more exact stochastic analysis.

1. INTRODUCTION

Different jack-up foundation modeling is subject of several recent numerical and experimental studies. Bienen et al. reviewed the development of numerical models for the analysis of spud cans for the jack-ups response in three dimensions. In above study, a formulation was presented for a six degrees-of-freedom model. Strain-hardening plasticity theory has been incorporated in formulation (Bienen 2005). In the other study, for determining appropriate stiffness levels of spud can foundations back-analysis of jack-up platforms has been performed by Cassidy et al. The records are observed from three different rigs at a total of eight locations, whichinclude a variety of soil conditions, water depths and storm severity in order to compare the responses of monitored jack-up units with their numerical simulations (Cassidy 2002). Temperton et al. covered the background of spud can modeling and the benefits of fixity models. They studied the results of monitoring of three harsh environment jack-up units over the period of 1991 to 1996. They compared the detail of measured results with the result of available numerical analysis methods (Temperton 1999). Amdahl et al performed static pushover analysis for an actual jack-up rig assuming both pinned and more realistic foundation behavior (Amdahl 1989). In this paper in order to investigate the effect of boundary conditions, five foundation models were chosen for a sample Jack-up in Persian Gulf. These include: perfect hinge model, fixed base model, more advanced models based on soil properties including linear springs & nonlinear springs with strain hardening plasticity models and finally a hinged base with linear rotational spring. Using computer program "USFOS" for dynamic analysis, a three dimensional finite element model of the complete structure was prepared and a simplified equivalent stick version of the model was constructed and calibrated to ensure consistency of the responses. The deterministic nonlinear dynamic responses including hull displacements, base shears and overturning moments were calculated. Next, by generating wave spectrum corresponding to the same maximum wave used in the previous deterministic analysis, stochastic dynamic analyses were performed. The maximum responses were obtained through fitting of appropriate statistical distribution and calculation of statistical parameters.

2. DESCRIPTION OF STRUCTURAL MODEL

Geometry and structural configuration of jack-up were selected on the basis of environmental conditions and preliminary estimate of penetration depth of spud can. Effects of back flow, back fill, and infill on bearing capacity and reaction point were considered.For all performed analysis, the most likely mass distribution, damping, hydrodynamic factors, stiffness and other affecting factors in overall behavior of structure were considered appropriately. Structural damping is considered using the Rayleigh approach in which damping behavior is assumed to be proportional to a combination of the mass and the stiffness matrices.Hydrodynamic added damping due to the relative wave- structures speed is also considered. Two models of detailed jack-up structures and its equivalent stick structure are shown in "Fig. 1." First model consists of detailed legs, leg/spud can connections and spud cans and second model consists of stick elements including all items mentioned above. Simplified stick model is used for a rapid capture of overall structural behavior. Stick model is calibrated against more detailed model such that the responses obtained are in agreement with the required degree of conformity (Saeidtehrani 2010).

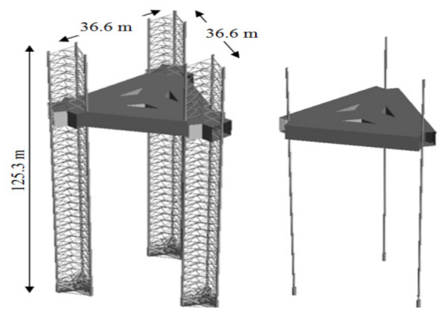

Fig. 1. Structural models of jack-up structure in “USFOS” program

3. DESCRIPTION OF FOUNDATION MODEL

Five foundation models were adopted, namely perfect hinged (a), fixed bases (e), more advanced models based on soil properties including linear springs (b), nonlinear springs (d) with strain hardening plasticity models and finally a hinge base with linear rotational spring (c). All foundation models are processed in "USFOS" (H.Soreide)which uses capacity interaction relations based on SNAME RP recommendation (SNAME 2002).Vertical, horizontal and rotational stiffnesses of the foundation in model (c) are based on the elastic solutions for a rigid disk on an elastic half-space with required modification factors to account for spud can embedment.
This stiffness which is directly defined with linear spring elements in “USFOS” are given in Eq. (1).

$$\begin{pmatrix} V \\ \frac{M}{R} \\ H \end{pmatrix} = \begin{bmatrix} \frac{4GR}{1-v} & 0 & 0 \\ 0 & \frac{8GR^3}{3(1-v)} & 0 \\ 0 & 0 & \frac{32GR(1-v)}{7-8v} \end{bmatrix} \quad (1)$$

In which:

B: effective spudcan diameter
G:shear modulus
v:Poisson's ratio

The advanced model (d) is a coupled nonlinear elastoplastic spring that is defined with a yield surface, an elastic representation, a hardening law, and a flow rule. This model is according to H.VanLangen, Shell Research. It has both a yield function and a separate plastic potential. With this model a smooth transition between elastic and fully plastic behavior is obtained. The plastic potential enables to use non-associated flow rule (H.Soreide). The yield function is given as:

$$\Gamma = f(V, H, M, V_0, \theta_P) = f_e + (f_u - f_e)G \quad (2)$$

In which:

f_e:aninitial yield surface
f_u:a bounding surface
G is a function of plastic rotation θp

$$f_e = \sqrt{(\frac{M}{c1M_0})^2 + (\frac{H}{H_0})^2} - c_2\left(\frac{V}{V_0}\right)(1 - \left(\frac{V}{V_0}\right)^{c_3}) \quad (3)$$

$$f_u = \sqrt{(\frac{M}{c_4M_0})^2 + (\frac{H}{H_0})^2} - c_5\left(\frac{V}{V_0}\right)(1 - \left(\frac{V}{V_0}\right)^{c_6}) \quad (4)$$

H_o: the base shear capacity at zero overturning moment (M=0)
V_o: the vertical preload
M_o: the overturning moment capacity at zero base shear (H=0).
H: base shear
V: the current vertical load
M: overturning moment

4. DETERMINISTIC NONLINEAR DYNAMIC RESPONSE

"Figure 2." shows displacement time histories of the sample jack-up for different foundation models to a wave with height of 12.2 m and period 12 sec. The maximum of total responses and the maximum of steady responses are given in "Table 1."

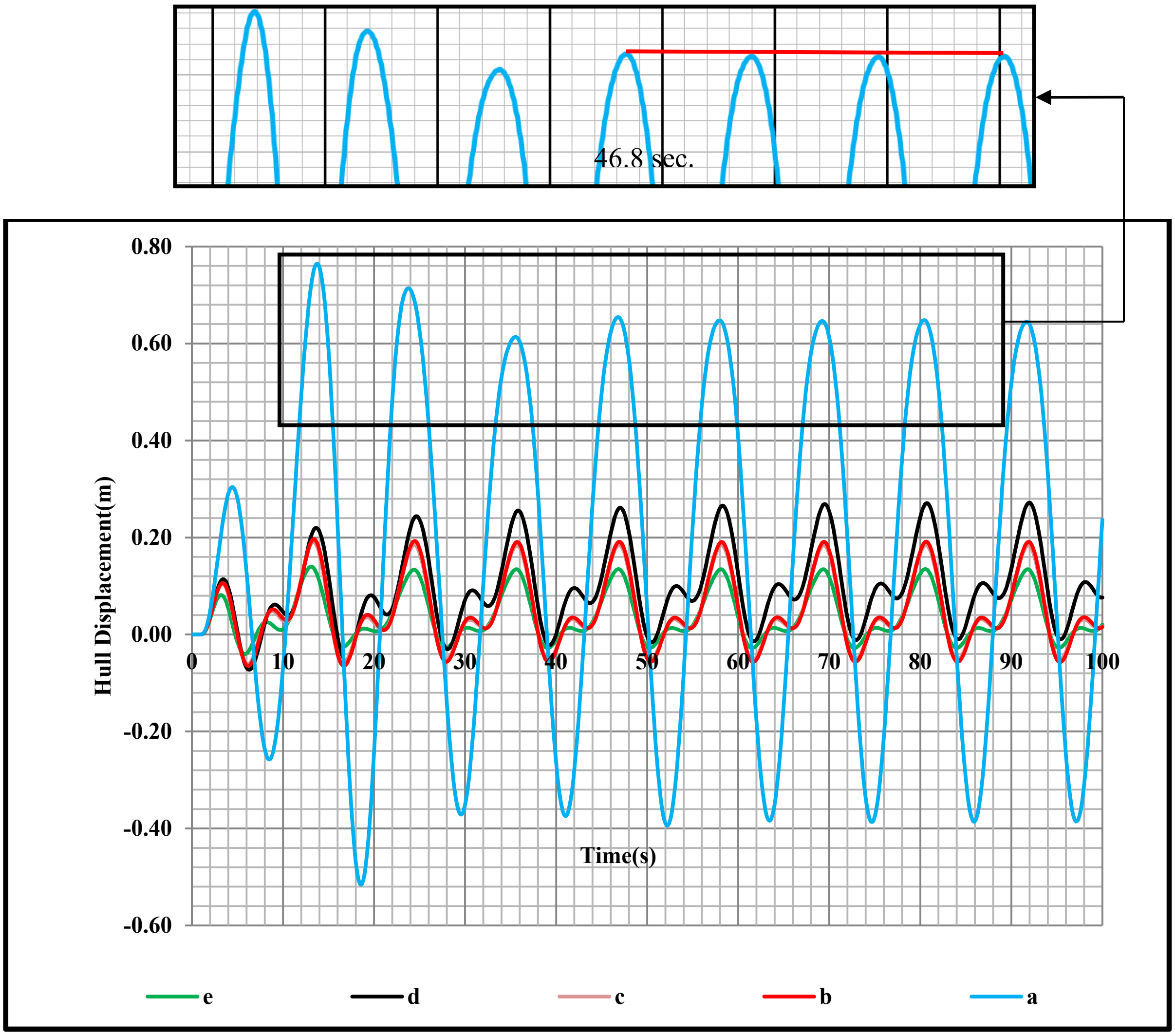

Fig. 2. Structural responses to wave with height 12.2 m, period 12 sec.

It can be seen from above figure and “Table 1.” that the dominant duration of transient response is highly dependent on foundation models which affect the natural period of structure. With increasing the simulation time of analysis, it is concluded that the required time to capture steady response exceed 46.8 sec. for pin foundation model.

The structure with fixed bases have natural period less than other models and "table 1." shows the transient response are damped out after about 35.4 sec.

Table 1- Structural responses to wave with height 12.2 m, period 12 sec.

Foundation Model	Period	Max. Total Response		Max. Steady Response	
		Displacement	Time	Displacement	Time
a	8.18	0.764	13.7	0.655	46.8
b	4.80	0.197	13.4	0.191	35.7
c	4.73	0.190	13.3	0.184	35.6
d	4.81	0.270	91.8	0.270	91.8
e	4.31	0.140	13.1	0.133	35.4

Comparing the response results of foundation models "b" and "c", it can be seen that the maximum differences is about 4%. This indicates that hinge supports strongly provide the same result as linear model for this particular soil data "Fig. 3". So the model “c” can be used as an alternative model for more detailed analysis instead of model b.

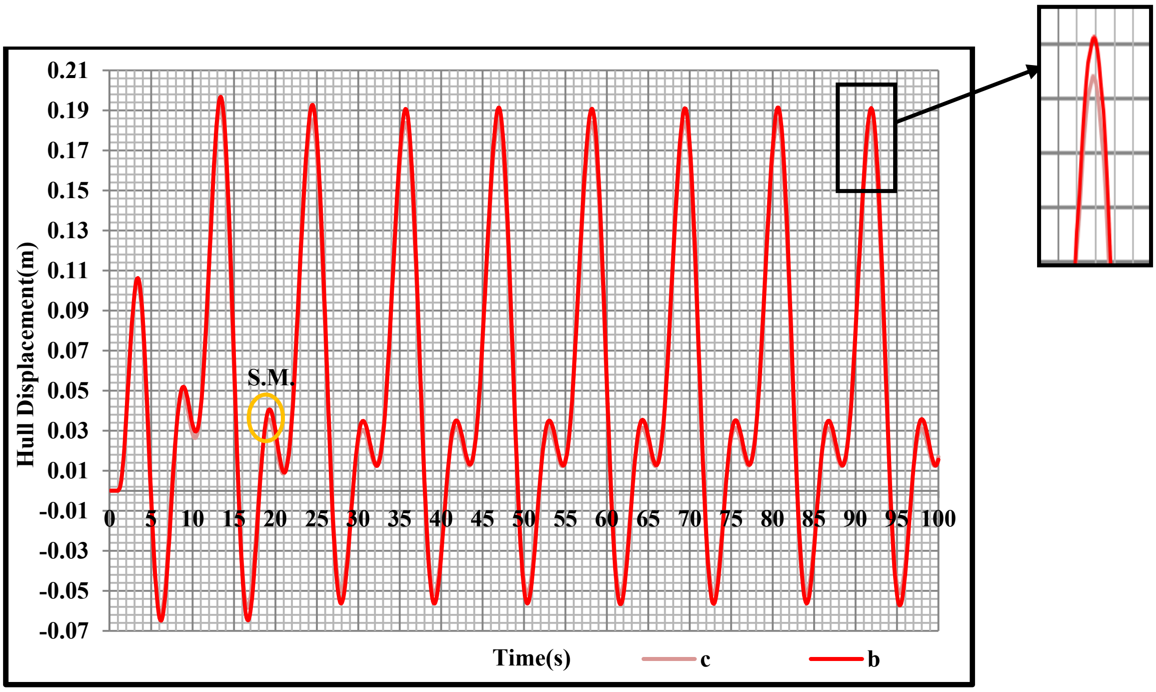

Fig. 3. Structural responses to wave with height 12.2 m, period 12 sec.

The maximum differences in responses with models "b" and "d" are more pronounced which shows the influences of nonlinear behavior of soil- spud can interaction "Fig. 4".

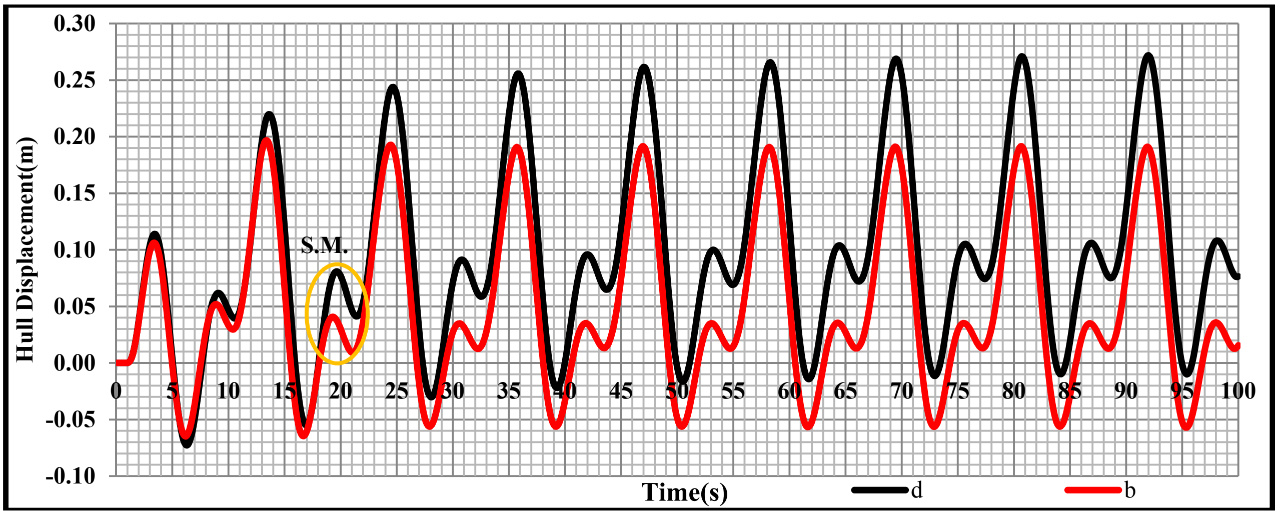

Fig. 4. Structural responses to wave with height 12.2 m, period 12 sec.

Time series responses of foundation model "c" and "e" are shown in Fig.5.The maximum differences is about 50%, which indicates that due to high soil stiffness the responses are more sensitive to rotational spring stiffness rather than vertical and horizontal stiffness as shown in Fig. 3.

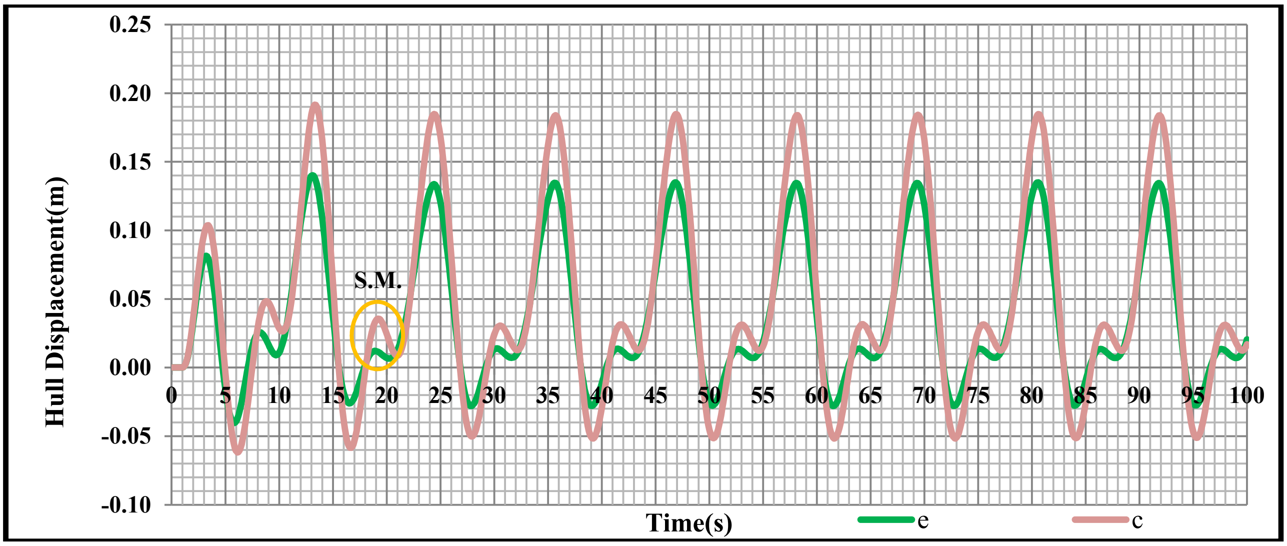

Fig. 5. Structural responses to wave with height 12.2 m, period 12 sec.

The above results show that a second maximum (S.M) occurs between harmonic responses. Returning to the time of maximum responses and noting that the natural period of structure with pin foundation is about 1.7 to 2 times of periods of other models, further verification analysis were carried out. Two typical time history responses for pin foundation and nonlinear spring foundation are shown in Figs. 6&7.

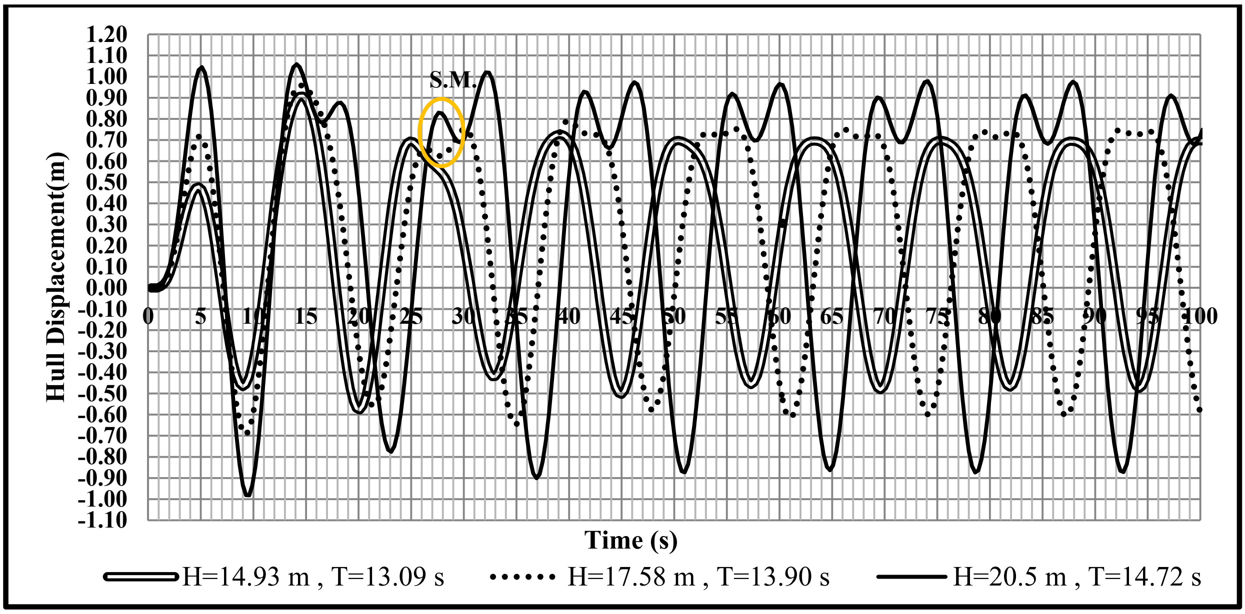

Fig. 6.Structural Responses with Pin Foundation model

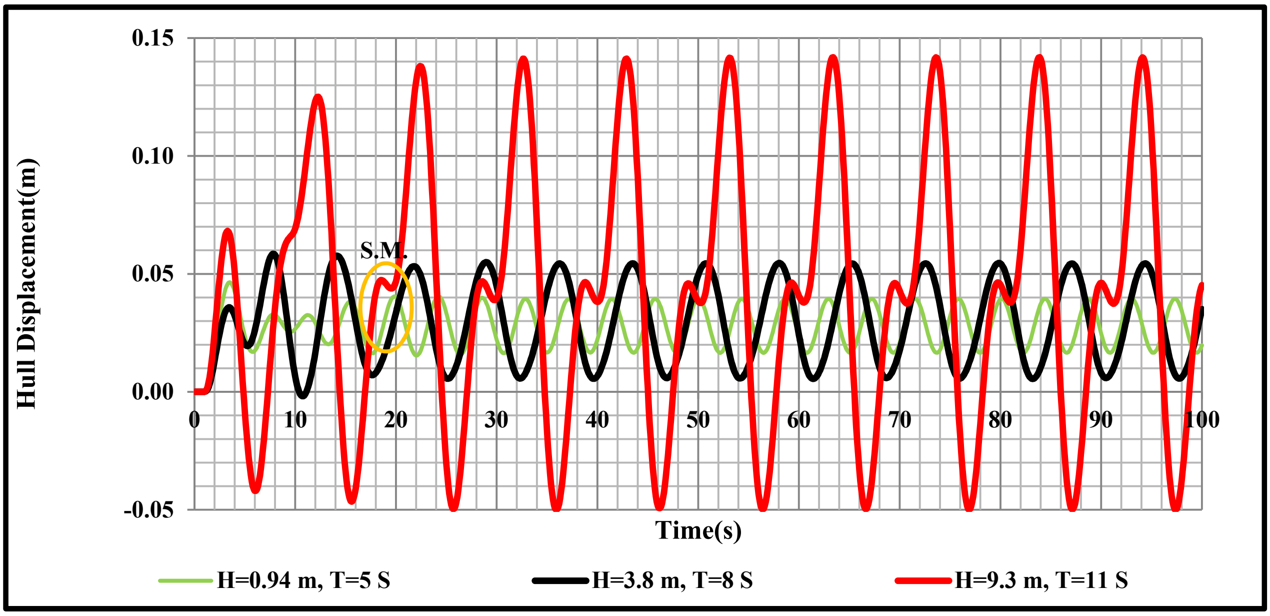

Fig. 7.Structural Responses with Nonlinear Spring Foundation model

The cycles of time series responses are studied to determine time intervals between maximum responses. It was concluded that this periods differ from periods computed by modal analysis. In order to simulate resonance response, time history responses are studied while the system is excited at resonance, and related base shear time histories are depicted in Fig. 8.

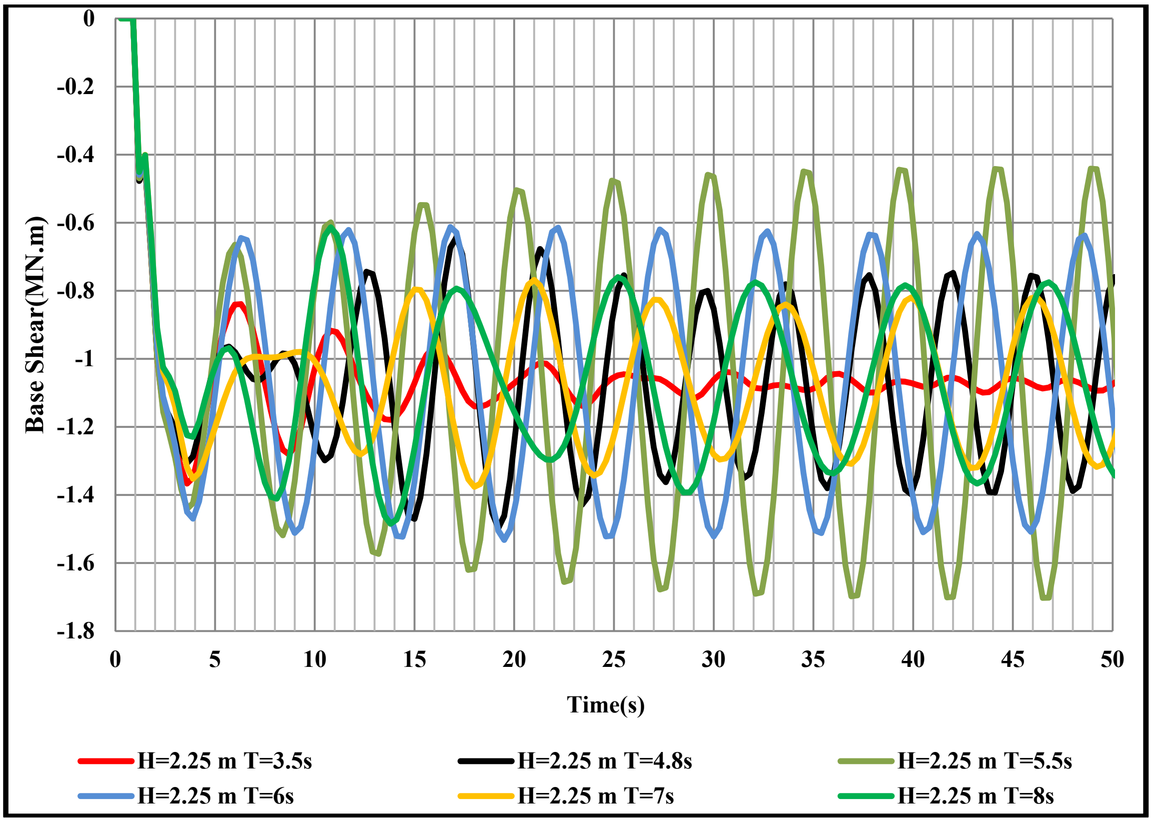

Fig. 8.Structural Responses of hinge base with linear rotational spring model

Although Modal analysis shows that period of the structure with nonlinear spring foundation is 4.81sec., the intervals of maximum response in time histories are about 5.5 sec., which shows why resonance in the structure response is observed at the environmental condition of H=2.25 m, T=5.5 sec.

5. STOCHASTIC DYNAMIC RESPONSE

By generating wave spectrum corresponding to the same maximum wave used in the previous deterministic analysis, stochastic dynamic analyses were performed (DNV). Then the maximum responses were obtained through fitting the appropriate statistical distribution and calculation of statistical parameters. To compare the fit of the extreme value distributions and to select the best fitting model, goodness the best fit are carried out. In general, the weibull distribution frequently provides best fit.

By using a deterministic analysis with two extreme support conditions i.e.: hinged and fixed, it is possible to estimate the dominant duration of transient response and thereby correctly truncate the time series of stochastic responses.

Procedures for estimation of extreme response of hull displacement are shown in Fig. 9.

It is observed that the values of median, mean and mode are the same for foundation models "b" to "d", and the values of skewness and kurtosis are approximately zero, thus the distribution is near to normal. But in the response time series of hinged model, the mode value is less than other central parameters, and the distribution have skewed to the left. Distributions indexes of model "c" are 70% less than model "a", these results demonstrate clearly how fixity is important.

For the sake of brevity, reference was only made to displacement responses.
Comparisons of other responses such as base shear and overturning moment could be found in (Saeidtehrani 2010).

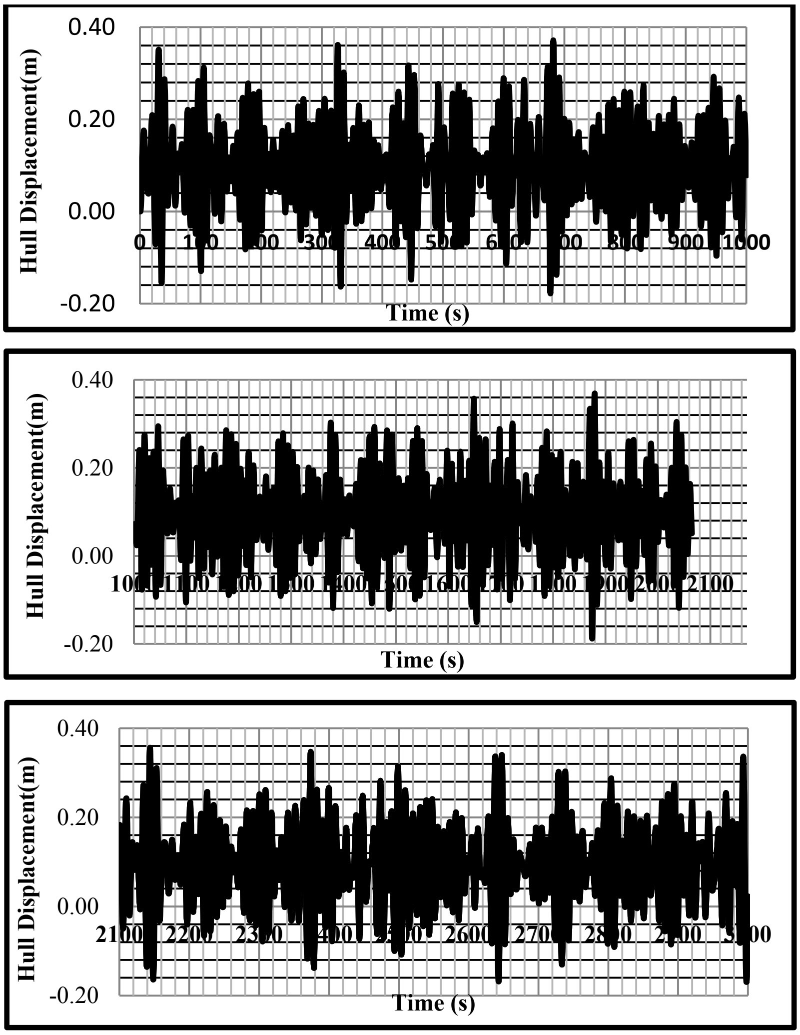

Fig.9-a) time series response

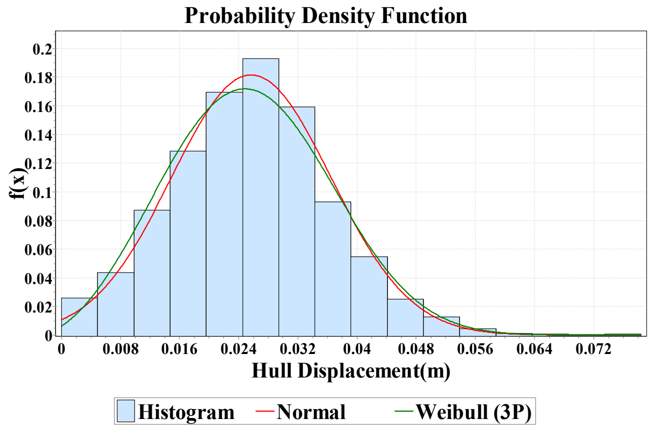

Fig.9-b) fitting of weibull distribution

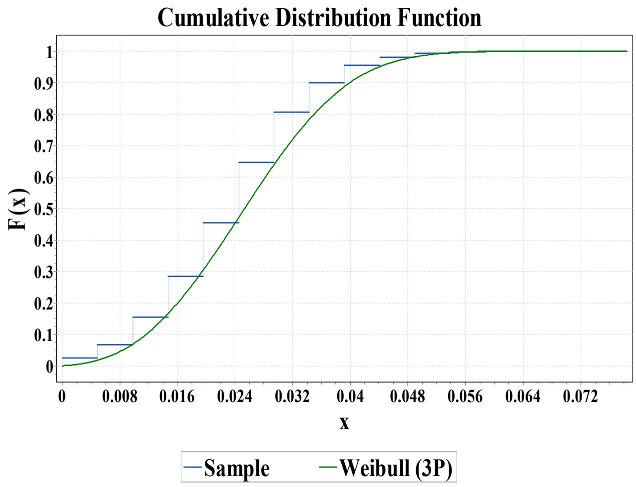

Fig.9-c) estimation of extreme response

Table 2-stochastic structural response indexes

Hull displacement	Foundation models				
Statistical index	a	b	c	d	e
Median	0.099	0.026	0.026	0.0256	0.0195
Mean	0.108	0.026	0.026	0.0256	0.0195
Mode	0.053	0.025	0.025	0.0248	0.0187
Skewness	1.22	0.192	0.192	0.191	0.2265
Kurtosis	1.91	-0.261	-0.261	-0.261	-0.2441
Shape parameter	1.46	2.92	2.93	2.93	2.829
Scale parameter	0.12	0.03	0.03	0.03	0.0235
location parameter	-0.002	-0.004	-0.004	-0.004	-0.001
x_e	0.371	0.08	0.078	0.078	0.06

6. CONCLUSION

The most significant environmental loads are those induced by wave action. Although the irregularity of sea can only be simulated by use of a stochastic wave model, the formidable volume of output results makes the interpretations a difficult and time consuming task and may obscure the influence of relevant soil and environmental parameters. On the other hand as shown earlier, using a time constant wave in a preliminary deterministic analysis, provides a much clearer picture of the influence of parameters involved and thus the required level of sophistication for the foundation model to be adopted in further elaborate investigations may be selected.

The comparison of numerical responses indicate that for the geometrical and environmental conditions of jack-up platform used in this study, the fixed based foundation model “e” could be selected for complete nonlinear dynamic simulations. The effect of other nonlinear sources in dynamic analysis can be evaluated by sensitivity analysis in other variable such as leg to hull connections, wave- structure interaction and wave simulation.

Studying the variations of natural period with respect to different support conditions is useful for the selection of analytical method and time duration and accuracy level to predict structural behavior. A comparison of time history results show that possibility of occurrence of a second maximum directly depends on the ratio of exciting period to natural period. The significance of occurrence of these second maximums on the structural behavior is the subject of further studies.

7. REFERENCES

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