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Effect of soil pile structure interaction on dynamic characteristics of jacket type offshore platforms

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Abstract. Dynamic response of Pile Supported Structures is highly depended on Soil Pile Structure Interaction. In this paper, by comparison of experimental and numerical dynamic responses of a prototype jacket offshore platform for both hinge based and pile supported boundary conditions, effect of soil-pile-structure interaction on dynamic characteristics of this platform is studied. Jacket and deck of a prototype platform is installed on a hinge-based case first and then platform is installed on eight skirt piles embedded on continuum monolayer sand. Dynamic characteristics of platform in term of natural frequencies, mode shapes and modal damping are compared for both cases. Effects of adding and removing vertical bracing members in top bay of jacket on dynamic characteristics of platform for both boundary conditions are also studied. Numerical simulation of responses for the studied platform is also performed for both mentioned cases using capability of ABAQUS and SACS software. The 3D model using ABAQUS software is created using solid elements for soil and beam elements for jacket, deck and pile members. Mohr-Coulomb failure criterion and pile-soil interface element are used for considering nonlinear pile soil structure interaction. Simplified modeling of soil-pile-structure interaction effect is also studied using SACS software. It is observed that dynamic characteristics of the system changes significantly due to soil-pile-structure interaction. Meanwhile, both of complex and simplified (ABAQUS and SACS, respectively) models can predict this effect accurately for such platforms subjected to dynamic loading in small range of deformation.

Keywords: steel jacket type offshore platform; soil-pile-structure interaction; dynamic characteristics; experimental modal analysis

1. Introduction

Pile foundations are used in many structures such as jacket type offshore platforms to transfer loads from superstructure to the layers of soil. When external forces such as earthquake, wind and wave act on pile-supported structures, structural, soil and pile displacements are not independent from the others. Response of the soil-pile system influences the motion of the structure, and the motion of the structure influences the response of the soil-pile, which is termed as soil-pile-structure interaction (SPSI). The effects of SPSI are prominent for pile-supported structures such as jacket type offshore platforms. Dynamic characteristic and response of such a structure is highly depended

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to effect of soil-pile-structure interaction.

There are many researches on dynamic soil-pile-structure interaction (Mizuno 1987). Some procedures have been developed for considering this effect in evaluating dynamic response of jacket type offshore platforms. Generally, there are two main methods for modeling of SPSI. The simplified double-step method in which superstructure and pile systems are uncoupled, is the first and less complex one. In this methods beam elements are used for the modeling of jacket, deck and pile members and soil media is discretized to parallel springs trying to represent soil real behavior. The second method, two and three-dimensional continuum modeling of the pile and surrounding soil is performed by using finite-element or finite-difference approaches. This type of modeling is more complex compared to first method. This method is presented by many researchers (Wu and Finn 1997 and Cai *et al*. 2000).

In the first category, dynamic beam on a nonlinear Winkler foundation (BNWF) model was used by Nogami (1992) to analysis dynamic response of pile foundations in time domain space. El Naggar (1992) and Novak (1995) presented a nonlinear analysis for pile groups in time domain space within the framework of the Winkler hypothesis. Wang *et al*. (1998) compared several implementations of the dynamic p-y method and showed that calculations can be sensitive to the details of the nonlinear springs and dashpots.

The effect of soil-pile interaction on nonlinear response of offshore piles are investigated by several researchers (Memarpour *et al*. 2012, Rovithis *et al*. 2009, Maheshwari *et al*. 2004). This effect are also considered in evaluating dynamic behavior of fixed offshore platforms (Asgarian and Lesani 2009, Asgarian *et al*. 2008) .

In this paper, effect of soil-pile structure interaction on dynamic characteristic of a prototype sample offshore platform is investigated through experimental and numerical studies. For this purpose, a prototype model of a sample steel jacket type offshore platform with a scale factor of 1:15 is fabricated as welded-steel space frame. Dynamic test of Sample Platform (SP) is conducted for two hinge-based and pile-supported conditions. The platform is installed first on strong rigid floor of the structural laboratory and it is tested as hinge based support condition, then the platform is removed and installed on eight skirt piles and it is tested as pile-supported condition. By comparison of platform's dynamic characteristics in both cases, effect of soil pile structure interaction on dynamic characteristics of the platform is investigated.

Numerical dynamic analysis of the model is also performed using two common models of soil-pile-structure interaction techniques. Continuum solid three-dimensional modeling of pile and surrounding soil is performed using ABAQUS finite-element software. In this model, the interaction between soil and pile is considered using interface contact elements. Dynamic analysis of the platform is also performed using two-stepped method in SACS software which is commonly used software in offshore application. *P-y*, *T-z* and *Q-z* nonlinear springs, according to the API RP-2A (2000) are modeled to simulate the soil-pile interaction.

2. Identification of the dynamic characteristics

Dynamic behavior of structures is investigated from some sources: observations from actual structures response during earthquakes, experimental test results on scaled or actual size models of the structures and finally from analytical or numerical analysis on structures. Experimental observation of the behavior of complex structures such as offshore platforms is valuable which can be used to verify the numerical result. The use of experimental results has been widely applied to predict dynamic response of structural systems. These techniques are being investigated in several fields such as mechanical engineering (Mohiuddin and Khulief 2002, Sabnavis *et al.* 2004), aerospace applications (Ghoshal *et al.* 2001) and the offshore industry (Idichandy and Ganapathy 1990, Mangal *et al.* 2001, Ruotolo *et al.* 2000).

Experimental dynamic investigation offers the opportunity to obtain information about the whole system dynamic characteristics based on small number of measurements. Usually, dynamic tests lead to determination of system modal characteristics. Experimental modal analysis is the term used for determination of modal properties such as natural frequencies, mode shape and modal damping experimentally. Two common methods of the structural modal testing are ambient and forced vibration tests (Salawu and Williams 1995). In ambient vibration tests, the excitation is not under the control which is usually considered as stationary random process. Ambient excitations are usually from different sources such as wind, pedestrian or vehicular traffic, earthquakes, waves or similar excitation. For very large and massive structures, ambient excitation is often the only practical choice. Structural identification through ambient vibration tests has been successfully identified in numerous cases (Ivanovic *et al.* 2000, Ventura *et al.* 2003).

In forced vibration tests, the input excitation to the structure is provided by properly designed excitation systems, which entails application of a known force at particular frequencies or frequency bands of interest (Kunert and Nigbor 2012, Yu 2005, De Sortis *et al.* 2005). This method is based on the fact that if loading on the structure and resulting responses are known, then the structural characteristics can be more unambiguously determined. These types of tests also have the advantage of the achieving larger signal to noise ratios in the response measurements (Salawu and Williams 1995).

Usually, experimental test of full-scale structures under dynamic loads is not practical. Experimental measurement of scaled model is one of the alternative methods for comparison and investigation of the performance of existing and new systems. In this paper, experimental forced vibration test is performed on a scaled model of a jacket type offshore platform.

2.1 Description of scaled model

Scaled model of a newly installed jacket type offshore platform in Persian Gulf is fabricated which is a welded steel space frame with six legs, horizontal and vertical braces, two-story decks and eight skirt piles. The details of the model are presented in Fig. 1. Due to limitation in size of available pipes and laboratory facilities, the geometric scale for structure is considered as 1:15. The legs have a diameter of 48 mm and a wall thickness of 3 mm. All horizontal bracing members have 34 mm diameter and 3 mm thick. The deck consists of intersectional beams with box section (60 × 40 × 3 mm). A plate with a thickness of 15 mm is welded to deck beams in order to simulate rigid diaphragm action and provide topsides weight. For considering effect of joint cans in jacket, the thickness of legs is increased to 5 mm in horizontal levels. Eight skirt sleeves with 88.9 mm diameter and 5 mm thickness is connected to the legs. Four samples of pipes are tested. The modulus of elasticity and yield stress of steel piles are determined as 200 GPa and between 265-285 MPa (respectively).

The three dimensional frame is constructed by qualified fitters and welders who all are engaged and quite experienced in real-scale jacket fabrication. Care is taken to insure proper alignment, minimize initial eccentricities, bevel the ends of members similar to API recommendations, specify

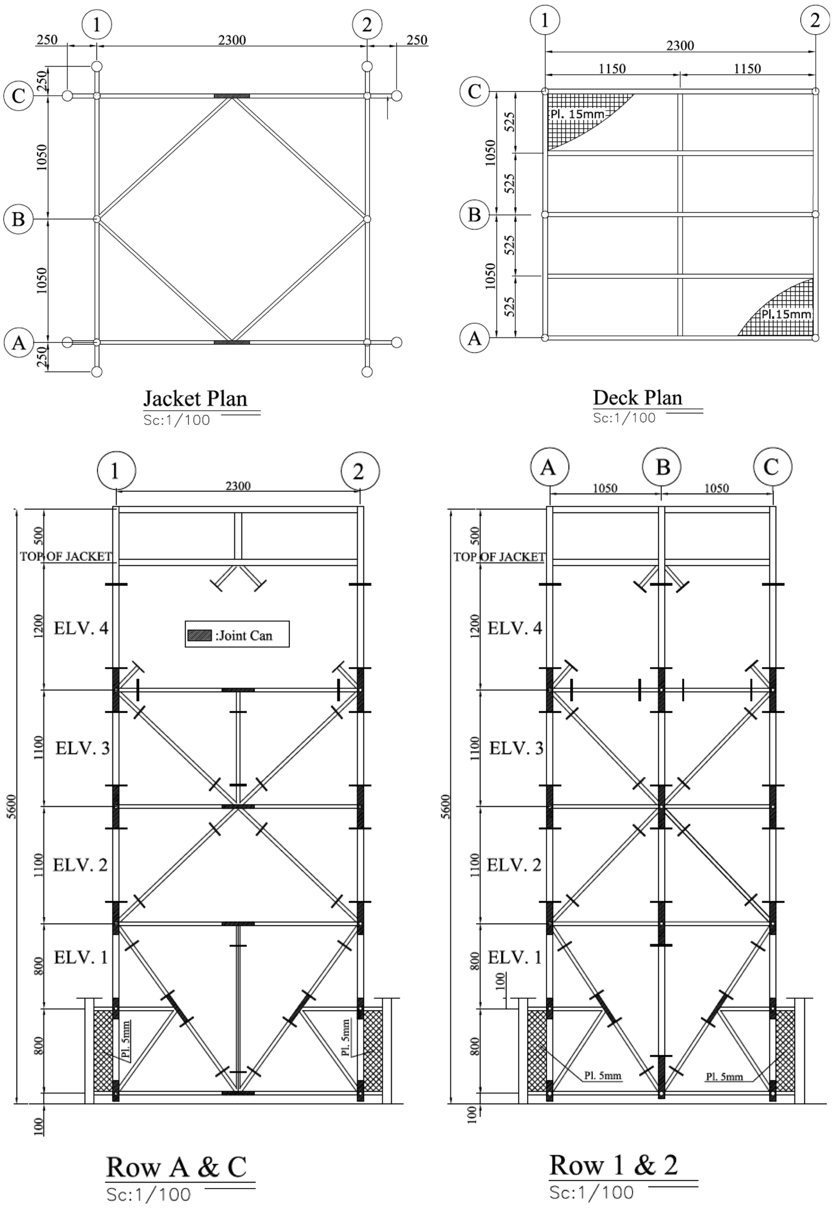


Fig. 1 Elevation of the scaled model SP

close fit-up of welded components and use the full penetration butt welds at member connections. The welding is done under the CO2 shielding gas. All welds are tested using NDT tests as PT (liquid penetrate examination) and MT (magnetic particle examination) and repairs are done to detect and remove the flaws that could cause premature failure.

2.1.1 Boundary conditions in experiment

Jacket type offshore platforms are usually connected to seabed by piles foundations with the sufficient penetration in soil to resist lateral and vertical loads in a safe manner. The effect of soil-pile interaction in the response of structure subjected to external forces is an important issue. This interaction on dynamic characteristic of the platform is investigated by comparison of experimental and numerical results of responses for two boundary conditions. Forced vibration tests are performed first on platform installed on rigid floor of laboratory. This case is a hinged base condition. For this condition, four corner legs of the platform are connected to floor beams by short stubs (20 cm length) through four bolts for each.

After performing measurement of forced vibration tests of this condition, prototype offshore model SP is removed from rigid floor and it is installed on eight skirt piles. For this purpose, a square cubes pit with approximately 7.00 m dimension is excavated in the open area of civil engineering faculty of K.N.Toosi University of Technology. To simulate the stiff bedrock in the bottom of the pit, a concrete layer with 200 mm thickness and compression strength of 28 MPa is constructed. To prevent underground water penetration and change the soil condition, all surrounding walls are impermeable. The pit is filled with homogenous sand with a volume of about 320 m^3. The process of filling the pit with sand is done in 10 months before driving skirt piles and installing jacket. The soil profile consisted of a monolayer uniformly graded sand with an angle of internal friction φ of 38° and the undrained shear strength, c_u of 9.8 KPa. Young's modulus for the

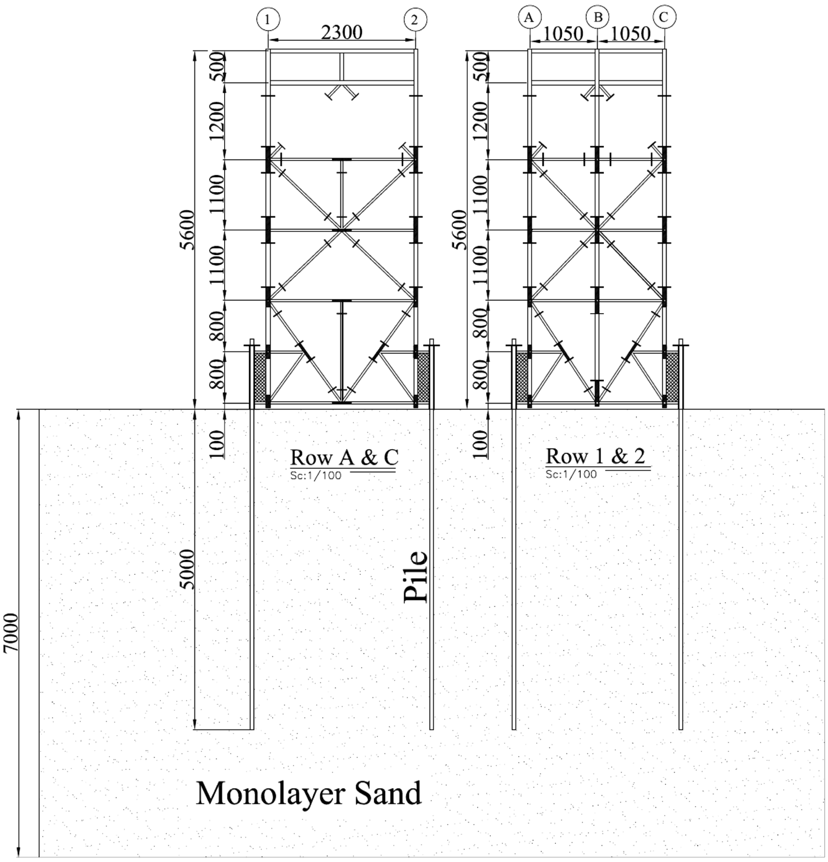


Fig. 2 General view of scaled model SP on (pile supported condition)

sand is varied between 12-25 MPa along the depth of the pile. The installation process of the scaled platform is conducted by driving eight piles through their sleeves using pile driving tool. Piles have a diameter of 60.3 mm, a wall thickness of 5 mm with total length of 6 meter (Fig. 2).

The connection between leg and pile consists of flange plates, shear plates and pile sleeves. Finally after completion of pile driving process, cement grouting is injected in space between piles and sleeves. The grout is made from water and cement type II (with Water/Cement weight ratio of 40%). Some sample cubes ($10 \times 10 \times 10\ \mathrm{cm}^3$) of grout are tested under compression. The 14 days compression strength of sample cubes is 39 MPa (same day that the forced vibration test is performed). Fig. 3 shows picture of the scaled model of the SP platform installed on rigid floor (a) and skirt piles (b).

2.1.2 Equipment description

For forced vibration tests, one vibration generating system which is an eccentric mass shaker is used. This system applies harmonic excitation across a wide frequency range in one or two horizontal directions and induces weak to strong forced vibration to structures. The eccentric mass shaker used for this study has an exciting horizontal force up to 12 kN which is capable to impose and hold frequencies in the range 0.0 to 10 Hz within 0.1 Hz intervals. The shaker is installed in the second level of the platform deck and it is fixed to rigid plates of deck (Fig. 4). The response of the scaled model of SP platform to the frequency sweep kind of excitation is measured using six two-dimensional accelerometers, four linear variable differential transformers (LVDT's). This response in both directions (Rows A& C and Rows1& 2) is measured in several stages. The first stage of the test is conducted by increasing the input frequency from 1 Hz to 4 Hz by 0.2 Hz intervals. In this stage, the approximate modal frequency values are evaluated. In the next stage of forced vibration testing, the exact value of natural frequencies and corresponding mode shapes is evaluated. In these stages, the frequency of excitation is increased around the preliminary resonant frequencies by a 0.1 Hz intervals and the response of the platform is measured.

(a) Hinge-based installation (b) Pile supported installation

Fig. 3 Installation of scaled model, SP, hinge-based and pile-supported conditions

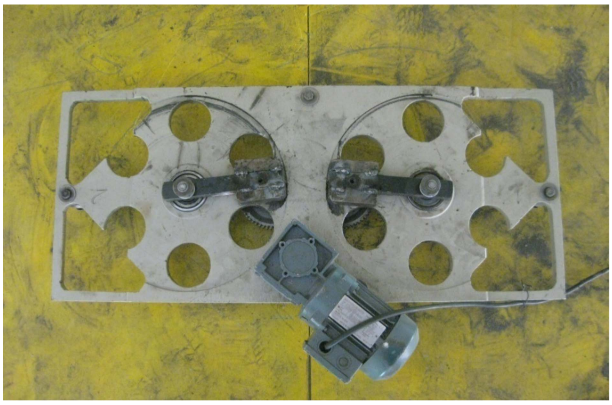


Fig. 4 Eccentric mass shaker

2.1.3 Description of test cases

In order to study effect of adding or removing vertical bracing of jacket in dynamic characteristics of SP jacket, they are fabricated using flange type connection plates. Two different vertical bracing configurations are selected for performing forced vibration tests. Two series of test are performed on above mentioned cases, first series on hinge based and second series on pile supported condition.

The vertical bracing configurations are shown in Fig. 5. First case (case No. 1) which is the base case has same member's configuration as original members of jacket. In case No. 2 (second case), four vertical braces are added to top bay of jacket in each direction as shown in Fig. 5.

2.2 Numerical modeling description

Dynamic characteristics of the SP is also computed numerically using modeling capability of

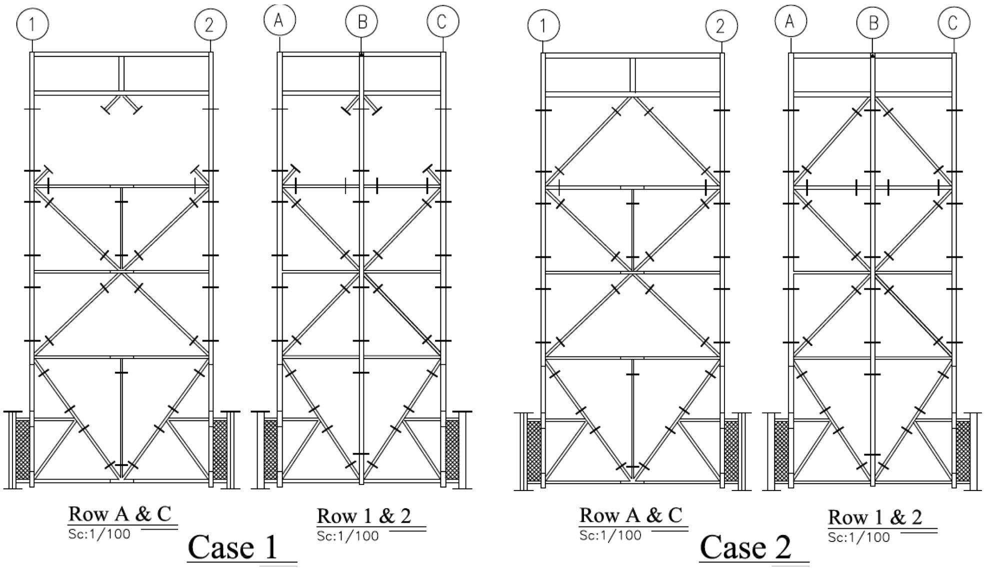


Fig. 5 Two bracing configuration case used in forced vibration test

ABAQUS and SACS software. For three-dimensional modeling of the soil media, piles and superstructure members, and considering interaction between soil-pile-structure, finite-element ABAQUS software is used. The common and less complex method which is used in many offshore engineering applications is also applied using modeling capability of SACS software.

In modeling using ABAQUS, superstructure elements, including legs, vertical and horizontal bracing members and deck beams are modeled using beam elements. Three dimensional solid elements are applied to model piles and soil media. Mohr-Coulomb geotechnical constitutive model is used for failure criteria of soil. The soil-pile interfaces are assumed as a frictional interface where soil-pile slipping and gapping may occur. Generally, Coulomb's law of friction is used to model slipping and gapping between piles and surrounding soil. When interface surface is in contact, full transfer of shear stress is ensured and surfaces are separated when the contact pressure becomes zero or negative, and the constraint is removed. Thus in Finite Element model using ABAQUS, the contact constraint is applied between two surfaces of pile and soil.

In the second type of SP modeling, beam elements of SACS is used for jacket and deck members. Effect of piles below jacket legs are considered using equivalent super element module in terms of linearized foundation stiffness matrix. The seismic equivalent linear spring model has been derived by an iteration procedure using employing super element module of SACS software.

3. Results

In this section, results of experimental and numerical analyses are presented in terms of modal characteristics. Dynamic response of scale model is derived from experimental data and two ABAQUS and SACS numerical results. To identify modal characteristics of the scaled platform SP, power spectral density function of response is used. Modal frequencies and mode shapes are also obtained numerically using SACS and ABAQUS outputs.

3.1 Natural frequencies of the platform in different cases

Natural frequency of the scaled platform, SP is obtained using power spectral density (PSD), cross correlation spectrum (CPS), phase relationship, and the coherence spectrum (CS), (Eq. (1) through Eq. (5)). The CPS, phase relationship and CS are estimated between all response measurement points and one reference point. The segment averaging method (also known as Welch's method) is used for better correlation and minimizing errors. The method consists of dividing time-series data into (possibly overlapping) segments, computing a modified spectrum of each segment, and then averaging the PSD and CPS estimates. Therefore, PSD and CPS are estimated by dividing each acceleration data to eight segments and using a Hanning window with 50% overlap.

To distinguish spectral peaks representing the platform vibration modes from those corresponding to peaks in the input spectrum, the advantage concurrency of the CPS peak and the orthogonality condition of mode shapes are used.

$$PSD : S_{xx}(f) = \int_{-\infty}^{+\infty} R_{xx}(\tau) e^{-j2\pi f\tau} d\tau \tag{1}$$

$$CPS : S_{xy}(f) = \int_{-\infty}^{+\infty} R_{xy}(\tau) e^{-j2\pi f\tau} d\tau \tag{2}$$

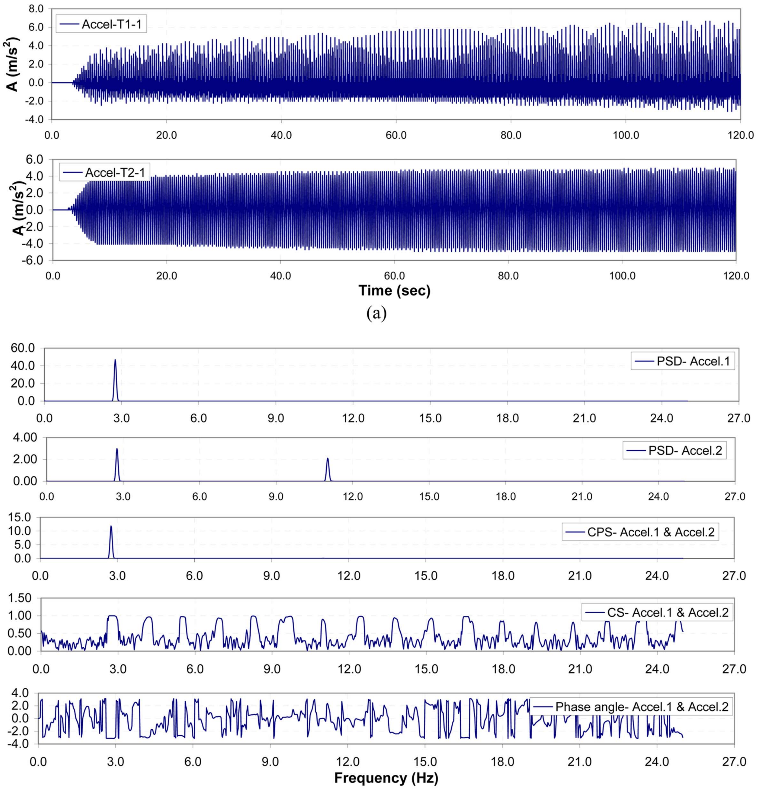
$$S_{xy}(f) = C_{xy}(f) - jQ_{xy}(f) \tag{3}$$

$$\theta_{xy}(f) = tg^{-1}\left[\frac{Q^2{}_{xy}(f)}{C_{xy}(f)}\right] \tag{4}$$

$$CS : \gamma^2{}_{xy} = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)} \tag{5}$$

In the above equation S_{xx} and R_{xx} are power spectral density and the auto-correlation of a measurement point of the structure respectively. S_{xy} and R_{xy} are cross correlation spectrum and the cross-correlation between two response measurement points of the structure respectively. Cross correlation spectrum, S_{xy} is a complex value that is shown by the real value C_{xy} and imaginary value Q_{xy}. The phase spectrum of the CPS is calculated from Eq. (2) and detect that two-point of vibrations (X and Y) is in-phase or out-phase.

The degree of linear association between two signals is compared by ordinary coherence function. Two signals are completely correlated when its function is a unit value and when there is no noise during the vibration recording and there is not any computational error in the spectral density calculation. The coherence spectrum has a peak in the resonant frequency of the platform, and its



(a)

(b)

Fig. 6 (a) Recorded Acceleration in Rows A& C (from Accelerometer No. 1 & 2) and (b) power spectral density, cross spectral density, coherence spectrum and phase spectrum between Accelerometer No. 1 & 2 respectively value is generally greater than 0.5.

As a sample, two signal processing output for the force excitation in the direction of Rows A&C with the constant frequency of 2.7 Hz, are presented in Fig. 6. Fig. 6(a) shows recorded acceleration No. 1 and 2. Fig. 6(b) shows power spectral density, cross spectral density, coherence spectrum and phase spectrum of accelerometer No.1 & No. 2.

Tables 1 and 2 present experimental and numerical natural frequencies of hinge based and pile supported condition of scaled model platform for different vertical bracing configurations. Cases No. 1 and 2 refers to base case and strengthened condition as shown in Fig. 5. Change of natural frequencies from hinge based to pile supported condition are shown in Table 3. By comparing the natural frequency of the scaled platform for both boundary conditions, it is observed soil-pile-structure interaction decreases natural frequencies of different modes. Meanwhile, it has significant

Table 1 Natural frequency of scaled model platform with the hinge based case

Case No.	Direction	Test		ABQUS software		SACS software	
		Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
1	Row A&C	3.1	20.32	3.20	20.07	3.27	21.06
	Row 1&2	3.24	19.69	3.44	19.49	3.41	20.57
	Torsion	6.15	24.86	5.87	24.73	5.01	26.11
2	Row A&C	8.24	23.68	8.40	23.88	8.40	22.92
	Row 1&2	7.86	-	8.10	26.21	7.96	23.91
	Torsion	16.36	-	16.59	35.96	14.88	30.27

Table 2 Measured natural frequency of the platform for pile supported case

Case No.	Direction	Test		ABQUS software		SACS software	
		Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
1	Row A&C	2.75	11.02	2.95	12.03	2.99	13.78
	Row 1&2	2.89	11.78	3.10	12.12	3.07	13.88
	Torsion	5.49	13.93	5.64	14.25	5.70	14.30
2	Row A&C	4.08	14.12	4.55	14.90	4.47	17.22
	Row 1&2	4.67	16.88	4.87	17.30	4.51	19.40
	Torsion	9.34	23.97	9.82	24.52	9.90	24.60

Table 3 Change percentage of natural frequency (pile supported case compared to hinge based condition)

Case No.	Direction	Force vibration test		ABQUS software		SACS software	
		Mode1%	Mode2%	Mode1%	Mode2%	Mode1%	Mode2%
1	Row A&C	11.29	45.77	7.81	40.06	8.56	34.57
	Row 1&2	10.80	40.17	9.88	37.81	9.97	32.52
	Torsion	10.73	43.97	3.92	42.38	13.77	45.23
2	Row A&C	50.49	40.37	45.83	37.60	46.79	24.87
	Row 1&2	40.59	--	39.88	33.99	43.34	18.86
	Torsion	42.91	--	40.81	31.81	33.47	18.73

decrease on second mode of both directions. In addition ABAQUS and SACS software can predict natural frequency of such a system accurately.

The result of natural frequencies in the first and second modes at the pile supported condition is lower than the hinge based condition which is due to the fact that the movement of the bottom level of platform are constrained in hinge based condition and there are no displacements for at this level. However in pile supported condition, the connection between legs and the skirt piles are fully rigid and the bending moment can be transferred from jacket to piles. In this condition pile heads have degree of freedom compared to hinge based condition.

Adding vertical braces in upper bay of the jacket (case No.2) causes significant increase in natural frequencies. The amount of these increases is about 11% and 43.3% for the first and second mode respectively in hinge based condition. The differences in pile supported condition are about 44.6 and 40.4 for first and second mode respectively.

It can be seen that adding vertical braces in upper level of jacket causes significant increase in stiffness of the structure. Meanwhile efficiency of adding such an offshore installed bracing system to avoid soft story mechanism in upper bay of such a jacket can be concluded indirectly from above experimental observation. However, more experimental study in nonlinear range of deformations is required for strength of jacket.

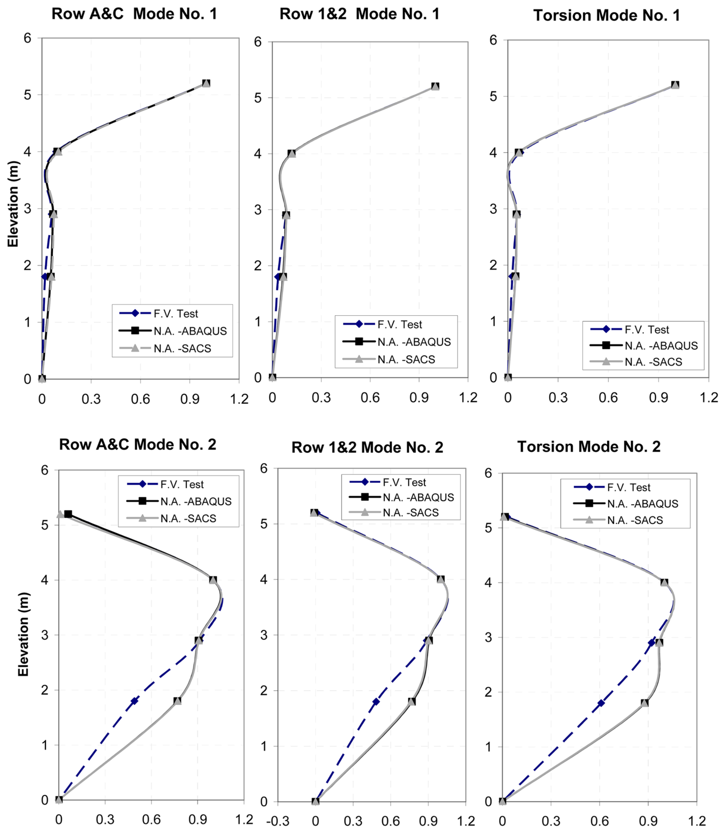


Fig. 7 Mode shapes of platform for Hinge-based condition - case 1

3.2 Platform mode shapes

For estimation of the mode shapes of scaled SP the amplitude of PSD is obtained for each point, and its root is calculated. The phase difference of each point relative to the reference point is determined by phase spectrum. If the phase angle is in the first or fourth quarter of the circle, that point is in-phase with reference point, otherwise, that point is in out-phase respect to reference point. Figs. 7 to 10 show mode shapes for both pile-supported and hinge-based cases. ABAQUS and SACS model results are also shown for comparison. By comparing mode shapes of the scaled platform for two boundary conditions, it is observed soil pile structure interaction decreases the stiffness of structure and increases the lateral relative displacement of the jacket. It can be observed that the first mode shape of scaled platform at pile supported condition compared to hinge based is changed slightly. Nevertheless, the effect of pile supported condition is illustrated in higher mode shapes. In addition, both of ABAQUS and SACS software's estimate first mode shape of scaled model, SP, more accurately compared to second mode shape. From comparison of mode shapes for both support conditions, it can be seen that adding vertical braces in upper bay of jacket causes simpler modes

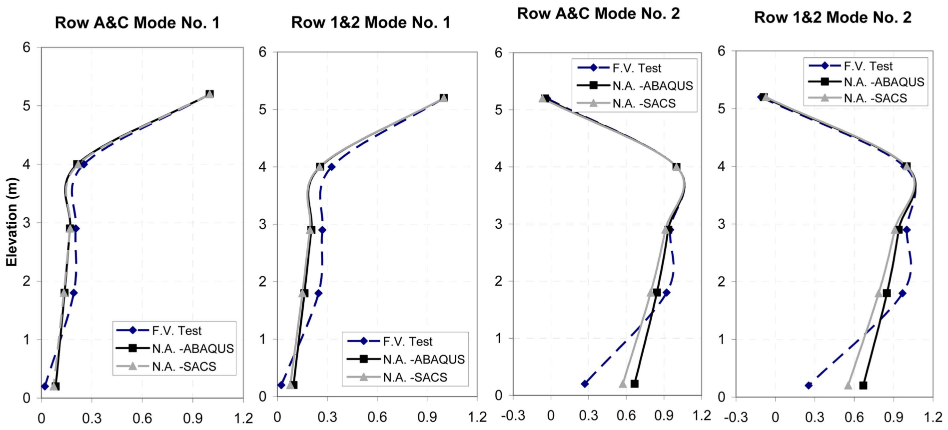


Fig. 8 Mode shapes of platform for pile supported condition - case 1

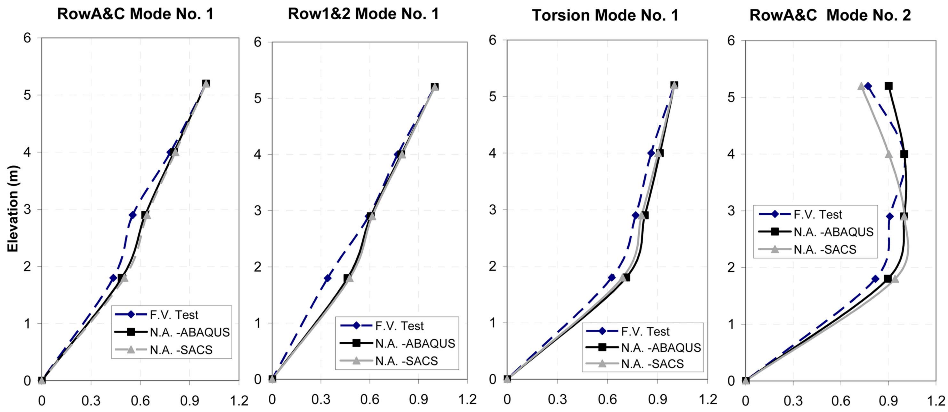


Fig. 9 Mode shapes of platform for Hinge-based condition - case 2

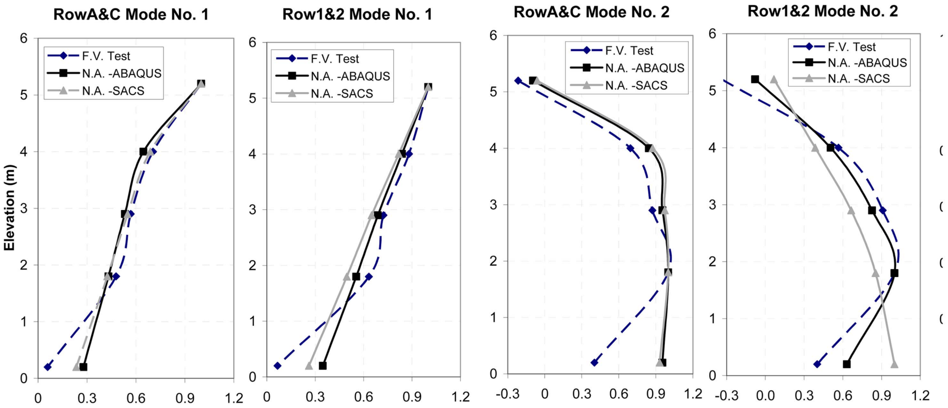


Fig. 10 Mode shapes of platform for pile supported condition - case 2

and dynamic behavior. Mode shapes of strengthened platform are similar to mode shapes of shear regular structures for both cases.

3.3 Estimation of modal damping

Half-power bandwidth method is used for calculating modal damping. The damping ratio is calculated using Eq. (6) in which frequencies f_a and f_b are illustrated in Fig. 11. Table 4 shows damping ratio for different modes of both boundary conditions.

$$\zeta = \frac{f_b - f_a}{f_b + f_a} \tag{6}$$

It can be seen that generally equivalent damping increases in the pile supported case compared to hinge based condition which is relative of damping sources in soil. Similar to the results of modal characteristics, effect of soil-pile structure interaction to the modal damping at higher modes is more significant compared to first mode.

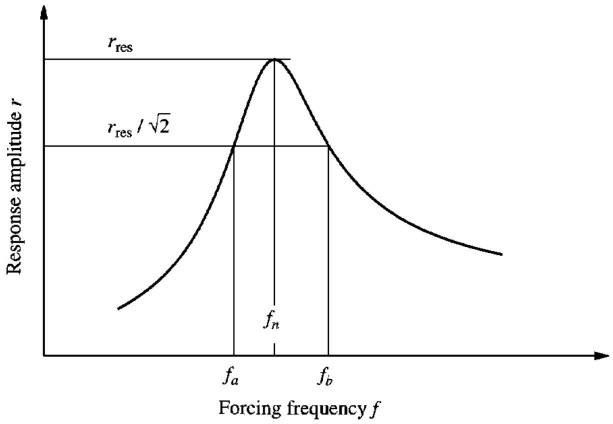


Fig. 11 Typical frequency response curve

Table 4 Modal damping for both boundary condition cases

		Hinge based condition		Pile supported condition	
		Mode 1	Mode 2	Mode 1	Mode 2
Case 1	Row A&C	0.0121	0.0029	0.0132	0.0041
	Row 1&2	0.0139	0.0020	0.0169	0.0042
	Torsion	0.0058	0.0017	0.0082	0.0029
Case 2	Row A&C	0.0049	0.0015	0.0120	0.0038
	Row 1&2	0.0093	--	0.0151	0.0041
	Torsion	0.0049	--	--	--

4. Conclusions

In this paper, dynamic characteristics of scaled model of a jacket type offshore platform in Persian Gulf are studied using experimental and numerical simulation. The model is tested first on a hinge based condition and then on a pile supported condition in order to investigate effect of soil-pile-structure interaction. Strengthening of jacket type offshore platforms with float over deck is also studied by adding vertical bracing members in upper bay of jacket from experimental and numerical models. Forced vibration dynamic tests are conducted for both support conditions to identify modal characteristics of the structure. Power spectral density function is used to extract dynamic characteristics from experimental results. The numerical modeling of scaled platform SP is performed using ABAQUS and SACS software. The results of experimental analysis show that soil-pile-structure interaction decreases natural frequency of structure and increases equivalent modal damping of the structure. The effects of SPSI are significantly illustrated at higher modes compared to first mode for all dynamic characteristics. Efficiency of offshore installed vertical bracing members in upper bay of jacket is also observed from improvement of dynamic characteristics of structure experimentally and numerically. The numerical results obtained from SACS and ABAQUS model matches more with experimental observation at first mode compared to higher modes.

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