

## **Effect of Pile- Soil- Structure Interaction on Dynamic Characteristic of Sample Jacket Type Offshore Platform by Experimental and Numerical Investigation**

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**Abstract.** Dynamic response of Pile Supported Structures is highly depended on the Pile Soil Structure Interaction. In this paper, by comparison of experimental and numerical dynamic response of a prototype jacket type offshore platform for both hinge based and pile supported boundary conditions, effect of soil-pile-structure interaction 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 both cases of platform in term of natural frequencies, mode shapes and modal damping are computed and compared with the others.

Numerical simulation of responses for the studied structure is also performed for both cases using capability of ABAQUS and SACS software. The 3D model of ABAQUS is created using continuum elements for soil and piles, and beam elements for jacket and deck elements. Mohr-Coulomb model and pile-soil contact theory are used for considering nonlinear inelastic soil properties. Simplified modeling of soil-pile-structure interaction 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) models can predict this effect accurately for the studied platform in small range of deformation.

**Keywords:** Steel Jacket type Offshore Platform: Soil-Pile-Structure Interaction: Experimental Modal Analysis; Finite element.

### **1. Introduction**

Pile foundations are a part of many structures such as jacket type offshore platforms used to transfer loads from superstructure to the soil layer. When external forces such as earthquake, wind or wave act on pile-supported structures, structural, soil and pile displacements are independent of the others. Response of the soil-pile 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 heavy structures resting on soft soils, high-rise buildings and jacket type offshore platforms. SPSI has an important effect in analysis result of jacket type offshore platforms. Meanwhile, dynamic characteristic and response of such a structure is highly depended to dynamic pile-soil structure interaction.

There are considerable researches on dynamic soil–pile–structure interaction (Mizuno 1987). Some procedures have been developed for considering this effect in evaluating of the dynamic response of steel jacket platforms. The simplified double-step method in which uncouples superstructure and pile systems portions is the first and less complex method. 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. Two and three-dimensional continuum modeling of the pile and surrounding soil by using finite-element or finite-difference approaches is more complex and high computational demands method presented by many researchers (Wu and Finn 1997 and Cai et al. 2000).

In the first category, dynamic beam on a nonlinear Winkler foundation 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. These approaches can be performed by using available computer codes.

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 platform SP (sample platform) is conducted for two hinge-based and pile-supported conditions. The platform is installed first on strong rigid floor of the 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 dynamic characteristics platform 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 modeling techniques. Continuum 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 contact elements. Then, the two-step method is considered using SACS software. P-y, T-z and Q-z nonlinear springs, according to the API RP-2A (2000) are modeled to simulate the soil-pile interaction. As SACS is commonly used in offshore engineering applications, it is selected for the simplified modeling of pile and surrounding soil.

## **2. Identification of the Dynamic Characteristics**

Earthquake response of any structure comes from some sources: observations made from the structural response during last earthquakes, experiments conducted on reduced scaled or actual size models of the structures and finally from analytical or numerical study. Performing experimental investigation is unavoidable issue in complex structure such as offshore platforms to verify the numerical result. The use of experimental techniques has been

widely applied to detect dynamic behavior of structural systems subjected to dynamic. These techniques are being investigated in several fields, such as mechanical engineering (Ziebath, and Baumgartner, 1981, James et al, 1994), aircraft testing (Shelleye et al, 1993), aerospace applications (James II et al, 1998) and the offshore industry (Vandiver, 1975, Hamamoto and Kondo, 1993, Ruotolo et al, 2000).

Performing tests using dynamic measurement offers the opportunity to obtain information about the whole system based on small number of measurements. Usually, these tests are based on determining system vibration response and relating it to the modal properties. Experimental modal analysis is the term used for determining the modal properties of a system experimentally. In many cases, the modal properties consist of the modal frequency, mode shape and modal damping. Two very common methods of the structural modal testing are the force vibration and ambient vibration (Salawu and Williams 1995). In ambient vibration tests, the excitation is not under the control and is usually considered as a stationary random process, which means that response data from the structure alone can be used to estimate the dynamic parameters. Ambient excitation can be from sources such as wind, pedestrian or vehicular traffic, earthquakes, waves or similar. For very large and massive structures, ambient excitation is often the only practical choice. Structural identification through ambient vibrations has been successful in numerous cases (Ivanovic, et al. 2000; Ventura, et al. 2003).

In case of the forced vibration testing, 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 (Causevic 1987; 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).

The need for testing the behavior of full-scale structures under dynamic loads and studying the modified structural system cannot be implemented due to its complexity and operation. Fabricating the laboratory scale model of the structure is one of the alternative methods to comparison and investigation of the performance of existing and new systems.

## **2.1. Description of Scaled Model**

Scaled model of a newly installed jacket type offshore platform in Persian Gulf SP1 is considered for this study. The laboratory model 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 Figure 1. Due to available pipes and laboratory facilities, the geometric scale used is 1:15. The legs had a diameter of 48 mm and a wall thickness of 3 mm. All horizontal bracing was 34 mm in diameter and 3 mm thick. The deck is consisted of intersectional beams with box section (60×40×3 mm). A plate with a thickness of 15 mm is welded to deck beam in order to simulate rigid diaphragm action and topside weight. For considering joint cans in jacket, the thickness of legs is increased to 5 mm. Eight skirt sleeves with 88.9 mm in diameter and 5 mm thickness is connected to the legs. Totally 4 sample of pipes is tested. One sample is tested for each size of used pipes. The modulus of elasticity and yield stress of steel piles are determined as  $2 \times 10^8$  KN/m<sup>2</sup> and between 265-285 MN/m<sup>2</sup> (respectively).

The 3D frames were constructed by qualified fitters and welders who all is 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 close fit-up of welded components and use the full penetration butt welds at all tubular member connections. The welding is done under the CO<sub>2</sub> shielding gas. All welds are tested under PT (liquid penetrate examination) and MT (magnetic particle examination), NDT tests, and the repairs are done to detect and remove the flaws that could cause premature failure.

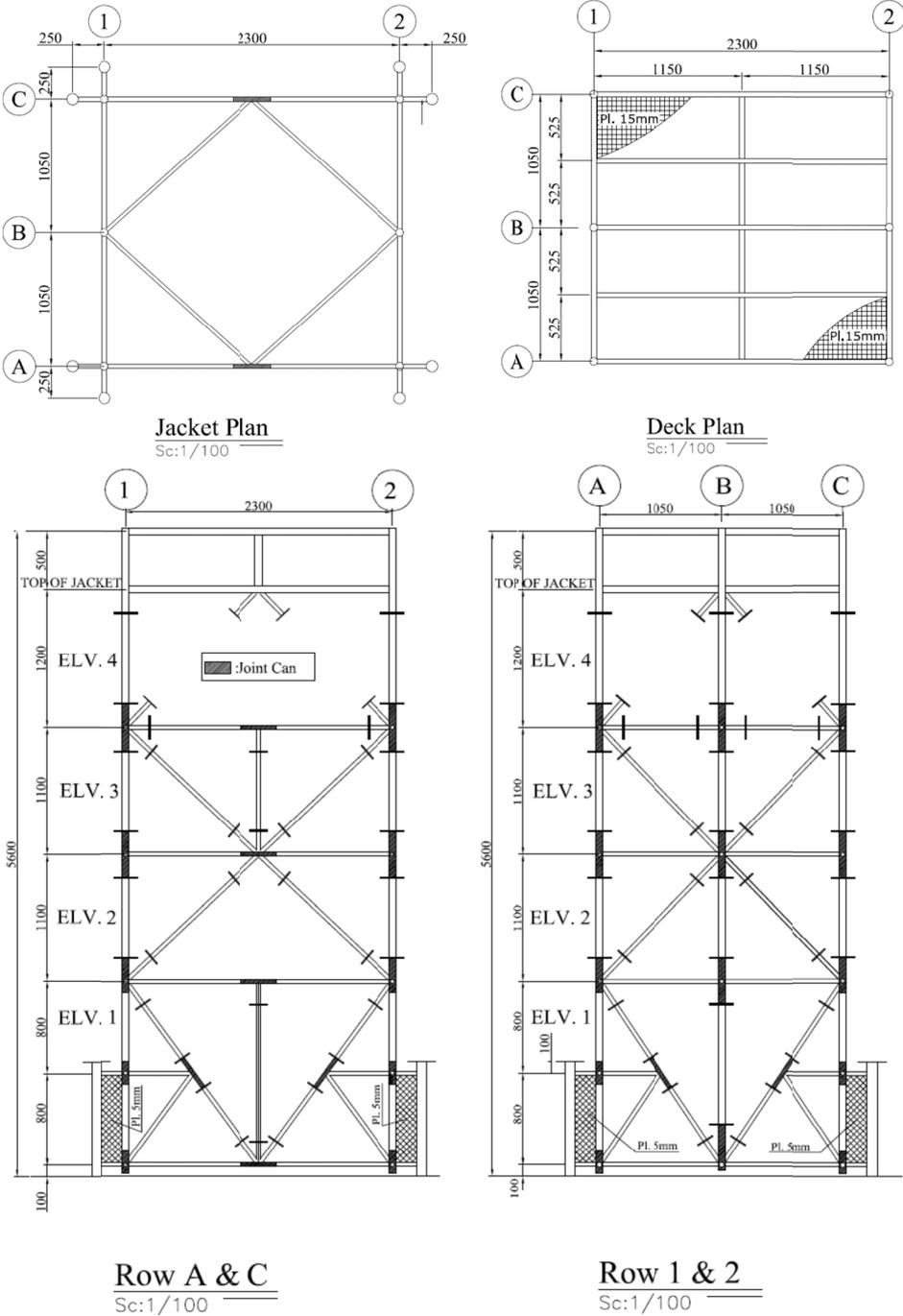


Figure 1. Elevation of the scaled model SP1

2.1.1. Boundary Conditions in Experiment

Jacket type offshore platforms are connected to seabed by piles foundation with the

sufficient penetration in soil to resist lateral and vertical loads is a safe manner. The effect of soil-pile interaction in the response of structure subjected to external forces is an important issue. In this paper the effect of soil-pile-Structure interaction on dynamic characteristic of a prototype offshore platform is investigated by comparison of experimental and numerical results of platform responses for two boundary condition cases. Firstly forced vibration tests are performed for the platform installed on rigid floor of laboratory as hinged base condition. For this purpose, four corner leg of the platform is connected to floor beam by a short stub (20 cm length) through four bolts for each leg.

After completing forced vibration tests of hinged condition, prototype offshore model SP1 is installed on eight skirt piles. For this purpose, a square cubes hole with approximately 7.00 m dimension is excavated in the yard of civil engineering faculty of K.N.Toosi University of Technology. In order to simulate the stiff bedrock in the bottom of the hole, a concrete layer with 500 mm thickness and compression strength of 28MPa was constructed. To prevent underground water penetration and change the soil condition, all surrounding walls were impermeable. The hole was filled about 320 m<sup>3</sup> homogenous sand. The process of filling the hole with sand was done in 10 months before performing driving skirt piles and installing jacket. The soil profile consisted of a monolayer uniformly graded sand with an angle of internal friction  $\phi$  of 38° and the undrained shear strength,  $c_u$  of 9.8 KN/m<sup>2</sup>. Young's modulus for the sand was varied between 12,000-25,000 KN/m<sup>2</sup> along the depth of the pile. The installation process of the scaled platform was conducted by driving eight piles through their sleeves using pile driving tool. Piles had a diameter of 60.3 mm, a wall thickness of 5 mm with total length of 6 meter (figure 2). To prevent buckling of piles during the driving process, they were divided to two segments with 3 meter length.

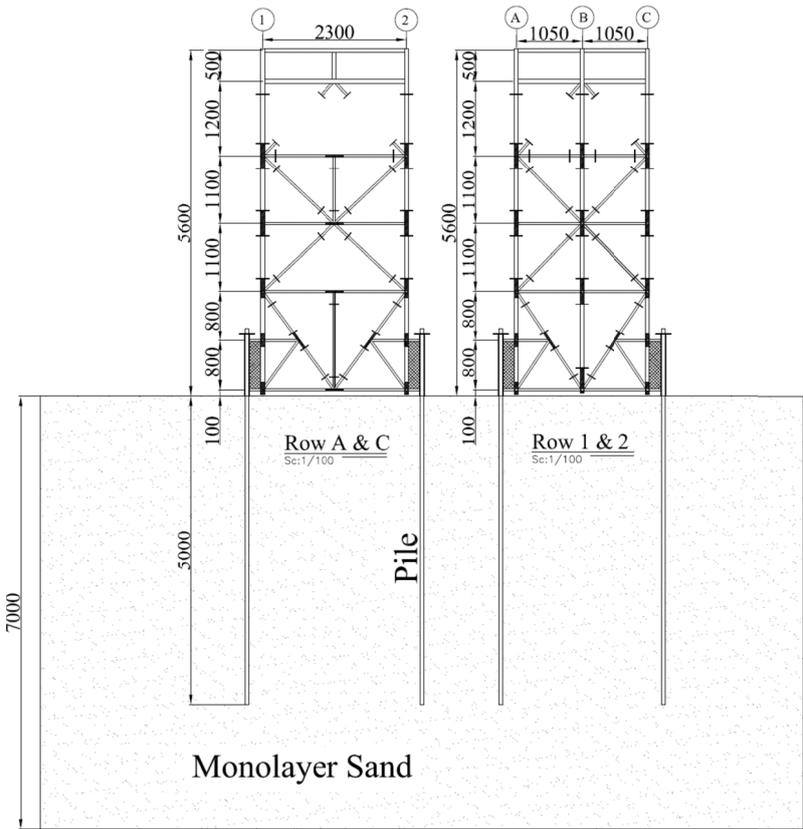
The connection between leg and pile consisted of flange plates, shear plates, pile sleeves, and grouted connections. After the completion of the pile driving process, one was grouted in the gap between pile and leg. The grout was made of seawater and cement type II (with Water/Cement weight ratio of 40% and 20.0 KN/m<sup>3</sup> density). Some sample cubes (10×10×10 Cm<sup>3</sup>) of grout were tested under compression. The compression strength of sample cubes was 390 MPa after 14 days (on the same day that the force vibration test was performed). Finally, the flange plate of each pile was welded to it and connected to the flange of the skirt-pile sleeve using four bolts. Figure 3 shows picture of the scaled model of the SP1 platform installed in the laboratory and the dense monolayer continuum sand.

### **2.1.2. Equipment Description**

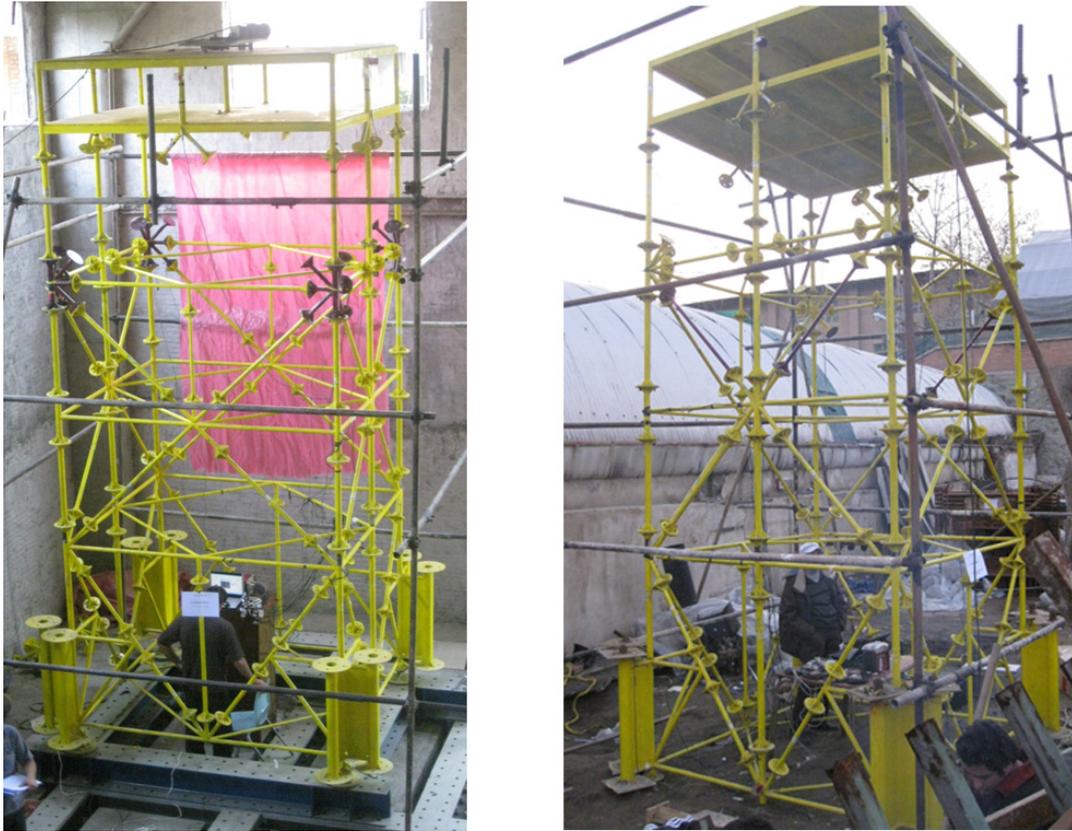
In the forced vibration tests, one vibration generating system having an eccentric mass shaker was used to excite the structure. This system can apply harmonic excitation across a wide frequency range in one or two horizontal directions and can induce weak to strong forced vibration to structures. The eccentric mass shaker was designed and fabricated for this study and had an exciting horizontal force up to 1.2 ton and a precise and stable control system, which is capable to impose and hold a frequency in the range 0.0 to 10 Hz within 0.1 Hz intervals. The shaker was installed in the second story of the platform deck and fixed to rigid plates of deck (figure 4). The response of the scaled model of SP1 platform to the frequency sweep kind of excitation was measured by six two dimensional accelerometers, four linear variable differential transformers (LVDT's) and TMR-200 portable digital central recording systems. The recording system supports 24 channels with following characteristics.

The response of the scaled model of SP1 platform in two directions (Row A&C and

Row1&2) was measured in several stages. The first stage of the test was 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 were evaluated. In the next stage of force vibration testing program the exact value of natural frequencies and corresponding mode shapes was evaluated. In these stages, the frequency of excitation was increased around the preliminary resonant frequencies by a 0.1Hz intervals and the response of the platform was measured by accelerometers.



**Figure 2.** sketch of scaled model, SP1, on soil-pile supported condition.



**Figure 3.** Installation of scaled model, SP1, on Hinge Support and soil-pile supported condition.



**Figure 4.** Eccentric mass shaker

## **2.2. Numerical Modeling Description**

Dynamic characteristics of the scaled platform SP1 is also computed numerically using modeling capability of ABAQUS and SACS finite-element software. For three-dimensional modeling of the soil media, piles and superstructure elements, and also considering direct interaction between soil-pile-structure, finite-element ABAQUS software is used. The common and less complex method that used in many offshore engineering applications is used by modeling capability of SACS software.

### **2.2.1. Modeling in ABAQUS**

Finite-element code ABAQUS is used in this study for the numerical modeling of scaled offshore platform SP. The superstructure elements, including legs, vertical and horizontal bracing members and deck beams are modeled using nonlinear two nodes beam elements. Three dimensional solid elements are applied to model piles and soil media. Mohr-Coulomb geotechnical constructive model is assumed for modeling soil material behavior.

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 in the soil and pile. If interface surface is in contact, full transfer of shear stress is ensured and separation will occur when there is tension between the soil and pile interface. Thus in ABAQUS, the contact constraint is applied between two surfaces of pile and soil. The surfaces separate when the contact pressure between them becomes zero or negative, and the constraint is removed. This behavior, referred to as hard contact. Because the system is subjected to a small force which does not induce slip, for the tangential component, rough interaction is assumed between surfaces.

### **2.2.2. Modeling in SACS**

In present, SACS software is widely used in practice for modeling soil-pile interaction in both research and professional jobs because it is simple and conceptual definitude. In the software, the pile and surrounding soil are divided into a number of discrete layers. Pile is simulated by Beam element, and its response is traced independently at nodal points of the pile segments within each layer. The stiffness and mass of the pile segments are established at these nodes. Soil resistance is assessed at each node and represented as a non-linear spring. In the present study, the p-y, t-z and q-z curves are used for considering the soil stiffness. The procedures for generating these curves are recommended by the American Petroleum Institute (API-RP-2a, 2000). Some tests are conducted at various deep of soil for calculating the p-y, t-z and q-z curves.

## **3.Result and Analysis of the Experimental Recorded Data**

In this section, the result of experimental and numerical analyses are presented in the term of modal characteristics. Force vibration tests of scaled model of platform are performed and response of system to excitation is derived. To identification of the modal characteristics of the scaled platform SP1, signal processing method was used based on the power spectral density function. Modal frequencies and mode shapes are also obtained numerically using SACS and ABAQUS outputs.

### **3.1.Estimation of Natural Frequencies**

The natural frequency of the scaled platform, SP is calculated using power spectral density (PSD), Equation 1, cross correlation spectrum (CPS), Equation 2, phase relationship, Equation 3, and the Coherence Spectrum (CS), Equation 4. 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) was 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 the 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. That is, all points of the platform in a lightly damped mode of vibration are in-phase or 180° out-phase with each other, depending only on the shape of the normal mode. Moreover, the large amount (approximately 1) must be occurred in the value of the coherence spectrum at the candidate frequency. A MATLAB subroutine is coded for this aim.

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

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

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

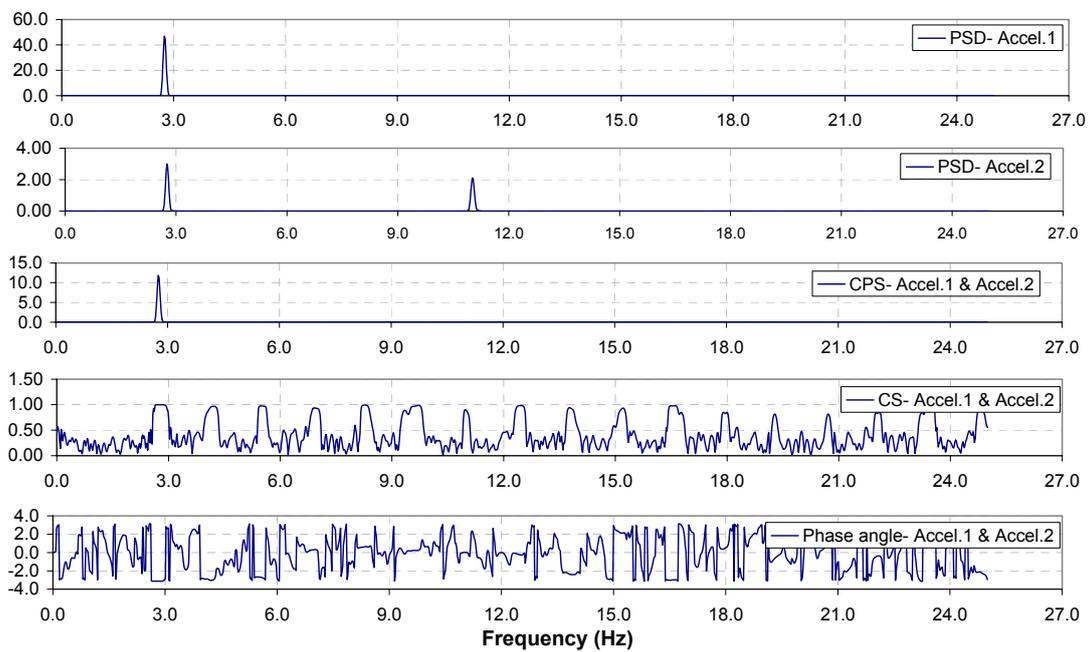
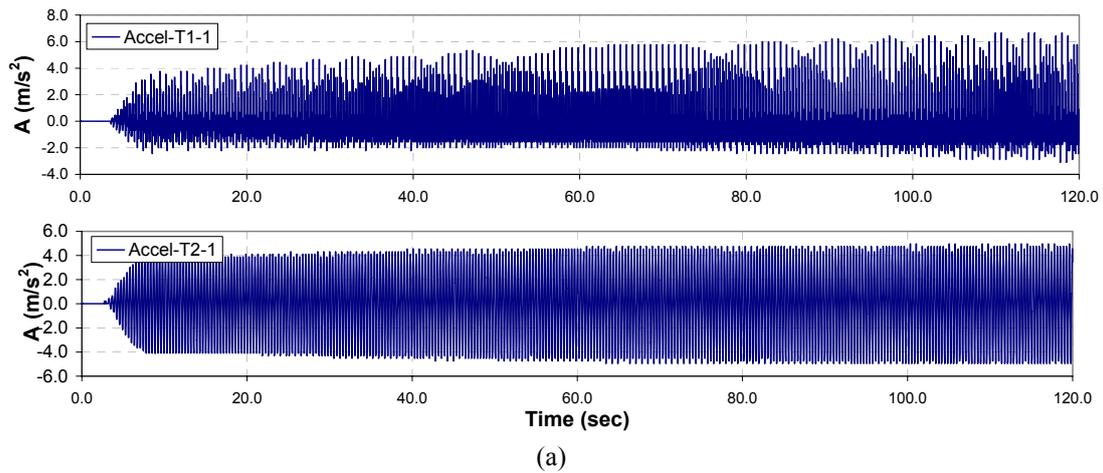
$$\theta_{xy}(f) = \text{tg}^{-1} \left[ \frac{Q_{xy}(f)}{C_{xy}(f)} \right] \quad (4)$$

$$CS: \gamma_{xy}^2 = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)} \quad (5)$$

In the above equation  $S_{xx}$  and  $R_{xx}$  are respectively power spectral density and the auto-correlation of a measurement point of the structure.  $S_{xy}$  and  $R_{xy}$  are respectively the cross correlation spectrum and the cross-correlation between two response measurement points of the structure. The 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 Equation 2 and detect that the 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, and its function is shown unity value, if there is not any noise during the vibration recording and also, there is not any computational error in the spectral calculation. The coherence spectrum has a peak in the resonant frequency of the platform, and its value is larger than 0.5.

Two typical signal processing output for the force excitation in the Row A&C direction with the constant frequency, 2.7 Hz, are presented figure 5. The figure 5-a is shown the recorded acceleration No. 1 and 2, and in the figure 5-b, the above method is executed for these two accelerations that installed at the top of the jacket of the scaled platform.

Tables 1 and 2 present natural frequencies of the scaled model platform with hinge based supports and pile supported condition respectively. The ratio of natural frequency changes in both cases (Hinge based and pile supported) of scaled platform illustrated in table 3. By comparing the natural frequency of the scaled platform at two boundary condition cases, it is observed soil-pile-structure interaction decreases natural frequencies of different modes. Meanwhile, it has significant decrease on second mode of each direction. In addition ABAQUS and SACS software can predict natural frequency of such a system accurately. ABAQUS model is more complex model compared to SACS model which is a simplified one.



**Figure 5.** (a) the recorded Acceleration in Row A&C direction for Acceleration No. 1 & 2. (b) respectively, power spectral density of Accel. No.1 & No. 2, cross spectral density between Accel. No. 1 & No. 2, coherence spectrum between Accel. No. 1 & No. 2 and phase spectrum between Accel. No. 1 & No. 2.

**Table 1.** Natural Frequency of Scaled model platform with the hinge based case

	Test		ABQUS Software				SACS Software			
	<i>M.1</i>	<i>M.2</i>	<i>M.1</i>	<i>M.2</i>	<i>Error M.1 %</i>	<i>Error M.2 %</i>	<i>M.1</i>	<i>M.2</i>	<i>Error M.1 %</i>	<i>Error M.2 %</i>
<b>Row A&amp;C</b>	3.1	20.32	3.20	20.07	3.42	-1.20	3.27	21.06	5.62	3.64
<b>Row 1&amp;2</b>	3.24	19.69	3.44	19.49	6.23	-0.97	3.41	20.57	5.18	4.47
<b>Torsion</b>	6.15	24.86	5.87	24.73	-4.61	-0.5	5.01	26.11	-18.56	5.03

**Table 2.** Measured Natural Frequency of the platform for pile supported case

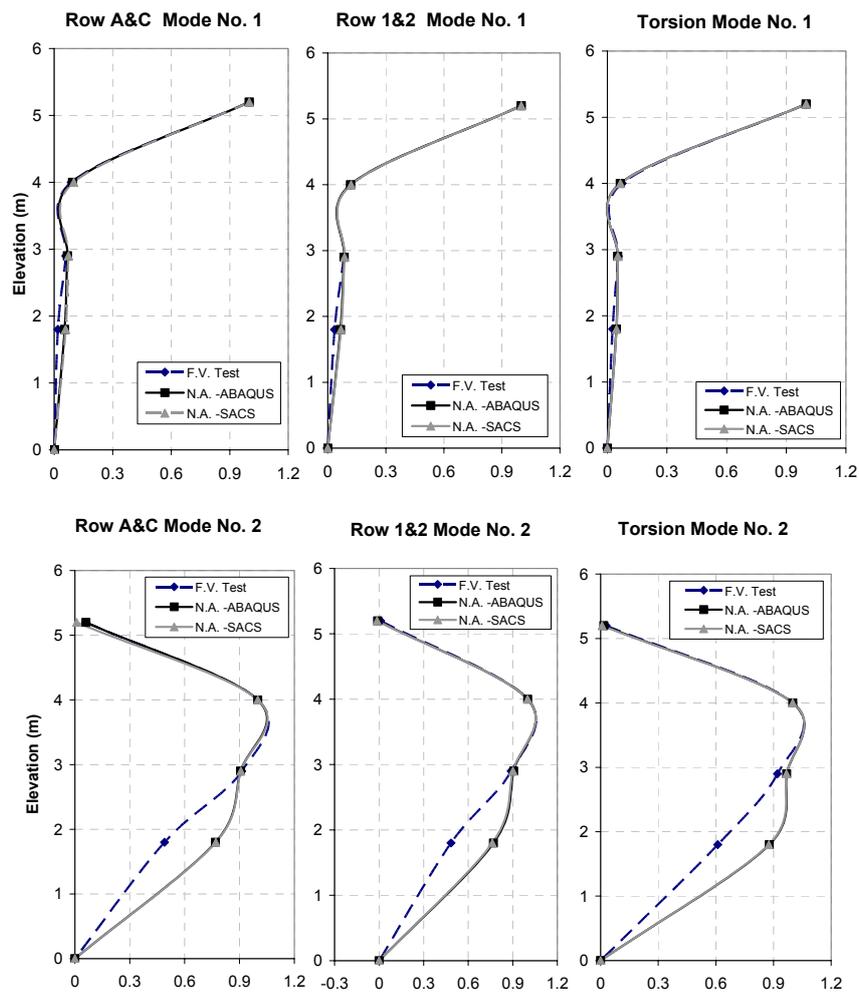
	Test		ABQUS Software				SACS Software			
	<i>M.1</i>	<i>M.2</i>	<i>M.1</i>	<i>M.2</i>	<i>Error M.1 %</i>	<i>Error M.2 %</i>	<i>M.1</i>	<i>M.2</i>	<i>Error M.1 %</i>	<i>Error M.2 %</i>
<b>Row A&amp;C</b>	2.75	11.02	2.95	12.03	6.97	9.24	2.99	13.78	8.64	25.12
<b>Row 1&amp;2</b>	2.89	11.78	3.10	12.12	7.30	2.91	3.07	13.88	6.18	17.86
<b>Torsion</b>	5.49	13.93	5.64	14.25	2.68	2.36	5.70	14.30	3.86	2.69

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

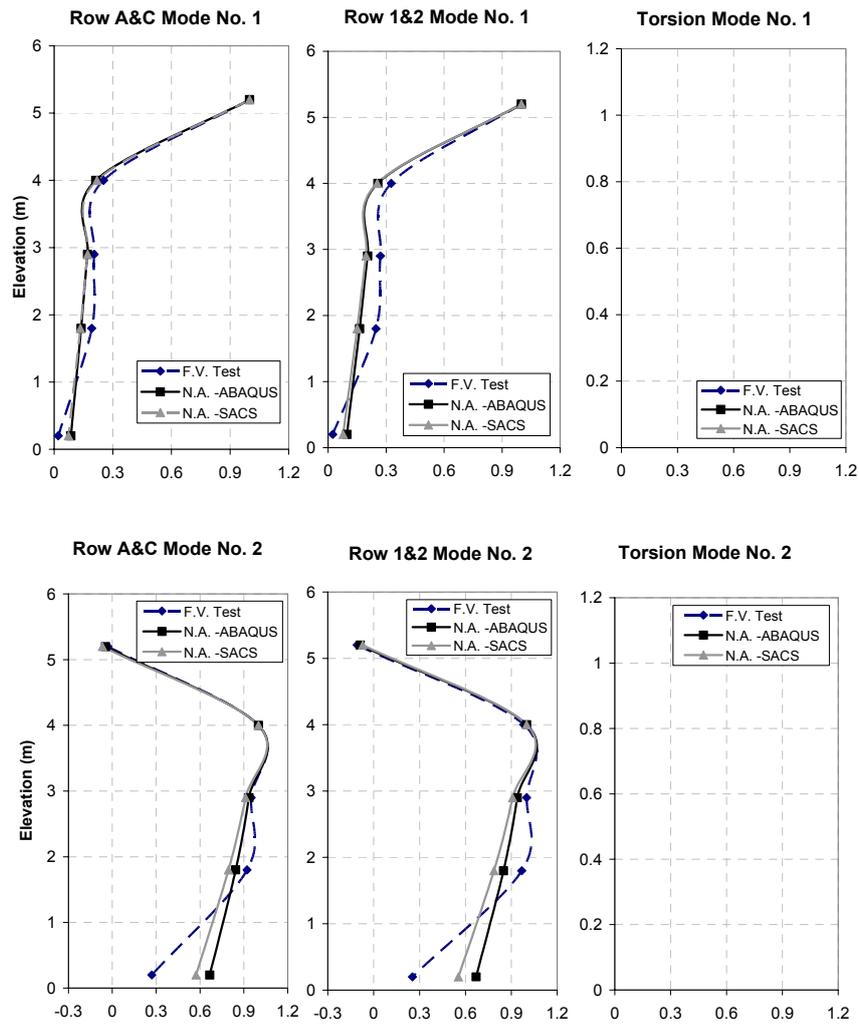
	Test		ABQUS Software		SACS Software	
	M.1 %	M.2 %	M.1 %	M.2%	M.1%	M.2%
<b>Row A&amp;C</b>	-12.56	-84.45	-8.62	-66.77	-9.29	-52.79
<b>Row 1&amp;2</b>	-12.07	-67.19	-10.89	-60.80	-11.08	-48.19
<b>Torsion</b>	-12.06	-78.51	-4.17	-73.49	12.10	-82.58

### 3.2. Platform Mode shapes

For estimation of the mode shape of scaled model platform, SP at the candidate frequency, the amplitude of PSD is obtained for each point, and its root calculated. Then the obtained value was ranked relative to the reference point to unity the amplitude of all mode shapes. 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 unit circle, that point is in-phase with reference point, but if the phase angle is in the second or third quarter of the unit circle, that point is out-phase with the reference point. The mode shapes are determined according to the obtained amplitude root of PSD and the phase difference (in or out- phase). Figures 6 and 7 show mode shape of scaled model platform, SP1, for both pile-supported and hinge-based cases. ABAQUS and SACS model results are also shown for comparison.



**Figure 6.** Mode shapes of platform for Hinge-based condition



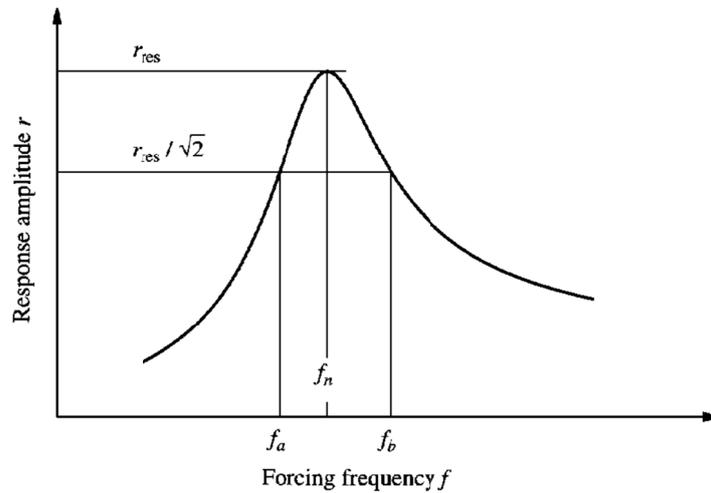
**Figure 7.** Mode shapes of platform for pile supported condition

By comparing the mode shape of the scaled platform at two boundary condition cases, 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 soil pile supporting condition to the hinge base is changed slightly. Nevertheless, the effect of soil pile support is illustrated at the higher mode shapes. In addition, both of ABAQUS and SACS software's estimated first mode shape of scaled model, SP1, more accurately than the second mode shape.

### 3.3. Estimation of Modal Damping

Half-power bandwidth method is used for calculating the modal damping. The damping ratio is calculated using equation 6 in which frequencies  $f_a$  and  $f_b$  are illustrated in figure 8. Table 4 shows damping ratio for different modes of both boundary condition cases.

$$\zeta = \frac{f_b - f_a}{f_b + f_a} \quad (6)$$



**Figure 8.** Typical frequency response curve.

**Table 4.** Modal Damping for both boundary condition cases

	Hinge Based Condition		Pile Supported Condition	
	M.1	M.2	M.1	M.2
<b>Row A&amp;C</b>	0.01211	0.00291	0.01324	0.00409
<b>Row 1&amp;2</b>	0.01389	0.00200	0.01689	0.00416
<b>Torsion</b>	0.00586	0.00171	0.00819	0.00287

It can be seen that generally equivalent damping increases in the pile supported cases compared to hinge based condition. Similar to the previous modal characteristics' result (natural frequency and mode shape) the effect of soil pile support to the modal damping at higher modes is so significantly than the first mode.

#### 4. Conclusion

In this paper, dynamic characteristics of a scaled model of steel jacket type offshore platform is studied using experimental and numerical studies. The simulated hinge bases at the structure laboratory and the soil-pile supporting with monolayer soil are considered as a base supporting condition for investigation the effect of soil-pile-structure interaction. The force vibration dynamic test is conducted at each supporting condition, and to identification of modal properties, signal processing is used based on the power spectral density function. The numerical modeling of sample platform, SP1, are performed using ABAQUS and SACS software. The result of experimental analysis is shown that the soil-pile-structure interaction decrease the natural frequency of structure. The same result is also observed in the other modal properties, and considering SPSI is increased the relative lateral displacement at mode shapes and modal damping. The effects of SPSI are significantly illustrated at higher modes than the first mode for all the dynamic characteristics. The numerical results obtained using SACS and ABAQUS software, SP1, at first mode to second mode is a better match with experimental results. Due to the complexity of modelling in ABAQUS software, in most cases, it results is more accurately than the SACS software.

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