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Comparative Analysis of Distorted Froudian and Equivalent Single Degree of Freedom Models in Offshore Jacket Platform Seismic Simulation

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ABSTRACT

The techniques of modeling are a very powerful way to simulate offshore platforms. For situations where the numerical modelling of structure process is very complex, these methods are preferred, and the model cannot be expressed in precise mathematical formulas. Dynamic characteristics of the structure shall be taken into account in order to determine simulation specifications. In this article, two methods of distorted Froudian models and an equivalent single degree of freedom system were used to model the platform. In the distorted Froudian method, by allocating different scale coefficients for geometric features and other specifications, the problem of modeling members that suffer from problems such as unreality due to applying some scale coefficients (such as the thickness of tubular members) is solved. In the second method, due to the more significant effect of the first mode on the vibration of the system (more than 90% mass participation), the structure becomes an equivalent single degree of freedom model and the construction of the platform in the laboratory becomes very simple. The obtained results showed the excellent accuracy of both methods and the excellent efficiency of the equivalent system with an equivalent single degree of freedom in the specific conditions in this research.

1. Introduction

For oil and gas exploitation, steel jacket platforms are frequently used. At a depth of 100 to 150 meters, these platforms are typically used. The steel jacket platforms have a low vibration frequency of 0.125 to 0.5 Hz [1]. If the frequency of the jacket platform is in the range of earthquake loading frequency, it may induce resonance and increase the dynamic responses of the structure. Due to the difficulty of obtaining data from prototypes, it is important to develop and test offshore platform models. Therefore, it is necessary to ensure that the model accurately replicates the behavior of the original sample. It is not easy to draw accurate analytical expressions for the modelling of structure behavior, as offshore platforms dynamics and description of their mechanical properties are complex. However, this behavior can be modeled using similarity techniques. Similarity analysis is a partial analysis that leads to the extraction of dimensionless equations or π expressions. The advantage of this method is that it simplifies the problem and provides the scale of the model. Each dimensionless parameter of a functional equation or π term shall have the same numeric value for both models and prototypes when modelling with simulation methods [2]. Using simulation theory, it is necessary to fulfill geometric, kinematic and dynamic simulations. Experimental modeling has an important effect in evaluating the dynamic behavior of offshore platforms. In fact, it is fundamental for the validation and calibration of numerical models and the evaluation of design procedures. In the offshore industry, Froudian scaling lows are adopted because this method usually keeps the ratio between the hydrodynamic and gravitational forces on the prototype and the model constant [3]. However, this traditional scaling approach does not take into account several phenomena that arise in many practical cases. The seismic behavior of offshore jacket platforms has been discussed by many researchers using different methods [4–8]. Trung [9] present a new Ensemble Empirical Mode Decomposition-Hilbert transform (EEMD-HT)-based analysis structures under an artificial and natural excitation. Walia et al. [10] address the setup of the scaled model testing as carried out at the offshore basin of the Ecole Centrale de Nantes, as well as the numerical model for the GICON®-TLP[1], and shows good agreements for the tank tests and the numerical models. In Erfani's research [11], results of buckling analysis of 384 finite element models, verified using three different test results obtained from three separate experimental investigations, were used to study the effects of five parameters such as D/t, L/D, imperfection, mesh size and mesh size ratio. Ou et al. [12] showed that for an offshore platform, if the mass contribution coefficient of the first mode is more than 90%, the structure can be considered as an Equivalent Single Degree of Freedom (ESDOF) system. In another study, Hosseinlou et al. [13] presented static and dynamic compression methods to determine the dynamic characteristics of the offshore jacket platform in terms of uncertainty. Also, Leng et al. [14] achieved favorable results of the dynamic control of the structure by physically modeling a jacket platform with three degree of freedom and another jacket platform with five degree of freedom as an equivalent single degree of freedom structure.

The purpose of this article is to present two modeling methods for offshore platforms. These two methods are: (i) Distorted Froudian (DF) [15] and (ii) ESDOF model [16]. The scales of thickness, length and modulus of elasticity are limited due to the Froudian conditions. This is leading to modelling problems, and certain scales have to be distorted. The length scale may not be as similar to the modulus of elasticity scale, e.g. In the past, all models have been built on the basis of equal internal and external forces inside or outside the members. Therefore, under those conditions the distorted Froudian models developed in this area are also defined. In the undistorted Froudian model, which is not applicable for modeling offshore platforms, each scale is fixed according to the ratio of modulus of elasticity or the equivalent length scale (because the length scale is fixed based on the ratio of modulus of elasticity). In the second method, an MDOF[2] system is modeled as an ESDOF structure based on the first mode. It is necessary to explain, since in offshore platforms the first mode is the dominant mode and the participation coefficient of the first mode is greater than 90% [17], the assumption of the SDOF system of the simplified jacket platform is confirmed. In the following, a jacketed offshore platform is modeled using these two methods and the advantages and disadvantages of each method is discussed.

2. Methodology

Laboratory modeling of an offshore platform is of great importance for predicting the behavior of the structure due to the high cost of marine projects. This modeling, when the loading is dynamic (such as an earthquake), the complexity of predicting the behavior of the structure multiplies. But due to the many limitations that exist for modeling (such as model dimensions, behavior of materials, behavior of external loads, etc.), it is necessary for this modeling to be accurate. In this section, the rules governing the similarity between the model and the prototype are explained. The distorted Froudian model is defined as a model that satisfies the conditions of equal internal and external forces and equality of the Distorted Froudian number. Generally, in this model, the speed scale defined by the Froudian condition λ_{vw} is considered equal to the structure speed scale λ_v. The equality of the Distorted Froudian number in the main structure and the model requires that [18]:

$$\left(\frac{v}{\sqrt{gl}}\right)_m = \left(\frac{v}{\sqrt{gl}}\right)_p \tag{1}$$

Where the index m is defined for the model and p for the main structure. Also, l represents the length (or dimension), v is the velocity of the structure, and g is the acceleration of the earth's gravity. If the length scale of a structural member is as $\lambda_l = l_m/l_p$, the modulus of elasticity (E) is as $\lambda_E = E_m/E_p$, the thickness scale of members (t) is as $\lambda_t = t_m/t_p$ and the density scale of members (ρ) is as $\lambda_\rho = \rho_m/\rho_p$ are defined, it can be written:

$$\lambda_v = \sqrt{\lambda_l} \tag{2}$$

Since $\lambda_v = \lambda_\rho^{-0.5}\lambda_E^{0.5}$, therefore by placing it in Eq. (2) it can be shown that:

$$\lambda_l = \lambda_\rho^{-1}\lambda_E \tag{3}$$

For tubular members with diameter D and thickness t, considering the moment of inertia of the section ratio and Eq. (3), the following thickness scale factor is obtained:

$$\lambda_t = \lambda_l^2\lambda_E^{-1} = \lambda_l\lambda_\rho^{-1} \tag{4}$$

If the model is without distortion ($\lambda_\rho = 1$), from Eqs. (3) and (4) we can write: $\lambda_E = \lambda_l$ and $\lambda_t = \lambda_l$. This case is defined as a Froudian model without distortion. Therefore, for a Froudian model without distortion, the relationships are presented as follows [15]:

$$\lambda_\rho = 1, \lambda_l = \lambda_E, \lambda_t = \lambda_l \tag{5}$$

In the case of the distorted Froudian model, Eq. (5) is not met, while Eq. (4) is met. In this case, the length scale may not be the same as the modulus of elasticity or the thickness scale. But this scale coefficient is associated with Eq. (4). Therefore, the length and

[1] Tension Leg Platform

[2] Multi Degree of Freedom

thickness of scales may differ according to the modulus of elasticity.
According to Eq. (4), the density and thickness scale coefficients are limited by the scale coefficient of the modulus of elasticity in the distorted Froudian model. Usually the designer decides on a length scale in that case. However, it is theoretically possible to select a scale factor for thickness and modulus of elasticity from Eq. (4), then calculate the length scale factor accordingly. Alternatively, Eq. 4 shows a density scale coefficient when the thickness and length coefficients have been selected. As a result, mass must be corrected in order to satisfy the Eqs. of (3) and (4). For the distorted Froudian model, Eqs. (3) and (4) need to be fulfilled. The results suggest that a scale factor of internal and foreign forces should be identical. Considering these requirements, it can be written: (i) Eqs. (3) or (4) do not need to be fulfilled at the same time. (ii) Scale factor is different for internal and external forces. (iii) In addition to the precise determination of the structure speed and force scales, it is provided to select the thickness, length and modulus of elasticity scales λ_t, λ_l, and λ_E separately.
In the undistorted Froudian model, the length scale coefficients and the modulus of elasticity are equal. In practical terms, however, it is not possible to build such a model due to the very small, perhaps unrealistic thickness required for the model and the use of a material whose modulus of elasticity is in line with the length scale factor. Low thickness may cause buckling of the structure. These problems are solved by selecting the various scales for length and modulus of elasticity according to a distorted Froudian model. Therefore, despite the fact that with this method, suitable values can be assigned for the thickness and modulus of elasticity of the model, Eqs. (3) and (4) cannot be satisfied simultaneously [15].

3. Jacket Platform Prototype

In this project, the platform model defined in the article [19] was used for modeling. In the oil and gas industry, the structures of this type of platforms are prevalent and even similar to real platforms [20–22]. The steel structure of this platform is 90 meters high and 80 meters deep. The platform jacket has four legs with symmetrical dimensions of 32×32 (m^2) on the seabedand 20×20 (m^2) on the topside. The total dead and live load of the topside is 4850 tons. On the vertical side, the platform has an inverted V shape steel bracing with similar mechanical properties to the footings and horizontal bracing. To consider the effects of soil-pile interaction, the equivalent pile length method was used at a height equal to 8 times the diameter of the pile [23]. Figure 1 displays the perspective of the jacket platform, while Table 1 provides the detailed geometric and mechanical characteristics of the jacket components.

Table 1. Mechanical and geometric characteristics of jacket members [19]

Mechanical	Modulus of elasticity of steel	200,000	MPa
	Poisson ratio	0.3	-
	Yield stress	320	MPa
	Ultimate tension	405	MPa
	Topside mass	4800	tos
	Steel density	7.8n	tons/m^3
Geometric	Horizontal members diameter	1	m
	Horizontal members thickness	0.012	m
	Braces diameter	1.1	m
	Braces thickness	0.012	m
	Legs diameter	1.5	m
	Legs thickness	0.025	m

According to the dynamic equation of motion presented in Eq. (1), the dynamic characteristics of the 5DOF jacket platform system were given in Table 2. By performing modal analysis, the frequencies and contribution coefficients of the first five modes were presented in Table 3. As shown in Figure 3, the natural frequency of the first mode is equal to 1.98 (rad/s).

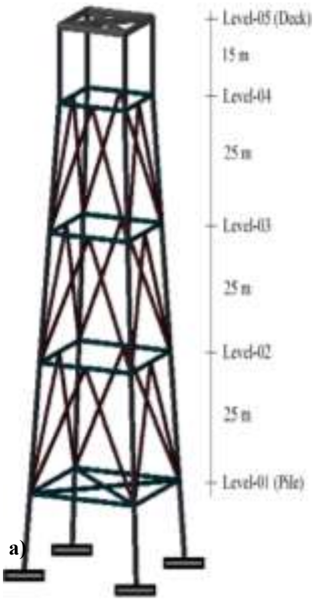

Figure 1. Jacket platform [19]

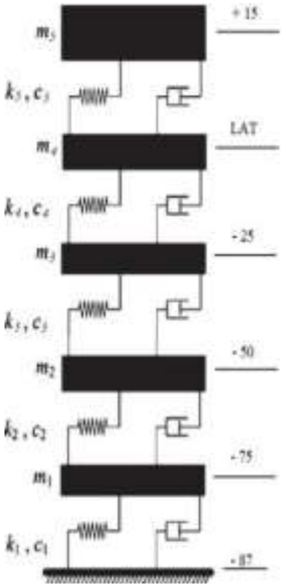

Figure 2. Platform model with an ideal 5DOF system

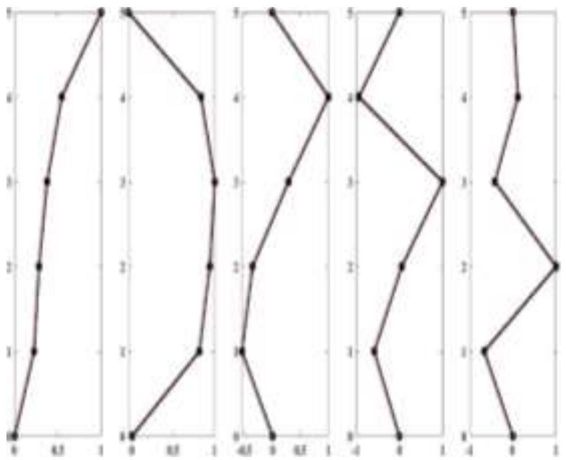

Figure 3. Vibration mode and frequencies of the jacket platform [19]

Table 2. Dynamic characteristics of the 5DOF system of the jacket platform [19]

	Level 1	Level 2	Level 3	Level 4	Level 5
Mass (tons)	220	200	195	130	4850
Stiffness (MN/m)	90	350	210	115	42

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=F_e \quad (6)$$

In Eq. 6, the matrices [M], [C] and [K] are the matrices of the mass, damping and stiffness of the jacket structure, and $\{\ddot{x}\}$, $\{\dot{x}\}$ and $\{x\}$ are the acceleration, velocity and displacement vectors, respectively; and F_e is the external force of the earthquake.

Table 3. Modal mass participation percentage (cumulative)

Mode	Frequency (rad/s)	UX	UY	UZ	RX	RY	RZ
1	1.98	45	45	0	0	0	0
2	12.83	90	90	0	0	0	0
3	30.96	90	90	0	0	0	73
4	46.43	92	92	0	6	6	73
5	66.34	94	94	0	8	8	77

To numerically solve Eq. (6), the Simulink module of MATLAB software was used, using the fourth order Runge-Kutta method. In this research, in order to validate and define the jacket platform model (Figure 4), Mousavi et al.'s numerical research [24] has been used.

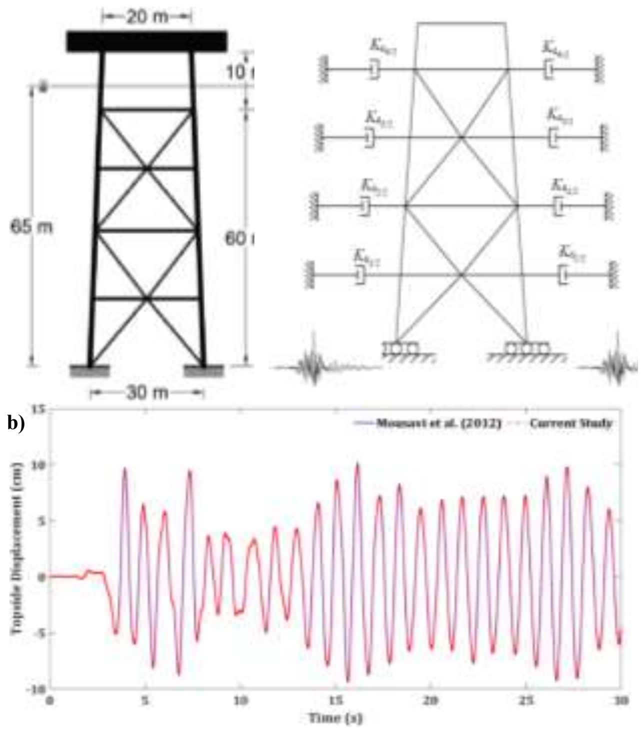

Figure 4. a) Mousavi et al.'s Jacket platform model [24] and b) Comparison of platform topside displacement time history under Kern County earthquake

The density of water was assumed to be 1024 kg/m^3, and the density of steel was 7800 kg/m^3 respectively. The mass and stiffness matrices of the structure as a model of a 5DOF system are presented in Table 4.

Table 4. Dynamic characteristics of the 5DOF system of the research jacket platform [24]

	Level 1	Level 2	Level 3	Level 4	Level 5
Mass (tons)	157	154	151	137	1087
Stiffness (MN/m)	556	444	375	286	67

This jacket platform was investigated with three earthquake accelerations (San Fernando 1971, El Centro, 1940, Kern County 1952 and Northridge 1992). For the structure to be in the linear range during the analysis, the value of earthquake accelerations was scaled to PGA = 0.3g factor. Figure 4b shows the time history of platform topside displacement under the Kern County earthquake. The RMS[3] time histories of platform topside displacement are listed in Table 5 for research [24] and the present study.

According to the results of the analysis of the desired platform with the codes written using MATLAB software (Figure 4b) and according to Table 5, an insignificant difference (less than 5%) was observed between the results, which indicates the accuracy of the method used in this research.

Table 5. RMS response of platform topside

Earthquake	Mousavi et al. (cm)	Current research (cm)	Difference (%)
Kern County	4.89	4.72	3.5
San Fernando	4.38	4.28	2.3
Northridge	5.42	5.36	1.1
El Centro	3.96	3.88	1

4. Modeling of Jacket Platform

For the modeling of the structure, due to the existing limitations for the dimensions of the seismic table, a sample platform made of steel was considered. Based on the dimensions of the shaking table, the first limitation is determining the length scale factor (λ_l). Knowing the λ_l, it is possible to calculate the thickness of the tubular components in a platform model and this will give very small value for its size. On the other hand, for modeling the thickness (λ_t) of the pipe sections used in the platform, due to the lack of construction in very small dimensions, the same length scale factor can not be used. So, it is necessary to increase λ_t as much as possible using the distorted Froudian model. The second important limitation is the determination of the materials of the modeled platform. In order to choose the type of material for the model, it is necessary to use the proportional scaling factor for the modulus of elasticity (λ_E) according to the similarity rules of the distorted Froudian model based on the nature of the problem. Availability, quick and easy construction, strength and low cost are the most important characteristics of model materials. In desktop FDM[4] 3D printing, the most commonly used materials are ABS[5], PLA[6] and PETG[7] 3D printing filaments. The three materials ABS, PLA and PETG differ in many aspects. The difference between them can include tensile strength, density or even application. Table 6 compares the important properties and characteristics of these three filaments [25]. Availability and simplicity of construction and implementation are important factors when choosing materials. In this report, according to Table 6, ABS material was used to build a small-scale platform model [25]. As mentioned earlier, two limitations were raised for platform modeling. The first limitation was the longitudinal scale factor and the second was the material type. However, the third limitation is the amount of thickness of the tubular members of the platform, which is very challenging due to the limitation of making the thickness of the tubes, due to their very small thickness as a result of small scaling. Therefore, it is necessary to distinguish the length scale factor from the scale factor for the thickness of the tubular members. This problem is solved using the method of distorted Froudian modeling.

Table 6. Differences among ABS, PLA and PETG [25]

Properties	ABS	PLA	PETG
Tensile strength	27 MPa	37 MPa	37 MPa
Strain	3.5-50 %	6 %	6 %
Flexural modulus	6.1-7.2 GPa	4 GPa	4 GPa
Density	g/cm³ 4.1-1	1.3 g/cm³	1.3 g/cm³
Melting point	200 °C	173 °C	173 °C
Biodegradability	No	Yes, under the right conditions	Yes, under the right conditions
Glass transition temperature	105 °C	160 °C	160 °C
Advantages	More ductility and higher bending strength	Easier to print	High strength and less brittleness
Disadvantages	Harder to print	Low heat resistance	Possibility of scratching

With the coefficients of modulus of elasticity and thickness being known, according Eqs. (1) to (5), density and length coefficients are calculated. These coefficients are presented in Table 7.

Table 7. Modeling scale coefficients

[3] Root Mean Square
[4] Fused Deposition Modeling
[5] Acrylonitrile Butadiene Styrene
[6] Polylactic Acid
[7] Polyethylene Terephthalate Glycol

λ_t	λ_E	λ_l	λ_T	λ_p	λ_m
1:35.714	1:70	1:50	1:7.071	1:1.4	1:125000

In Table 7, λ_T is the time scale coefficient and λ_m is the mass scale coefficient. For a better and simpler modeling of the platform structure, the platform model of the article [19] presented in Figure 1 was used. According to the dynamic equation of motion, the dynamic characteristics of the original and modeled jacket platform are given in Table 8. As shown in Figure 3, the frequency of the first vibration mode of the main platform is e qual to 1.98 (rad/s).

Table 8. Dynamic characteristics of the 5DOF system of the jacket platform

Prototype					
	Level 1	Level 2	Level 3	Level 4	Level 5
Mass (tons)	220	200	195	130	4850
Stiffness (MN/m)	90	350	210	115	42
Model					
Mass (kg)	1.76	1.6	1.56	1.04	38.8
Stiffness (KN/m)	36	140	84	46	17

The damping matrix is calculated through the Rayleigh damping equation by considering 2% damping ratios for all vibration modes of the platform [26]. The dynamic characteristics of the original and modeled structure used as equivalent SDOF in the longitudinal direction are presented in Table 9.

Table 9. Dynamic characteristics of the platform of Enferadi et al. [19] as ESDOF

	Fundamental frequency (rad/s)	Mass (kg)	Stiffness (KN/m)	Damping (KN.s/m)
Prototype	1.98	4.94×10^7	1.95×10^5	3929.6
Model	14.05	395.4102	78.1	0.222

5. Results

At first, to check the results of using the ESDOF method for the prototype platform, by applying the four earthquake records mentioned earlier, the time history analysis was performed in the Simulink module of MATLAB software using the fourth order Runge-Kutta method and the results The following was obtained. According to Figures 5 and 6, which are respectively the time history of displacement and acceleration of the platform topside for four earthquake records, a good match was observed between the MDOF and the ESDOF platform.

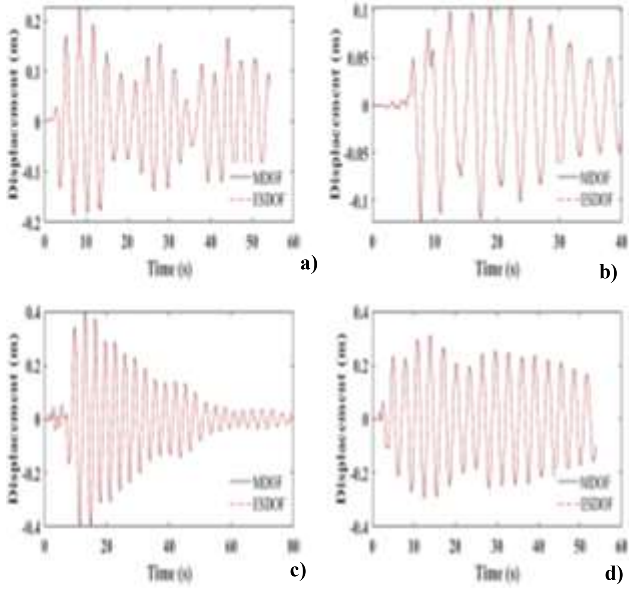

Figure 5. Time history of topside displacement for (a) Kern County, (b) Northridge, (c) San Fernando and (d) El Centro earthquakes

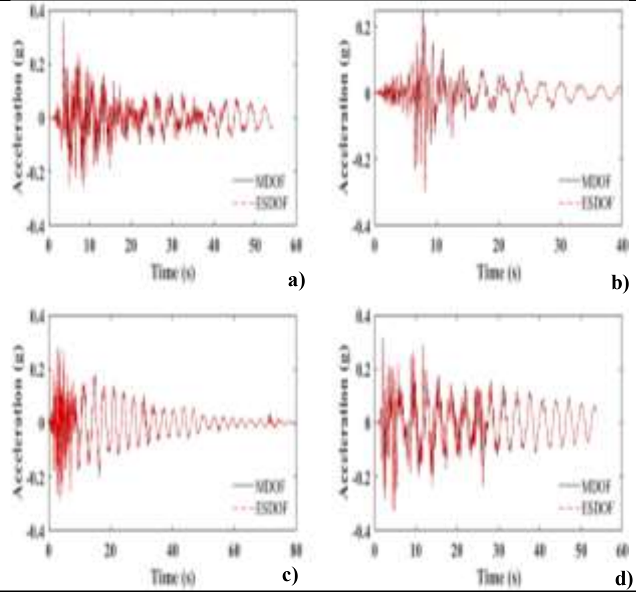

Figure 6. Time history of topside acceleration for (a) Kern County, (b) Northridge, (c) San Fernando and (d) El Centro earthquakes

In order to quantitatively check and compare the results of the time history analysis of the MDOF system and the ESDOF system, the Max[8] and RMS values of the displacement and acceleration of the topside for each of the four earthquake records were averaged and shown in Table 10.

Table 10. Comparison of the prototype MDOF system with the ESDOF system

	MDOF	ESDOF	Error (%)
Max displacement (m)	0.26	0.25	3.8
RMS displacement (m)	0.11	0.105	4.5
Max acceleration (m/s^2)	0.3	0.291	3.3
RMS acceleration (m/s^2)	0.06	0.06	0

According to figures 5 and 6 as well as table 10, it can be seen that a good match is observed for the results of the structure analysis of an equivalent degree of freedom. The errors between the obtained results are below 5%, which is negligible from an engineering point of view.

By using the modeling method of the ESDOF structure, the dynamic characteristics of the modeled structure are presented in Table 9, in Figures 7 and 8, respectively, the time history of the displacement and acceleration of the modeled platform topside with a longitudinal scale factor of 1 to 50, for four Earthquake record is drawn. Since the coefficient of numerical longitudinal scale is smaller than one, therefore, in the modeling of the structure, the duration of the earthquake excitation is also reduced in proportion to λ_l (equal to λ_T). A good match between the MDOF platform and the modeled ESDOF platform is observed.

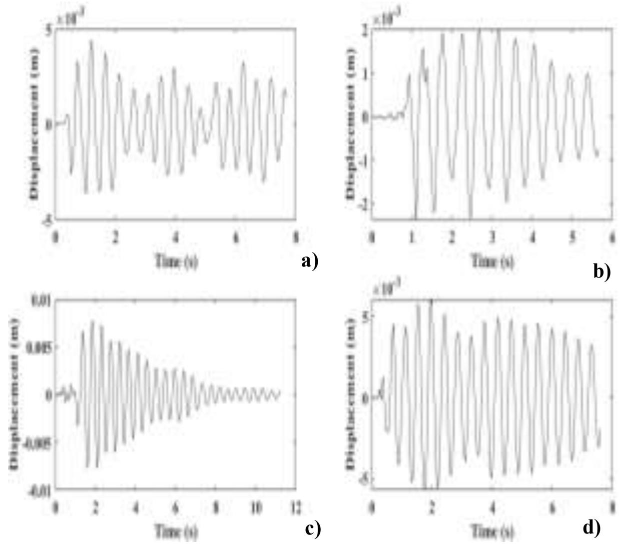

Figure 7. Modeled topside displacement time history for (a) Kern County, (b) Northridge, (c) San Fernando and (d) El Centro earthquakes

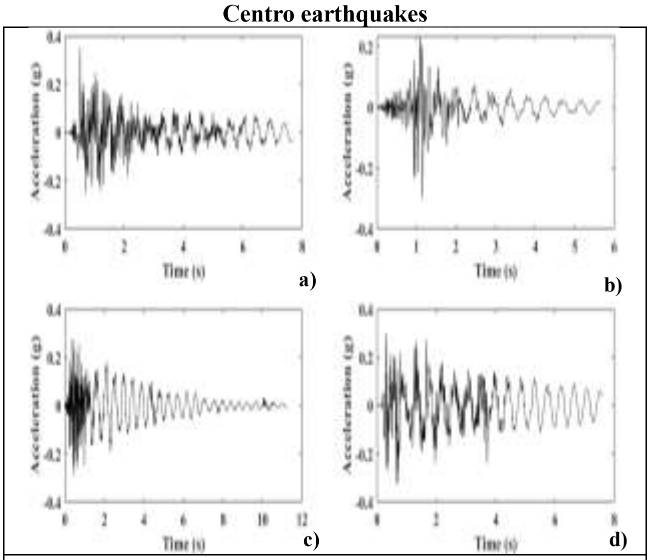

Figure 8. Modeled topside acceleration time history for (a) County, (b) Northridge, (c) San Fernando and (d) El Centro earthquakes

[8] Maximum

As can be seen in Figures 7 and 8, the values of the range of changes in the diagrams are proportional to the scale factor defined for the main model of the platform. To investigate this issue quantitatively, the Max and RMS values of displacement and acceleration of the topside for each of the four earthquake records were averaged and shown in Table 11.

Table 11. Responses of the modeled ESDOF system

	Max. displacement (m)	RMS displacement (m)	Max. acceleration (m/s^2)	RMS acceleration (m/s^2)
ESDOF	0.005	0.0021	0.291	0.06

For a more detailed investigation and comparison of the structure modeling method using the distorted Froudian method (DF) with the modeled ESDOF structure, in Figures 9 and 10, respectively, the time history of the displacement and acceleration of the modeled platform topside is drawn for four earthquake records, which indicates the good agreement of the results obtained with both methods.

For quantitative analysis, the Max and RMS values of displacement and topside acceleration for both modeling methods under each of the earthquake records were averaged and shown in Table 12.

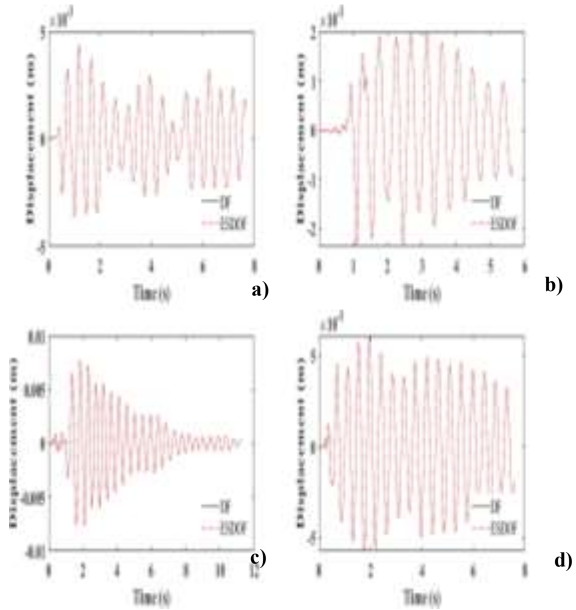

Figure 9. Comparison of the topside displacement time history of the DF with the ESDOF for the (a) Kern County, (b) Northridge, (c) San Fernando and (d) El Centro earthquakes

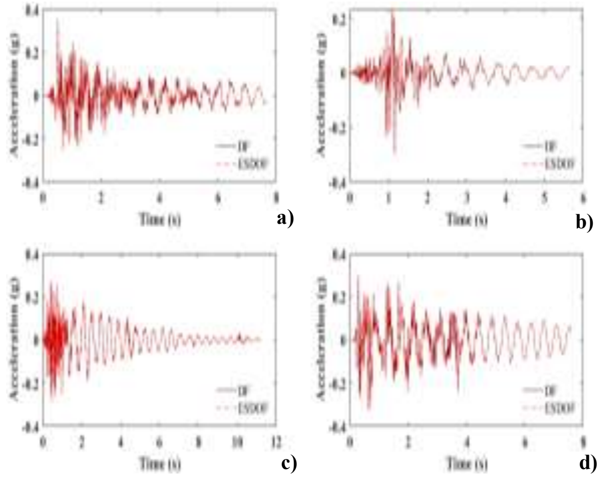

Figure 10. Comparison of the topside acceleration time history of the DF with the ESDOF for the (a) Kern County, (b) Northridge, (c) San Fernando and (d) El Centro earthquakes

Table 12. Comparison of the results of the modeled platform

	DF	ESDOF	Difference
Max displacement (m)	0.0052	0.005	3.8 %
RMS displacement (m)	0.002	0.0021	4.5 %
Max acceleration (m/s^2)	0.3	0.291	3.3 %
RMS acceleration (m/s^2)	0.06	0.06	0

As mentioned earlier, to use the technique of an ESDOF system, it is very important and decisive to determine the vibration modes and the corresponding frequencies. In Figure 11, the mode shapes for both the DF and the ESDOF are drawn and compared with each other. As shown in Figure 11, a perfect match is observed for the mode shapes for both methods.

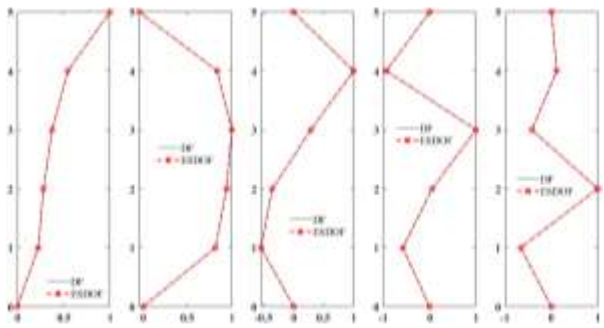

Figure 11. Vibration mode shapes and frequencies of the DF and ESDOF jacket platform

6. Conclusion

In this article, two methods were proposed for the physical modeling of the offshore jacket platform. In the first method, which is called Distorted Froudian (DF) modeling, the modeling parameters for an offshore platform under seismic loading were investigated and the platform was modeled in a small scale. For three parameters: length geometry, thickness geometry, and material geometry, and corresponding coefficients for time, mass, and stiffness of the members, the DF model method has been used due to operational constraints on the construction of tubular members of the platform, in particular for thickness. In the second modeling method, which is called the Equivalent Single Degree of Freedom (ESDOF) system method, the structure is modeled as a single degree of freedom system for simplicity of analysis and especially model construction. It is necessary to explain that the use of the ESDOF method has a very important condition that the mass contribution coefficient of the first mode should be more than 90%. A verification of the Mousavi's platform model [24] was used, and by analyzing the mentioned structure, the accuracy of the numerical analysis method, which was with Simulink of MATLAB, and the accuracy of the written codes were obtained. To verify that the two proposed modelling methods are accurate, Enferadi et al.'s offshore jacket platform model [19] was used. For modeling, scale factors of 1 to 50 for length, 1 to 70 for modulus of elasticity, 1 to 35.714 for thickness, 1 to 1.4 for density, and 1 to 71.071 for time were used. The qualitative and quantitative results showed the correctness and precision of the physical modeling methods for this study. Since the construction of the accompanying laboratory model has many problems and complications, for the structures that have a mass contribution coefficient of more than 90% for the first mode, for the simplicity of the model construction, the entire structure can be a simple ESDOF structure is modeled where the frequency of the first mode of the MDOF structure is equal to the frequency of the SDOF structure. Finally, the results of this research can be summarized as follows:

1) Distorted Froudian (DF) Model:
- These models address issues related to geometric features and other specifications.
- By allocating different scale coefficients, they solve problems like unreality due to applying certain scale factors (e.g., thickness of tubular members).

2) Equivalent Single Degree of Freedom (ESDOF) System:
- In this method, the structure is simplified to behave like a single mass-spring-damper system.
- The first mode (vibration mode) dominates the system response (more than 90% mass participation).
- This simplification makes laboratory construction easier.

Both methods demonstrated excellent accuracy and ESDOF system proved efficient under defined specific conditions.

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8. References

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