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التحليل الديناميكي للرايزر البحري الثابت مع أموج روجو من المرتبة الأولى والخامسة

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الخلاصة

يعتبر الراي زر في المناطق البعيدة عن الشاطئ عنصرا هاما ومستخدما في صناعة النفط والغاز. تؤثر ارتفاعات الصلب التقليدية على بنية الدك deck في المنصات البحرية بشكل واضح تبعا لوزنها تحت تأثير الأحمال البيئية وتأثير الإجهاد وعمر الصلابة لبنيتها. يمكن أن تسهم عملية دراسة سلوك الرايزر في حالة الشروط البيئية الحدية إلى تطوير بدائل اقتصادية فعالة تزيد عمر الصلابة في بنيته. لتحقيق هذه الهدف فإن الدراسة الحالية تفترض استخدام رايزر نقل الغاز ورايز نقل النفط المستخدمين عادة، بالإضافة إلى الأنابيب المعالجة حراريا كمواد جديدة في تطبيقات المناطق البعيدة عن الشاطئ وذلك للجاكيت البعيد عن الشاطئ والمتواضع في شمال البحر. في هذه الدراسة تم الأخذ بعين الاعتبار موجات روجو كي يتم محاكاة الشرط الإضافي الحدي، حيث تم اقتطاف موجة روجو بزمن عوده قدرة 100 سنة للرايزرات المذكورة سابقا وذلك عن طريق التحليل الديناميكي في المجال الزمني بطريقة العناصر المنتهية باستخدام برنامج ANSYS. وحتى يتم التأكد من صحة التحليل فقد تم استخدام نظريتين معروفتين للموجه هما نظريتي الموجه من المرتبة الأولى والمرتبة الخامسة. تم بعد ذلك مقارنة الازاحة وقوى رد الفعل العملية للارتفاعات المذكورة، حيث يظهر أن رايزرنقل الغاز ورايز نقل النفط بالإضافة إلى توضعات الموجة من المرتبة الخامسة أقل قوة على دِك جاكيت الشاطئ مقارنة بالموجة من المرتبة الأولى. إضافة إلى ذلك فإن الأنابيب المعالجة حراريا المستجيبة لموجة روجو تؤثر بشكل قليل على بنية الدِك مقارنة برايزرنقل الغاز ورايز نقل النفط.

Dynamic analysis of fixed marine risers with 1st and 5th order Rogue waves

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ABSTRACT

In offshore structures, risers are valuable constituents used in oil and gas industry. Conventional steel risers affect the deck of an offshore platform considerably due to their weight under the influence of environmental loads, impacting the fatigue and serviceability life of the structure. The study of behavior of the risers in extra critical environmental conditions could be contributory to developing the effective economical alternatives to boost up the serviceability life of the structure. To this aim, in the current study, a traditional gas export riser, oil export riser and also a thermoplastic composite pipe as a new material in offshore applications are assumed for an offshore jacket located in the North Sea. To simulate the extra critical condition, a Rogue wave has been considered. The Rogue wave with return period of 100 years has been exerted on the mentioned risers by dynamic analysis in the time domain with finite element method using ANSYS software. For an accurate analysis, two well-known wave theories including the 1st and 5th order wave theories are utilized. Afterwards, the displacements and in particular reaction forces of the mentioned risers were compared. It is shown that for gas export riser and oil export riser, 5th order wave places less force on the main deck of the offshore jacket in comparison to the 1st order wave. Also, thermoplastic composite pipe response to Rogue wave has a minimal effect on the deck structure as compared to the gas export riser and oil export riser.

Keywords: Dynamic analysis; offshore jacket; riser; Rogue wave; thermoplastic.

INTRODUCTION

Risers are significant constituents in offshore interventions. They are pipes or ducts that furnish a momentary extension of gas or oil to a surface infrastructure such as marine jackets. According to the structure of the platform (DNV-OSS-302, 2010), offshore risers are usually designed in a way that they could be fixed or operated while submerged. Fixed offshore steel jackets are the principal structures commonly utilized in petroleum industries for low and intermediary water depth (Mirtaheri *et al.,* 2009) in maritime environments. In this investigation, risers for offshore jackets are taken into account. A sample of riser on the jacket structure with various details is shown in Figure 1.

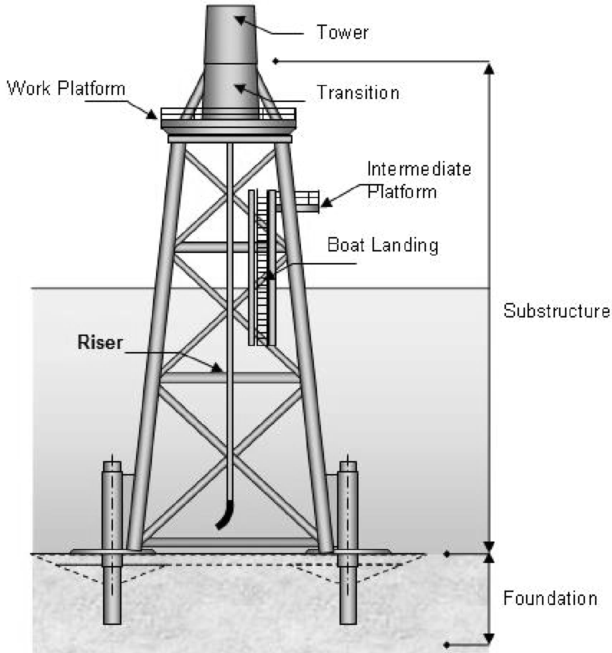


Fig. 1. A sample of an offshore jacket's riser (Saleem, 2011).

Risers are usually made of steel. In recent years, alternatives to traditional steel risers in various marine applications have been considered and composite materials as an alternative are introduced in offshore industries. A large amount of research was done to consider the usage of composite risers with notable benefits in the offshore fields such as lightweight, corrosion resistance, high strength, flexibility and affordable maintenance costs (Ochoa & Salama, 2005; Dalmolen *et al.,* 2009; Yu et al., 2015). Among composite materials, reinforced thermoplastic pipes (RTP's) are widely used in offshore industries because of their solid wall construction. Recently, more than 500 km of thermoplastic pipes have been utilized in Asia, especially in the Middle East (Dalmolen *et al.,* 2009). In this paper, full thermoplastic composite pipes (TCP's) are considered as new materials, which are presented by Van Onna *et al*. (2012).

Comparing the conditions faced by land-based structures, marine structures have more perplexity of being situated in maritime environment, where hydrodynamic interaction effects and dynamic reaction become principal issues (Haritos, 2007). For this reason, the analysis and design of marine structures that are correspondent with the marine environmental conditions could be the most demanding and creative work. Besides, the prediction of how the risers behave through natural phenomena under the effect of essential environmental loads over the operation period of the structure has major importance. These environmental loads include wave, wind, current, earthquake and ice. Among the different types of maritime loading, Sea waves are the dominant environmental forces, which marine structures are subjected to (Bargi *et al.,* 2011). Whether marine risers are fixed on the seabed or submersible, wave loads always affect them.

The study of wave loads has a long background and even if various research have been conducted to compute the wave forces on offshore structures, unfortunately a computational system with a total accord is not yet supplied. Different theories were introduced in the study of waves but usually the waves are sorted into two classes of linear and nonlinear (Arena & Soares, 2009). In relation to linear wave theory, Airy wave theory also known as the 1st order wave theory (Dean & Darymple, 1991), is one of the most prominent wave theories because it forms the basis for the probabilistic spectral definition of waves (Benaroya *et al.,* 2005)**.** The 1st order wave theory can be modeled in various water depths (Le Roux, 2007 & Le Roux, 2008).

Nonlinear waves commonly used in calculations for various depth are the theories of Stokes, Cnoidal and Solitary (Le Mehaute & Hanes, 2005). Among nonlinear waves, Stokes wave theory is developed for a large practical use of waves in intermediate and deep water depth. The 5th order theory was especially shown to succeed in estimate realistic wave profiles (Skjelbreia & Hendrickson, 1960). The 5th order Stokes wave is a much higher nonlinear wave solution at present and it gives a notable analytic understanding and solution to the wave problem. Although it just describes the periodic wave, it can accurately predict extreme wave crest, if proper wave period and input height are selected (Teng & Ning, 2009).

Among extreme waves, Rogue waves (RWs'), which occasionally manifest in the sea, can reach the amplitudes more than twice the value of significant wave height (Harif *et al.,* 2009). Therefore, they could be a notable hazard for offshore structures.

Over time, many endeavors have been dedicated to the comprehension of their formations. It should be noted that RW's like other waves could be categorized into two classes of linear and nonlinear (Chabchoub *et al.,* 2011, Chabchoub *et al.,* 2012 and Onorato *et al.*, 2013).

The study of the incidence of waves is ordinarily performed with analytical and numerical methods. With software development, numerical methods for solving differential equations such as finite element method for analyzing structures gradually even in nonlinear deformation modes have been introduced (Pattipawaej, 2006; Naimi *et al.,* 2013). One of the most notable software for finite element analysis is ANSYS (ANSYS Inc). Because of the dynamic nature of sea waves, time domain analysis is a trustworthy method for accurate valuations of structural performance especially for various depths (Low, 2009). Owing to the significance of critical environmental conditions in the study of wave-structure interaction, the study of extreme wave loads are a really significant case to determine the fatigue caused in the marine structures and to estimate the lifetime of the structure. Despite difficulties, the oil-gas fields discovered still keep increasing. As mentioned before, risers play an important role in various offshore applications, but traditional steel risers because their weight under the effect of environmental loads negatively influence the fatigue and serviceability life of the offshore structure. Each positive progress in the correct selection of material, analysis and design optimization of this indispensable member could be really efficient for reducing the tension and increasing the serviceability life of the offshore structure.

To this aim, we assumed a gas export riser (GER), oil export riser (OER) and also TCP as a new material of an offshore jacket. With software modelling, a comparison of the performance of risers with dynamic analysis in the time domain has been implemented under the effect of linear and nonlinear RW.

To this end, in this study, a brief presentation of thermoplastic composite pipes has been done. Then, a little introduction of Rogue waves is presented. Afterward, environmental and structural specifications of the jacket have been described. Then through the ANSYS software, dynamic analysis has been performed. The goal is to compare displacements and particularly reaction forces of the mentioned risers on the jacket's deck with using 1^{st} and 5^{th} order wave theories. Finally, the results have been evaluated.

THERMOPLASTIC COMPOSITE PIPES

As mentioned before, thermoplastic composite pipes (TCP's) according to their characteristics are a valuable new alternative to steel risers in oil and gas industries. The significant decreases in weight, top tensions and buoyancy requirements compared to traditional steel risers, are remarkable incentives for offshore companies to invest in this new product.

About the construction of these pipes, as shown in Figure 2, these type of pipes are made of a liner, thermoplastic composite reinforcement layers and a jacket (Onna *et al.,* 2012). All of them being the same thermoplastic polymer materials and with fiber reinforcements are melt-fused together during the manufacturing process to create a compound, solid and laminated cylindrical shell (Onna *et al.,* 2012). Details regarding theoretical and numerical studies performed for the laminated composite cylindrical shells are available in Chaudhuri *et al.* (1986), Chaudhuri *et al.* (2008) and Chaudhuri *et al.* (2015).

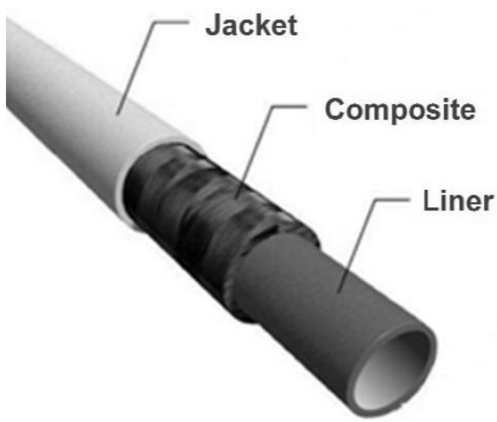


Fig. 2. A thermoplastic composite pipe (Onna *et al.,* 2012).

ROGUE WAVES

Rogue waves (RW's), also recognized as extreme waves, freak waves or killer waves, are large ocean waves considered in extra critical environmental conditions. The appropriate definition of RW is that it manifests casually out of nowhere and vanish without any kind of sign or mark. These waves are inclined to grow exponentially and thus have the possibility of rising up to very high amplitudes (Akhmadiev *et al.,* 2009; Akhmadiev *et al.,* 2013).

The Rogue wave theory considers a random summation of a large number of monochromatic waves with various frequencies and propagation directions. This pattern leads to a Rayleigh probability distribution of wave heights as follows:

$$f_{Rayleigh}(2H) = \frac{2H}{4\sigma^2}\exp(-\frac{(2H)^2}{8\sigma^2}) \quad (1)$$

In Equation 1, 2H is the wave height and, σ^2 is the variance of the surface elevation. Generally, compared to ordinary waves, RW's are assumed to have a wave height of $2H \geq 8.8\sigma$ (Ying & Kaplan, 2012).

The production of RW's does not have only one apparent reason. However, they take place where physical considerations like high winds and strong currents cause combinable waves that lead to a single unusual large wave (Rouge waves, 2009).

Formerly, the existences of RWs' were questioned due to lack of proof, but its scientific measurement was confirmed with the evaluation of "Draupner wave**".** A Rogue wave impacted to the Draupner platform in the North Sea on January 1, 1995, during which minor damage was done to the platform (Adcock *et al.,* 2011). The maximum amplitude of Draupner wave is shown in Figure 3 with the purpose of providing an idea about the intensity of RWs'.

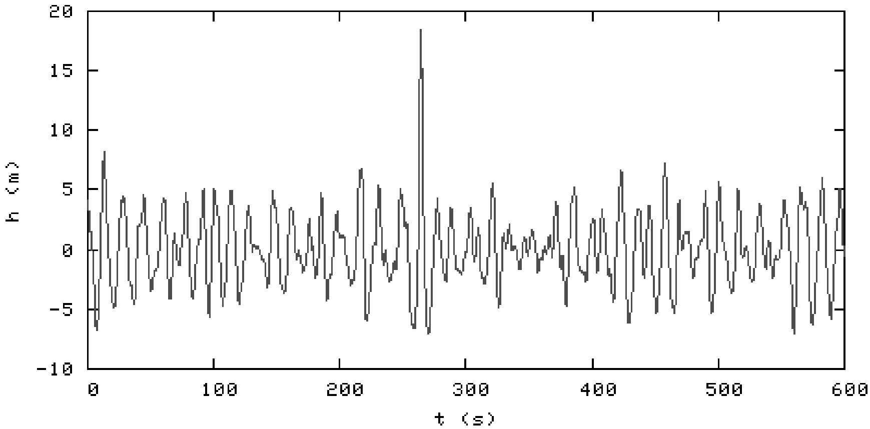


Fig. 3. The Draupner Rogue wave (Ciceron, 2014).

Currently, there is a general agreement about the safety of offshore structures on the risks of Rogue waves. Thus, the consideration of these kinds of waves on the marine structure could be really efficient for the analysis and design optimization.

GENERAL ENVIRONMENTAL AND STRUCTURAL SPECIFICATIONS

For the analysis, we have considered a fixed jacket type platform with four leg tubular steel frame as a 4-pile platform, located in the North Sea. The water depth is 70 m. A gas export riser (GER) of 32 inch (0.81 m) diameter, an oil export riser (OER) of 22 inch (0.55 m) diameter and a 20 inch (0.50 m) diameter thermoplastic composite pipe (TCP) for oil exportation, have been hypothesized for dynamic analysis. They are extending vertically from the seabed to 25.5 m above the sea level until the main deck.

As mentioned before, because of the importance of extreme loading conditions for analysis and design of offshore structures, we assumed for dynamic analysis a RW in extra critical condition with return period of 100 years. The wave height is 26 m and the wave period is 15 s (Raaij & Gudmestad, 2007).

Wave loads on marine structures have been normally considered for cylindrical elements such as tubular members or pipes and in calculating the wave-induced force as a horizontal force per unit length on a vertical element. There are various techniques for the estimation of wave forces, but two well-known methods are the Morison equation and the Diffraction theory. The computation of the force performed by waves on a cylindrical element depends on the ratio of the wavelength (L) to the member diameter (D).

When this ratio is bigger than 5, the element does not considerably modify the incident wave and also, the Morison equation is advisable. To determine which technique to use in the analysis, the wavelength has been calculated by trial and error with the following equation:

$$L = \frac{gT^2}{2\pi} \tanh \frac{2\pi d}{L} \tag{2}$$

In Equation 2, g is the acceleration of gravity (9.8 m/s^2), d is the water depth (70 m), T is the wave period (15 s) and π=3.14. As shown in Table 1, in all cases, the ratio of the calculated wavelength (311 m) to the riser diameter is very large. Therefore, the Morison equation is applicable for the analysis (Sorensen, 2006).

Table 1. The ratio of the wavelength (L) to the different riser's diameter (D).

Riser type	D (m)	L/D
GER	0.81	383
OER	0.55	565
TCP	0.50	622

Usually the concept of the Morison equation is the sum of the drag and inertia forces as follows:

$$F = F_D + F_I = \frac{C_d}{2} \rho D u^2 + C_m \rho (\frac{\pi D^2}{4}) \frac{\partial u}{\partial t} \tag{3}$$

Where F is the wave load, F_D and F_I respectively are the drag and inertia force (N/m^2), ρ is the total density of the sea water (1025 kg/m^3), D is the member diameter (m), u and ∂u/∂t respectively are the horizontal water particle velocity (m) and acceleration (m/s^2) at the axis of the member. The drag (C_d) and inertia (C_m) coefficients are 1.05 and 1.2.

They have been selected from American Petroleum Institute (API) standard (API, 2000), taking into consideration the effect of marine growth on drag and inertia coefficients because over time, marine structures may be covered with marine growth.

MODELING AND ANALYSIS

Modeling and analysis of GER, OER and TCP have been performed with finite element ANSYS software. Element type used for modeling in the software is PIPE 59. This element is being used for the simulation of sea conditions because it is an uniaxial member with tension-compression, torsion, bending and deflection capacities. For PIPE 59, it is also possible to comprise the hydrodynamic and buoyancy effects of water and the element mass, which includes the added mass of the water and the pipe internals (ANSYS Inc).

To simulate the real situation, it is assumed that oil with the density of 880 kg/m^3 is flowing in the OER and TCP. Also gas with the density of 0.8 kg/m^3 is flowing in the GER. About the boundary conditions, usually PIPE 59 has six degrees of freedom at each node and the jacket's riser considered in this study has been fixed in the seabed and also fixed on the platform's deck, taking into account only the rotational motion.

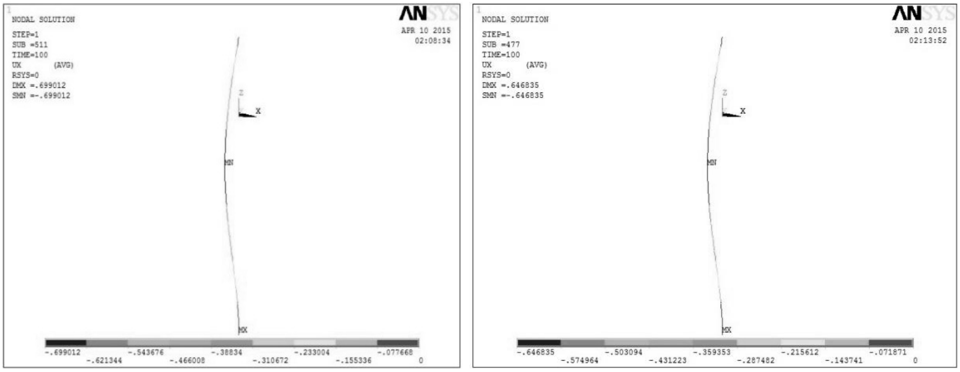
About the material properties for steel and thermoplastic composite pipes, data used in the analysis are mentioned in Table 2.

Table 2. Material properties used for GER, OER and TCP.

Material Properties	Steel	Thermoplastic Composite
Density (kg/m^3)	7850	1600
Young's Modulus (GPa)	210	6
Poisson's Ratio	0.35	0.25

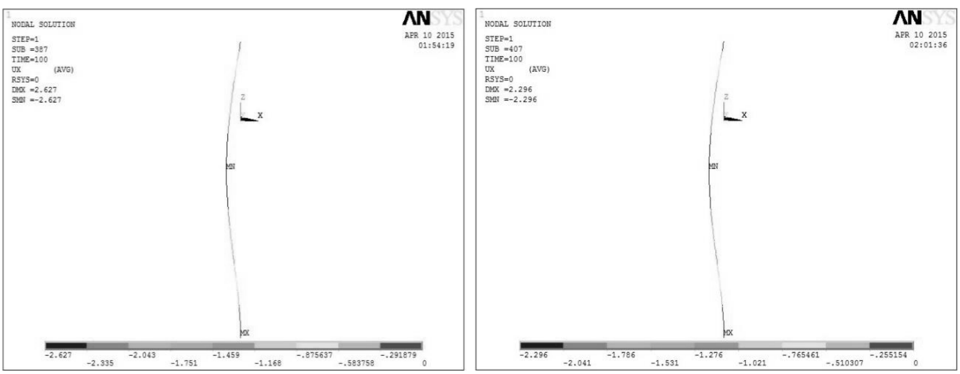
As mentioned before, dynamic analysis in the time domain is a reliable method in the study of structure performances under the effect of hydrodynamic loads that in this study is Rogue wave. To perform the dynamic analysis, we consider a 1st order (linear) and 5th order (nonlinear) Rogue wave that affect a GER, OER and TCP in extra critical environmental conditions and we compare the performance of the various risers under the effect of Rogue wave on the offshore structure. It should be mentioned that for the analysis, careful estimating of wave-induced damping has a significant importance in the design of platforms. Therefore, for the damping coefficient (ξ), the amount of 5 % has been considered (Wilson, 2003).

After dynamic analysis in the software, the nodal displacements for different risers, considering linear and nonlinear Rogue waves, are presented respectively in Figures 4, 5 and 6. It should be noted that the loading time of the wave is hypothesized to be 100 s.



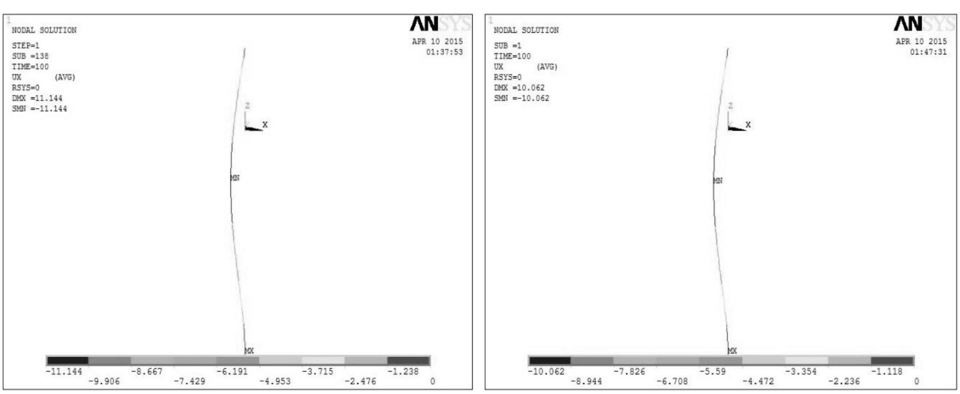
(a) (b)

Fig. 4. The GER nodal displacement after dynamic analysis under the effect of 1st order (a) and 5th order (b) RW.



(a) (b)

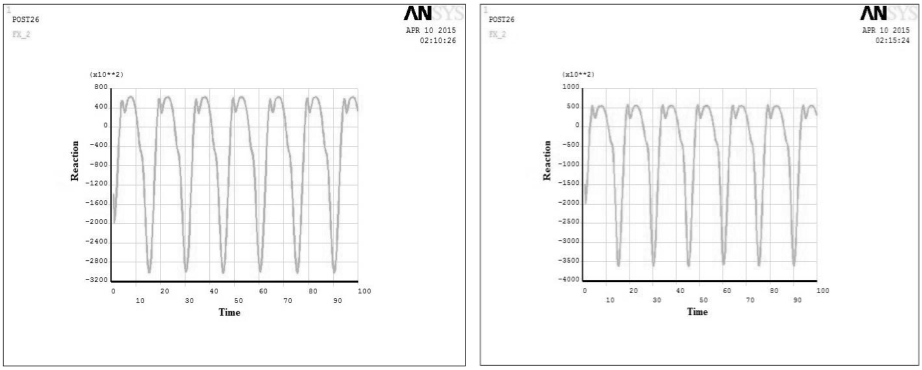
Fig. 5. The OER nodal displacement after dynamic analysis under the effect of 1st order (a) and 5th order (b) RW.



(a) (b)

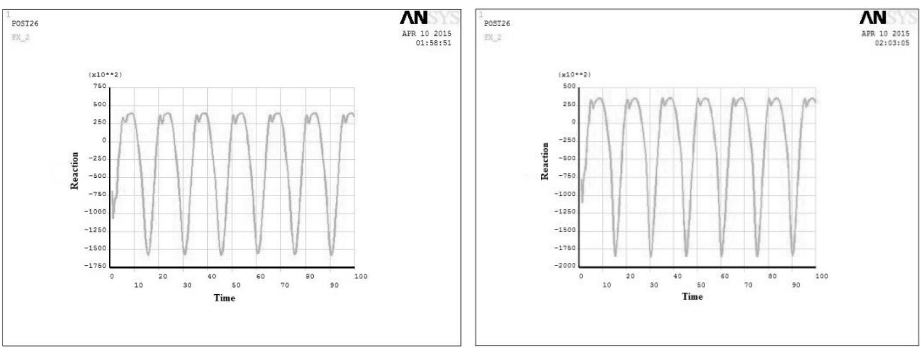
Fig. 6. The TCP nodal displacement after dynamic analysis under the effect of 1st order (a) and 5th order (b) RW.

The maximum reaction force on top of the GER, OER and TCP on the main deck of the platform, are shown in Figures 7, 8 and 9.



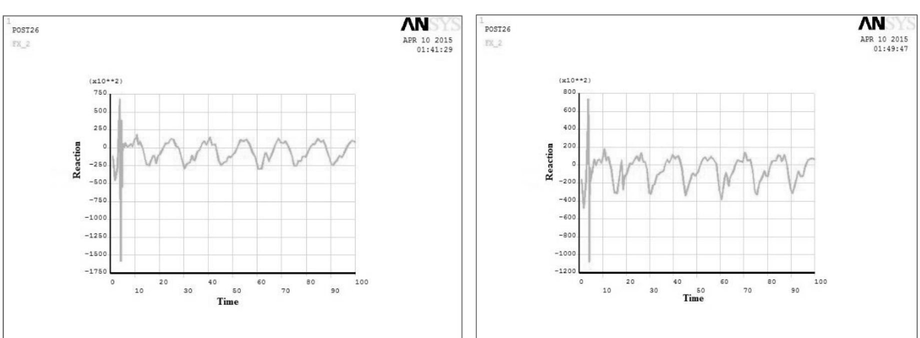
(a) (b)

Fig. 7. The time history chart of the reaction force on top of the GER under the effect of 1st order (a) and 5th order (b) RW.



(a) (b)

Fig. 8. The time history chart of the reaction force on top of the OER under the effect of 1st order (a) and 5th order (b) RW.



(a) (b)

Fig. 9. The time history chart of the reaction force on top of the TCP under the effect of 1st order (a) and 5th order (b) RW.

The general results have been presented in Tables 3, 4 and 5. The 5th order wave theory provides better and more reliable results for an economical design of steel risers. About the reaction forces, even though the maximum reaction force of the TCP at first place is more than GER and OER, but after t=10 s the reaction force on the deck structure is definitely lower than the mentioned risers.

Table 3. Comparison the response to Rogue wave for GER.

	1st order Rogue wave	5th order Rogue wave
Maximum reaction force (kN) on top of the GER	63.14	57.63
Maximum displacement (m) for GER	0.69	0.64

Table 4. Comparison the response to Rogue wave for OER.

	1st order Rogue wave	5th order Rogue wave
Maximum reaction force (kN) on top of the OER	40.08	35.42
Maximum displacement (m) for OER	2.6	2.29

Table 5. Comparison the response to Rogue wave for TCP.

	1st order Rogue wave	5th order Rogue wave
Maximum reaction force (kN) on top of the TCP	68.15 for t < 10 s 18 for t > 10 s	73.6 for t <10 s 20 for t > 10 s
Maximum displacement (m) for TCP	11.14	10.06

CONCLUSION

In this study, dynamic analysis has been performed on three various risers. GER, OER and TCP. The conditions that have been considered are extremely critical and this includes the RW with taking into account the 1st and 5th order wave theory for the analysis. A comparison about the performance of risers on the main deck of an offshore jacket has been implemented. According to Section 5, comparing the displacements and reaction forces of the risers, the 5th order wave theory with less displacements and reaction forces is advisable from economical point of view to use for time domain analysis of the GER and OER. The 5th order wave theory estimates reaction forces for GER and OER up to almost 9 % less respect to 1st order wave theory. Regarding the TCP, 1st order wave theory is recommendable. More importantly, it has been found that compared to GER and OER, TCP exerts less reaction forces on the deck structure.

At first impact, until t=10 s the Rogue wave create a big displacement and reaction force up to approx. 68 kN for 1st order and 73 kN for 5th order wave. After t=10 the reaction forces decrease a lot and the maximum reaction force on the main deck is up to approx. 18 kN for 1st and 20 kN for 5th order wave. It means more than 70% less than GER and approx. 50% less than OER. These points could be really helpful to optimize the design and also with the use of new materials like thermoplastics, could increase the fatigue and consequently the serviceability lifetime of the offshore platform.

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