

COMPARATIVE ANALYSIS BETWEEN SURFACE AND SUBSEA BOP OFFSHORE DRILLING SYSTEMS IN WAVES AND CURRENT

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Abstract. *In order to drill in deepwater, subsea equipment such as the drilling riser and the subsea Blowout Preventer (BOP) are necessary. The drilling riser is a vertical steel pipe that connects the wellhead at the sea bottom to the surface floating drilling rig. The BOP is the safety equipment used to control wellbore pressures in offshore drilling operations. Usually in deepwater offshore drilling operations, the BOP is lowered down hanging by the drilling riser and then connected to the wellhead. However, this procedure has been shown to be one of the biggest restraints in offshore deepwater drilling operations. Huge drilling platforms that can handle very heavy risers and BOPs are required. Furthermore, there are limited quantities of this type of drilling rigs available in the world, and then, new alternatives are desirable. Recently, an alternate technology which using a Surface Blowout Preventer (SBOP) has been applied. In this case, smaller drilling rig than usual with a lighter drilling riser and BOP with cheaper and more availability on the market are used. The main aim of the present study is the comparison between offshore drilling systems using a BOP and SBOP. The analysis is conducted by numerical simulations. Results are shown in time domain and discussions are carried out in term of riser and BOP displacements.*

Keywords*: Drilling Riser, BOP, Blow Out Preventer, Offshore Operational Safety*

1. INTRODUCTION

In ultra-deep water drilling operation, the floating platform is connected to the BOP (Blow-Out Preventer), installed to the wellhead on the seabed by the drilling riser. The riser is a steel tube containing the drillstring and enabling the flow of drilling fluids. In most drilling systems, the drilling fluid is pumped into the well flowing through the drillstring and returns to the surface flowing up through annular space between the drilling riser internal wall and outside surface of the drillstring. The BOP is safety equipment used to circulate kicks and control the pressure of the well while the kick is circulating. Kick is a phenomenon that occurs during the drilling operation when a high-pressure formation is reached causing a pressure gradient between the petroleum formation and the well. This pressure gradient will cause an influx of fluid from the formation to the well, which increases the pressure at the bottom of the well, if this continues it can bring about an uncontrolled flow of fluid to the surface referred to as a Blow Out.

The water depth of drilling operations is increasing, and then, the platform dimensions also increases to make possible the use of drilling risers with larger diameters, and designed to support more severe environmental loads. In the other hand, nowadays availability of large platforms is usually low in the world. The increase of petroleum price makes discovers in ultra-deep water economically viable to produce creating, then, a demand for this kind of platform.

The petroleum companies, motivated by the price of petroleum, are searching for new alternatives that make drilling in ultra-deep water feasible. A developing alternative is the surface BOP (SBOP) that is installed on the platform. The SBOP allows the use of lighter smaller diameter risers, which opens the door to the use of smaller more available platforms. Furthermore, according to technical literature, the use of the SBOP decreases the risk to the environment and the crew. It also decreases the duration of drilling operation. The SBOP was already used in ultra-deep water drilling operation as presented in Azancot, *et al* (2002) and Brander, *et al* (2004).

In this context, comparative analyses between an offshore drilling system using a submersed BOP and a system using a SBOP were carried out with a focus on the mechanical behavior of the drilling riser. The results were obtained by numerical simulation in the time domain.

2. OFFSHORE DRILLING SYSTEMS

In this work, the offshore drilling system using a submersed BOP will be called the traditional offshore drilling system and will follow the norm API (1993). Figure 1 illustrates this type of drilling system's main equipment.

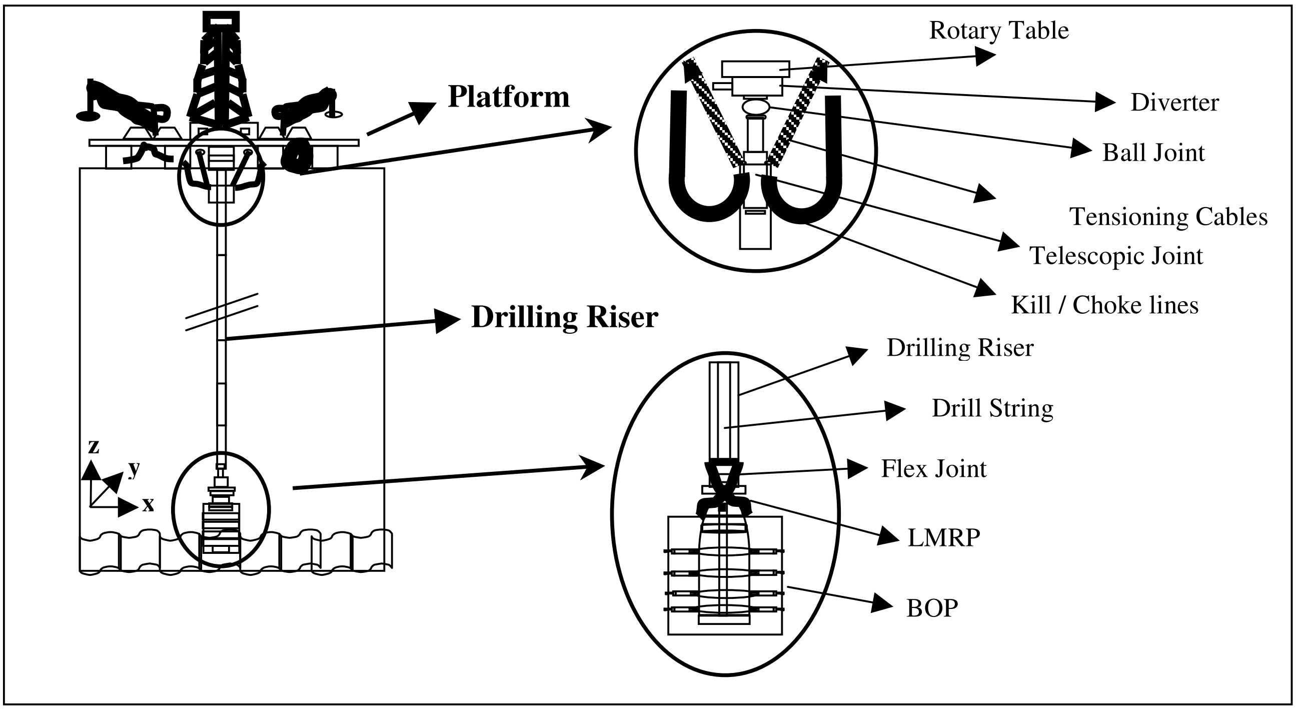


Figure 1 – Traditional floating drilling system's layout.

The interface between the riser and the platform is made by the telescopic joint, which avoids the transmission of heave motion of the platform to the riser. To increase the riser's rigidity thus minimizing the displacement, a tensioning system is used to increase the bending stiffness by tensioning the riser. This is done by cables that are installed at the telescopic joint. A ball joint is installed on top of the telescopic joint, which is a component used to avoid bending moment concentration at the riser's end. The ball joint is connected below the diverter. The diverter allows the flow of drilling fluid from the riser to the drilling fluid treatment system, and if necessary this equipment can route the kick fluids far away from the platform. The rotary table is used to transmit rotation to the drillstring.

At the seabed, the riser is connected to a flex joint, which has the same finality as the ball joint, but with controlled rotation angle stiffness. Below the flex joint is the LMRP (Low Marine Riser Package) to allow the disconnection of the riser and the BOP in the case of emergencies. The kill and choke lines assist the circulation of a kick. In the traditional drilling system these are connected on the outer surface of the riser along with other auxiliary lines.

The offshore drilling system using a SBOP will be described according to Brander, *et al* (2004). A general layout with main equipment used in that system can be seen in Fig. 2.

To make the SBOP system as safe as the traditional offshore drilling systems, equipment to allow the disconnection of the riser at the seabed in the case of emergency must be installed to the subsea wellhead. This equipment is called the Subsea Disconnected System (SDS). The SDS is not so different from the submersed BOP, it is formed by a set of rams that permits shearing of the drillstring and closes the well with the drillstring inside the well or not. A stress joint is installed on top of the SDS to minimize the variation of stiffness at the interface between the SDS and the riser avoiding stress concentration points.

At the top riser region another stress joint is installed to avoid stress concentration between the SBOP and the riser, this joint is connected to the tensioning ring where riser tensioners used to transmit tension to riser are connected. Between the SBOP and tensioning ring a spool extension is installed to lift the SBOP in order to increase the gap between the tensioner and the SBOP decreasing the chance of collisions. The VIV strakes are installed to avoid vortex shedding that induce VIV (Vibration Induced by Vortex), which reduce the riser's life due to fatigue. The diverter, telescopic joint and flex joint in the SBOP system have the same function as in the traditional offshore drilling system.

Currently, the SBOP system is restricted to drilling slender exploratory ultra-deep water wells which is a small well unable to production, however permits the use of smaller diameter risers; but there are intentions to apply SBOP to drilling production slender wells in the future. Furthermore, in smaller diameter riser the velocity of drilling fluid flow does not decrease inside the riser thus does not require a booster line. A booster line is usually used in the traditional floating drilling system to inject fluid at the riser's base to maintain the flow velocity inside the riser. Moreover, in the SBOP system, the kill, choke and the BOP's hydraulic action fluid lines are not connected to riser.

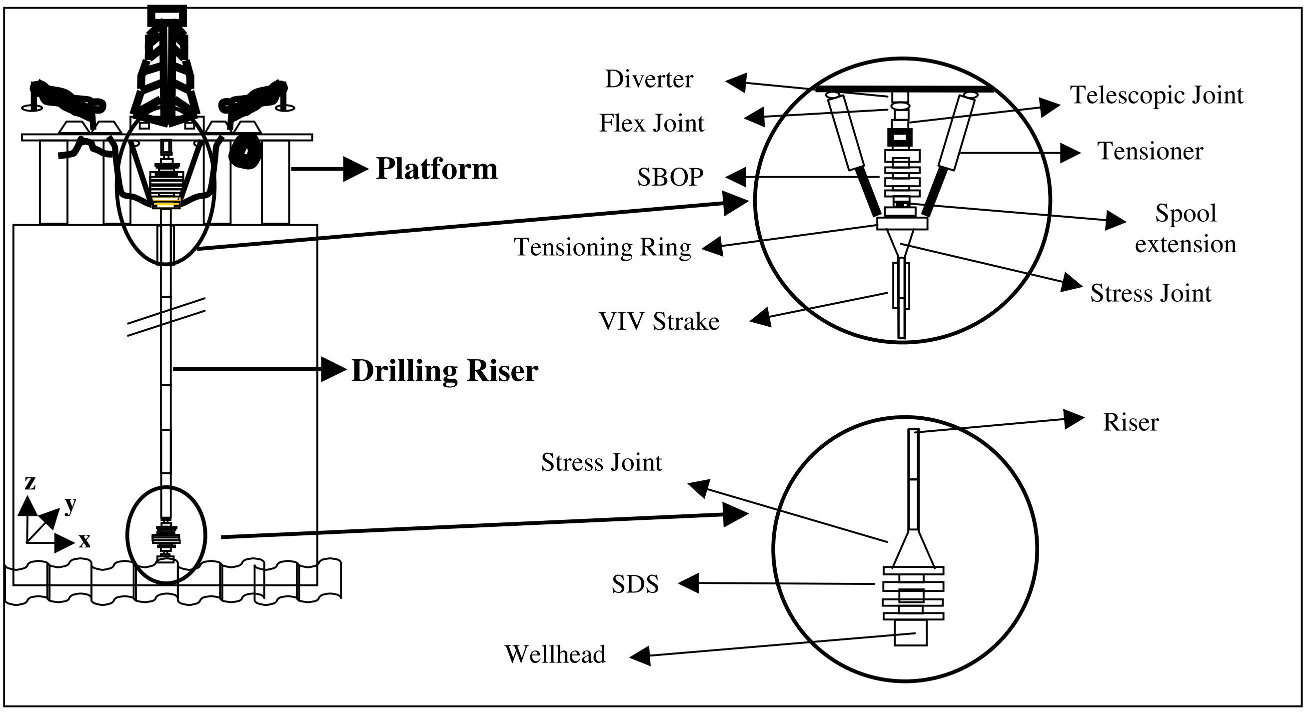


Figure 2- Layout of ultra-deep water drilling system using a SBOP.

3. DRILLING RISER BEHAVIOR

The vertical riser can be structurally modeled as an extensive beam element under axial tension, environmental loads and pressure effects due to internal and external fluid pressure (Morooka *et al*, 2005; Martins *et al,* 2003). The riser's Axial-Flexural Equation for in-line and transversal directions (Chakrabarti & Frampton, 1982) are given by Eq. (1),

$$\frac{d^2}{dz^2}\left(EI\frac{d^2x}{dz^2}\right)-\left(T+p_0A_0-p_iA_i\right)\frac{d^2x}{dz^2}-\left[\left(\gamma_sA_s-f_z+\gamma_iA_i-\gamma_0A_0\right)\right]\frac{dx}{dz}+m\ddot{x}=f_x \tag{1.a}$$

$$\frac{d^2}{dz^2}\left(EI\frac{d^2y}{dz^2}\right)-\left(T+p_0A_0-p_iA_i\right)\frac{d^2y}{dz^2}-\left[\left(\gamma_sA_s-f_z+\gamma_iA_i-\gamma_0A_0\right)\right]\frac{dy}{dz}+m\ddot{y}=f_y \tag{1.b}$$

where, x and $\ddot{x}$ are the in-line displacement and acceleration of the riser in that order (Fig. 3), y and $\ddot{y}$ are the transversal displacement and acceleration of the riser respectively (Fig. 3), z is the vertical coordinate of riser, *EI* represents the bending stiffness of the riser, *T* is the axial tension, p_0 and p_i are the pressures due to external and internal fluid respectively, γ_s, γ_0 and γ_i are the specific weight of the riser's material, external and internal fluid respectively. *m* is the mass of the segment of the riser including added mass per unit length. f_x , f_y and f_z represents the forces per unit length in the in-line, transverse and vertical direction, respectively. The total cross sectional area of rigid riser is given by A_0 , A_i is the internal cross sectional area (where the drilling fluid flows) of rigid riser and A_S is the cross sectional area of the rigid riser wall.

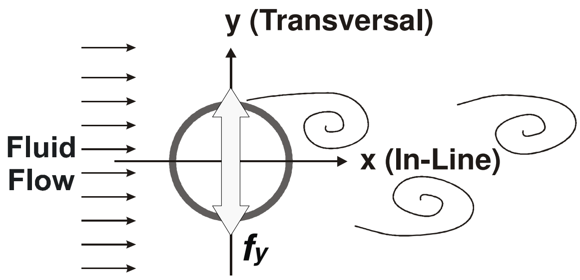


Figure 3 – Cross section of the riser.

Figure 3 shows the cross section of a riser. The fluid flow is given by the wave, current and riser's relative motion. The in-line direction (represented by x-coordinate of the reference observed in Fig.3) is the direction of the sea waves and current. In this direction the hydrodynamic force is calculated by a Morison's equation modified for relative motion given by Eq. (2),

$$f_x = A_I \dot{u} + C_D A_D |V_r| (u + U_c - \dot{x}) + C_A A_I (\dot{u} - \ddot{x}) \tag{2}$$

where, f_x is the force in the in-line direction per unit length, C_D and C_A are the hydrodynamic coefficients of drag and added mass. U_c, u and $\dot{x}$ are in this sequence, the current velocity, the water particle velocity due to the waves and riser velocity in the in-line direction. From the latter velocity, the relative velocity between the outer fluid and the riser is calculated which couples the in-line and the transverse directions ($|V_r| = \sqrt{(u + U_C - \dot{x})^2 + \dot{y}^2}$), where $\dot{y}$ is the velocity of the riser in the transverse direction, and finally $A_I = \rho\pi D_0{}^2/4$ and $A_D = \rho D_0/2$, where D_0 represents the outer diameter of the riser and ρ is the density of sea water.

VIV force is considered in the transverse direction (represented by y-coordinate of the reference observed in Fig.3). Forces in the transverse direction are estimated as presented in the Eq. (3) (Morooka, 2006).

$$f_y = \frac{1}{2}\rho[(u - \dot{x}) + U_C]^2 D_0 C_L \cos(2\pi\bar{f}_S t + \varphi) - C_D A_D |V_r| \dot{y} - C_A A_I \ddot{y} \tag{3}$$

where, f_y is the transverse force per unit of length, $\dot{y}$ and $\ddot{y}$ are respectively the velocity and the acceleration of the riser in the transverse direction, C_L is the lift coefficient; φ is the transverse force's phase and $\bar{f}_S$ represents the mean shedding frequency.

In this direction the riser's dynamic behavior for each element is described by a set of matrix equation to calculate the displacement in the in-line direction (Eq. 4) and in the transverse direction (Eq. 5).

$$[\mathrm{M}]\{\ddot{\mathrm{x}}\} + [\mathrm{B}]\{\dot{\mathrm{x}}\} + [\mathrm{K}]\{\mathrm{x}\} = \{F_x\} \tag{4}$$

$$[\mathrm{M}]\{\ddot{\mathrm{y}}\} + [\mathrm{B}]\{\dot{\mathrm{y}}\} + [\mathrm{K}]\{\mathrm{y}\} = \{F_y\} \tag{5}$$

where, *[M]* is the riser mass matrix, *[B]* is the riser structural damping matrix and *[K]* is the riser stiffness matrix. $\{F_x\}$ and $\{F_y\}$ are respectively, the vector of force in the in-line and transverse directions. (Martins et al, 2003).

In the extreme stress analysis, the Von Mises stress is employed in order to calculate if the stress throughout the riser exceeds the admissible stress recommended by the standard (API, 1993). The Von Mises stress is defined as the uniaxial tension wherein the distortion energy is equivalent to the distortion energy due to the applied stresses. In this work, the Von Mises stress is calculated based on the standard API (1993), which is better presented in the standard API (1998), as shown in Eq. (6).

$$\sigma_{eq} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{pr} - \sigma_{p\theta})^2 + (\sigma_{p\theta} - \sigma_{pz})^2 + (\sigma_{pz} - \sigma_{pr})^2} \tag{6}$$

where, σ_{pr}, $\sigma_{p\theta}$ and σ_{pz} represent the radial, hoop and axial stresses in the riser's wall respectively.

4. RESULTS

Numerical simulations have been carried out to conduct an introductory analysis of the riser behavior for the traditional offshore drilling system and for the offshore drilling system using SBOP. A vertical top tensioned riser (TTR) in 2887 meters of water depth is considered. The riser geometry and configuration for the offshore drilling system using SBOP is based on Brander *et al* (2004) and is displayed in Table 1. Table 1 also presents the geometry and configuration used in the traditional offshore drilling system case.

Table 1 - Riser geometry and configuration for the offshore drilling system using SBOP and for the traditional offshore drilling system.

	Nominal Size (m)	Material Grade	Density (kg/m^3)	Inner Diameter (m)	Yield Strength (MPa)
SBOP	0.339725	P110	8006	0.313614	759
Traditional	0.5334	H040	7860	0.48575	408

The minimum top tension for the drilling systems was calculated following the standard API (1993), however these values can be considered over estimated since the simulation did not considered the use of buoyancy modules along the riser length. The Table 2 shows the minimum top tension calculated for each drilling system. Table 3 provides other parameters adopted in the calculations.

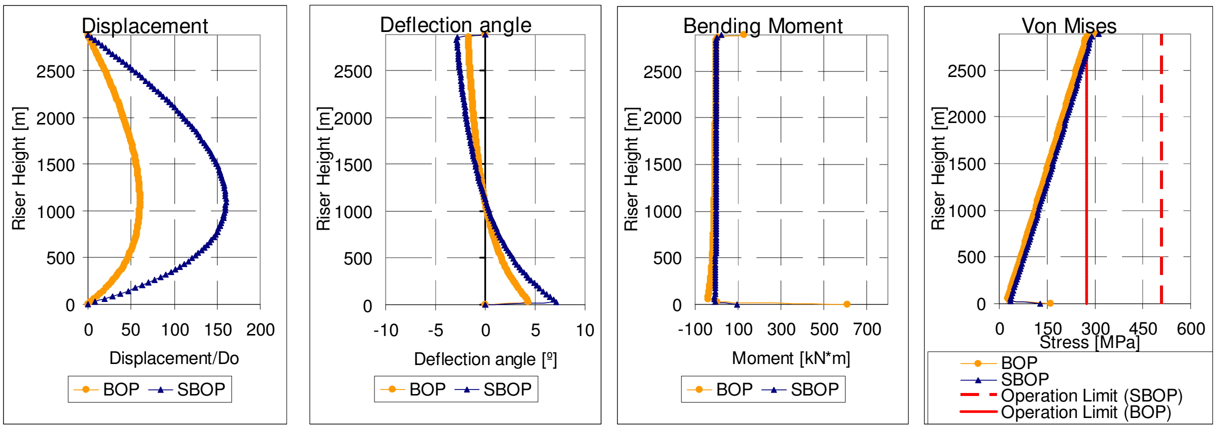
Table 2 – Minimum top tension of the drilling risers

SBOP	3.900 kN
Traditional	10.585 kN

Table 3 – Riser parameters in the simulations

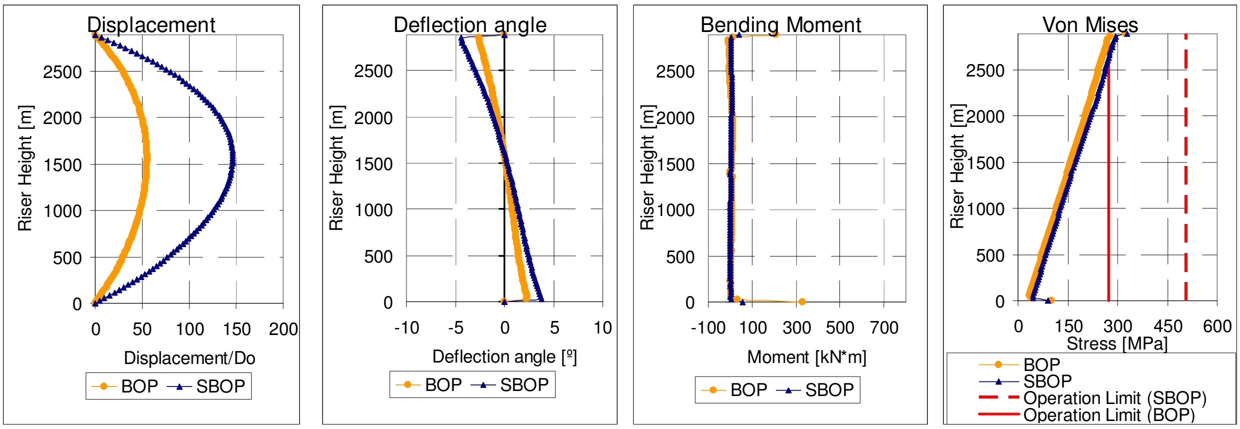
Sea water density	1025 kg/m^3
Drilling fluid density	1200 kg/m^3
Structural damping	0.03
Strouhal number	0.2
C_L	0.8
C_D , C_M	1

Only riser geometry is taken into account in the simulations, i.e., auxiliary components like buoyancy modules and VIV strakes are not considered in the presented results.



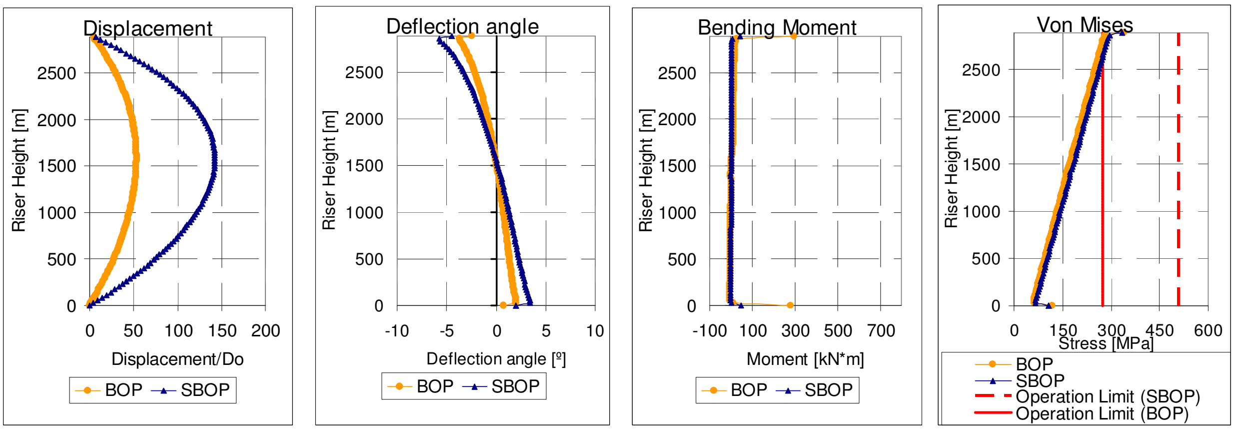
(a) (b) (c) (d)

Figure 4 – (a) Displacement; (b) Deflection angle; (c) Bending Moment and (d) Von Mises stress along the riser for a uniform current profile.



(a) (b) (c) (d)

Figure 5 - (a) Displacement; (b) Deflection angle; (c) Bending Moment and (d) Von Mises stress along the riser for a triangular current profile.



(a) (b) (c) (d)

Figure 6 - (a) Displacement; (b) Deflection angle; (c) Bending Moment and (d) Von Mises stress along the riser for a triangular current profile and waves.

Figure 4 introduces results of displacement, deflection angle, bending moment and Von Mises stress along the riser length, in uniform sea current profile with a velocity of 0.8m/s. In Fig. 4 (d), for comparison, the riser operation limits following the standard API (1993), which recommends Von Mises stress below to 67% of yield strength stress of riser's material along the riser length for normal operations are shown.

Figure 5 presents the results for a triangular current profile, with a 1.5m/s surface velocity and zero at the seabed. And Fig. 6 presents results for the same triangular sea current profile and waves having a height of 6 meters and a period of 10.5 seconds.

From Fig. 4, Fig. 5 and Fig.6, it can be observed that considering the simplification adopted for the simulation, the displacement of the riser in the SBOP system is higher than the displacement of the riser in the traditional drilling system, inducing greater deflection angle of the riser. This would happen because the riser used in the SBOP system is less rigid. However, the riser used in the traditional drilling system presents higher bending moments due to a possible higher inertia moment induced by a large diameter.

Due to increased displacement, the SBOP system's riser presents high deflection angle, especially at the ends of the riser, to avoid this deflection angle is transmitted to other equipments, ball / flex joints are installed, as showed in Fig. 2.

From Fig. 4d, Fig. 5d and Fig. 6d, the Von Mises stress at the top of riser for the traditional offshore drilling system is higher than the operation limit dictated by the standard API (1993). However, as presented in Fig. 7, due to the fact that top tension of the drilling riser increases the Von Mises stress. The use of buoyancy would decrease the top tension in turn decreasing the axial stress and consequently Von Mises stress.

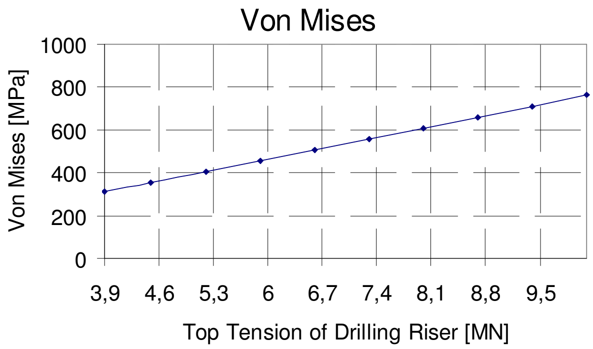
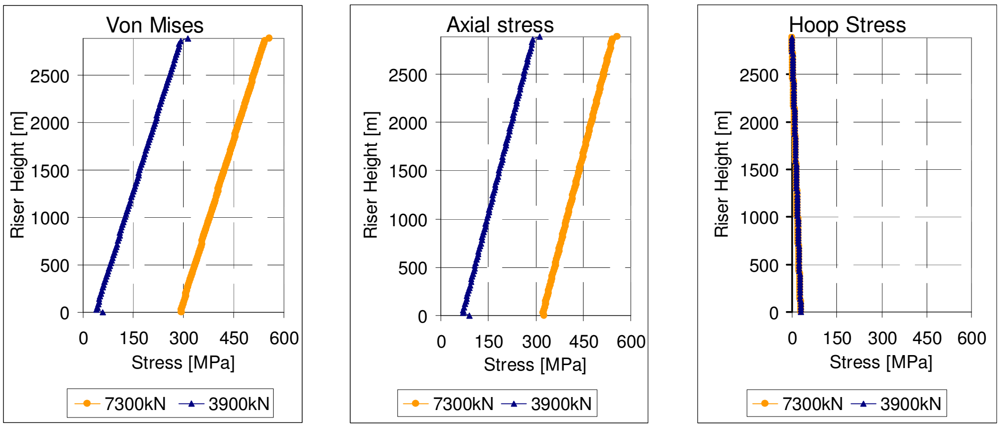


Figure 7- Von Mises stress variation according to top tension of drilling riser.



(a) (b) (c)

Figure 8- a) Von Mises stress; b) Axial stress and c) Hoop stress along the riser for a top tension of 3900kN and 7300kN.

Von Mises stress, Axial Stress and Hoop stress are presented in Figure 8, for the case of top tension with 3900kN and 7300kN, in order to make a comparative analysis of riser stresses between the drilling systems. For this study, the risers have the same geometry and the same environmental loads.

From Fig. 8 b) and Fig. 8 c), it can be observed considering the simplification given in this analyses that for greater top tensions the axial tension increases but the hoop stress seemed do not change. Hence, considering that the radial stress can be neglected, the main term that is prevailing in the Von Mises stress calculation (Eq.6) is axial stress.

5. CONCLUSION

The present study consisted on a comparative analysis of the riser behavior in two different offshore drilling systems. There are, respectively, the SBOP and the traditional underwater BOP, in both cases, connected to a floating drilling platform. The results were obtained through numerical simulations calculating the riser mechanical behavior due to the environmental loads such as sea currents and waves.

Results have shown that the riser close to the sea surface and the seabed regions are the most critical regions. The riser's top zone is critical due to riser top tension itself, which induces high axial tension in this region, combined with large oscillatory forces induced by the waves. The forces in the riser around the seabed region are critical, and together to the large riser deflection angle, they can cause high bending moments, which would cause severe damage.

Comparisons of Von Mises stresses, displacement and deflection angle observed in the two BOP systems suggest that, in general, they are bigger for the riser with SBOP. The use of more strong material for the riser itself and flex/ball joints for the both riser ends could minimize these observed problems.

Results for the SBOP have shown very promise perspective for this system, in spite of the SBOP system use more strong material for the riser and ball/flex joints at the riser ends, increasing involved costs. However, SBOP system presents good advantages, particularly, in ultra-deep water well drilling.

6. ACKNOWLEDGEMENTS

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