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Sensitivity analysis of fatigue life prediction for deepwater steel lazy wave catenary risers

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Steel lazy wave catenary riser (SLWR) has been an attractive choice for deepwater oil field developments. However, fatigue is a critical issue in assessing the feasibility of applying SLWR to large motion vessels such as floating production storage and offloading (FPSO) or semi-submersibles. In this work, the time-domain fatigue analysis of SLWR was adopted for better representing the structural nonlinearity, fluid load nonlinearity and riser-soil nonlinear interaction. The Palmgren-Miner rule was employed for the fatigue life prediction along the riser length. The main purpose of this analysis is to present sensitivity analyses of SLWR fatigue life under various input parameters, which include the structural damping, the hydrodynamic coefficients along the riser, the seabed stiffness, the vessel motions, etc. The analyses indicated the strong dependence of the riser fatigue life on these parameters. The results can help designers to understand the dynamic behavior of the SLWR and provide guidance for selection of some critical parameters that are used in the fatigue design.

catenary risers, fatigue life, time-domain analysis, nonlinear dynamic analysis, finite element method

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1 Introduction

In recent years, exploration and production activities have increased dramatically in deepwater. The steel catenary riser (SCR) was adopted by Petrobras as a cost-effective alternative for oil and gas export [1]. It is generally considered a great challenge to suspend SCR from vessels with relative higher motions, such as semi-submersibles and floating production storage and offloading (FPSO) [2, 3]. The large motions induce severe fatigue damage at the touchdown zone and at the riser hang-off location. Compared with the free hanging catenary configuration, the steel lazy wave catenary risers (SLWR) can reduce the top loads [4]. However, fatigue is a critical issue in assessing the feasibility of applying SLWR to these vessels, particularly, in understanding of the sensitivity of parameters for fatigue damage.

Two approaches may be adopted for fatigue estimation: frequency domain and time domain analyses. The main sources of SLWR nonlinearity are the nonlinear characteristic of riser-soil interaction, the viscous fluid drag, and the geometric nonlinearities. Compared with frequency domain analysis, time-domain analysis approach is considered to be more suitable to represent all nonlinear characteristics of the model [5].

Fatigue life prediction in marine risers is a complicated process involving many factors and has been dealt with in several papers, including Karunakaran et al. [6], Martins [7], Stahl [8] and Xue et al. [9]. Shen and Zhao [10] investigated

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*Corresponding author (email: yanghezhen@hotmail.com) the vortex-induced vibration of the suspended pipeline and gave the influences on the fatigue life. Iranpour et al. [11] carried out a series of experimental tests for fatigue damage due to vortex-induced vibration. The experimental results indicated that the higher harmonics cause significant fatigue damage. Xia [12] presented a parametric design study for SCR system in Northern North Sea. The parameters affecting the efficiency and accuracy of simulations were studied. The issue of riser soil interaction, however, was not dealt with in the above papers.

The global time-domain fatigue analysis of SLWR connected to an FPSO was presented in this work. To study the influence of various parameters on the fatigue life, sensitivity analyses have been carried out for several parameters, such as hydrodynamic coefficients, seabed stiffness, structural damping, and vessel motions. The results can provide guidance for the selection of some critical parameters that are used in the analysis and design of SLWR systems.

2 Theory

2.1 Dynamic analysis

The nonlinear dynamic analysis of marine riser is carried out in time-domain using finite element method. The analysis includes nonlinearities due to large deformation, buoyancy, added mass and drag force. A general equation of motion is given as

$$\boldsymbol{M}\Delta\ddot{\boldsymbol{u}} + \boldsymbol{C}\Delta\dot{\boldsymbol{u}} + \boldsymbol{K}\Delta\boldsymbol{u} = \Delta\boldsymbol{F}, \tag{1}$$

where $\boldsymbol{M}$ is the consistent mass matrix, $\boldsymbol{C}$ is the structural damping matrix, and Rayleigh damping is used to calculate the damping matrix, $\boldsymbol{K}$ is the whole stiffness matrix, which includes linear axial, bending, torsional stiffness matrix, nonlinear initial displacement, and initial stress stiffness matrix, $\Delta\boldsymbol{u}$ is the displacement of node, and $\Delta\boldsymbol{F}$ is the external force.

Viscous damping of the structural materials are considered in the second term of eq. (1), while drag damping is introduced through the generalized Morison's equation and is included in the external force term of eq. (1). Due to hydrodynamics of external fluid interactive, there are two directional forces acting on the riser body according to the Morison equation. The normal force can be expressed as

$$f_{\mathrm{n}} = \frac{1}{2}\rho_{\mathrm{w}} D_{\mathrm{oH}} C_{\mathrm{Dn}} \left(V_{\mathrm{n}} - \dot{\bar{u}}\right)\left|V_{\mathrm{n}} - \dot{\bar{u}}\right| + \rho_{\mathrm{w}} A_{\mathrm{oH}} C_{\mathrm{M}} \dot{V}_{\mathrm{n}} - \rho_{\mathrm{w}} A_{\mathrm{oH}} C_{\mathrm{A}} \ddot{\bar{u}}, \tag{2}$$

and the tangential force is given by

$$f_{\mathrm{t}} = \frac{1}{2}\rho_{\mathrm{w}} \pi D_{\mathrm{oH}} C_{\mathrm{Dt}} \left(V_{\mathrm{t}} - \dot{\bar{v}}\right)\left|V_{\mathrm{t}} - \dot{\bar{v}}\right| + \rho_{\mathrm{w}} A_{\mathrm{oH}} C_{\mathrm{M}} \dot{V}_{\mathrm{t}} - \rho_{\mathrm{w}} A_{\mathrm{oH}} C_{\mathrm{A}} \ddot{\bar{v}}, \tag{3}$$

where D_{oH} and A_{oH} denote the hydrodynamic diameter and the hydrodynamic cross-sectional area, ρ_{w} is fluid density, $\bar{u}$ and $\bar{v}$ denote the displacements in normal and tangential directions, respectively, V_{n} and V_{t} are the current velocities in normal and tangential directions, respectively, C_{Dn}, C_{Dt}, C_{M} and C_{A} represent the normal drag, tangential drag, inertia and added mass coefficients, respectively.

2.2 Fatigue analysis approach

The fatigue analysis of the riser is carried out in time-domain. The stress time series are calculated based on the stored force time series from nonlinear dynamic analysis. Rainflow cycle counting in time-domain is examined by taking the time history of load as an input. After the total number of cycles in time-domain is found, the Palmgren-Miner rule [13] for cumulative damage theory is used to estimate the fatigue life.

The signal with a small tensile mean stress would produce a shorter fatigue life than the signal with zero mean, and the signal with a larger tensile mean stress would produce an even shorter fatigue life. The mean stress axis can be made non-dimensional by dividing by the material ultimate tensile strength (UTS). The Gerber mean stress corrections are used with S-N curves. The non-linear Gerber mean stress correction is

$$\frac{S_{\mathrm{a}}}{S_{\mathrm{a0}}} + \left(\frac{S_{\mathrm{m}}}{S_{\mathrm{ult}}}\right)^2 = 1. \tag{4}$$

So that the effective stress amplitude at zero mean is

$$S_{\mathrm{a0}} = S_{\mathrm{a}}\left[1 - \left(\frac{S_{\mathrm{m}}}{S_{\mathrm{ult}}}\right)^2\right]^{-1}, \tag{5}$$

where S_{m} is the mean stress value of cycles with amplitude S_{a}, and S_{ult} is the tensile strength.

In this case, amplitudes of cycles and half-cycles of random histories with the given stress mean values have been transformed to the equivalent amplitudes of cycles and half-cycles with zero mean values S_{a0} by means of eq. (5).

The basic fatigue capacity is given in terms of S-N curves expressing the number of stress cycles to failure, N, for a given constant stress range, S:

$$\log(N) = \log(a) - m\log(S), \tag{6}$$

where a, m are the empirical constants established by experiments.

The stress range to be applied in fatigue damage calculation is found by application of a stress concentration factor as well as a thickness correction factor to the nominal stress range:

$$S = S_0 SCF\left(\frac{t_{\text{fat}}}{t_{\text{ref}}}\right)^k, \tag{7}$$

where S_0 is the nominal stress range, SCF is the stress concentration factor, t is the thickness, and $(t_{\text{fat}}/t_{\text{ref}})^k$ is the thickness correction factor.

A damage degree according to the Palmgren-Miner hypothesis $D(T_0)$, for calculations using the Gerber relationship at observation time T_0 is calculated by summation of damages from successive distinguished amplitudes of cycles and half-cycles S_{a0} according to the following equation:

$$D(T_0) = \sum_{i=1}^{k} \frac{n_i}{N_0\left(\dfrac{S_0}{S_{a0}}\right)}, \tag{8}$$

where k is the number of applied stress ranges, n_i is the number of cycles with amplitude S_a, N_0 is the number of the stress cycles before failure, as expressed by eq. (6).

The fatigue damage accumulated at a given structural location within timeframe T_0 can be expressed as

$$D_{\text{Tot}} = \sum_{j=1}^{l} p_j D_j(T_0), \tag{9}$$

where l is the number of relevant sea states, and p_j is the probability of occurrence associated with sea state j.

Fatigue life is determined according to the following equation:

$$T_{\text{cal}} = \frac{T_0}{D_{\text{Tot}}}, \tag{10}$$

where $D(T_0)$ is the damage degree at the observation time T_0.

2.3 Soil-riser interaction

In most deepwater fields, relatively loose clay is found on the seabed. The pipe will sink into this clay and might be buried over time. It is important to properly model riser-soil interaction effects [14]. The riser-seabed vertical interaction (Figure 1) is described by a nonlinear soil stiffness representing the interaction force per indentation depth per riser length. The stiffness of the spring is taken as the instantaneous slope of the P-y curve for a particular deflection.

For soil behaviors, the nonlinear characteristics of the springs are defined by P-y curves and the governing equations are as below:

$$\begin{cases} EI\left(\mathrm{d}^4 y/\mathrm{d}x^4\right) = W - P_{\text{ver}}, \\ EI\left(\mathrm{d}^4 y/\mathrm{d}x^4\right) = P_{\text{hor}}, \end{cases} \tag{11}$$

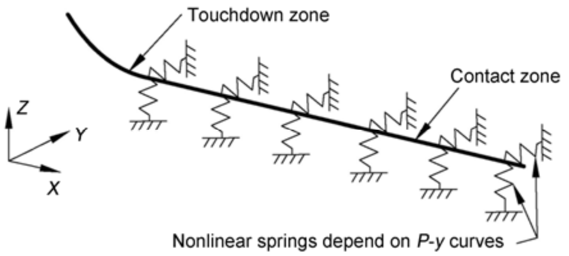

Figure 1 Model of riser-seabed interaction.

where E is the elastic modulus, I is the moment of inertia, y is the deflection value, W is the weight per unit length, P_{ver} and P_{hor} are the vertical and horizontal soil resistances per unit length, respectively.

3 Physical and mathematical model

A developed steel lazy wave catenary riser (SLWR) configuration for FPSO in 2460 m water depth is shown in Figure 2. Preliminary SLWR configuration is selected based on static design in the mean position. The riser is modeled as tensioned beam with six degrees of freedom at each node (three translations and three rotations). The static riser configuration is established by using the design current and vessel offset. Wave and current induced loads are included through drag and inertia coefficients by Morison equation. The suspended length is approximately 4000 m for SLWR. The riser model properties are shown in Table 1.

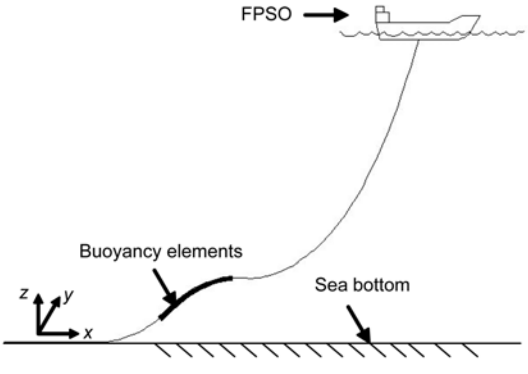

Figure 2 Steel lazy wave riser configuration.

Table 1 SLWR physical properties

Water depth	2460 m
Water density	1024 kg m^{-3}
Riser inner diameter	0.4064 m
Thickness	0.02 m
Modulus of elasticity	2.10×10^{11} N m^{-2}
Steel density	7850 kg m^{-3}
Poisson ratio	0.3
Coefficient of inertia	2.0
Added mass coefficient	1.0

The time-domain dynamic analysis approach is considered to be more suitable to represent the environmental loads and the structural response due to its capability to represent existing nonlinearities in the model. The nonlinear time-domain analysis program was employed for the determination of the time-history and stress variation in each selected node of the SLWR. Environmental data used for fatigue analyses were comprised of wave scatter diagrams that distributed the long term environment over a number of sea states. For each sea state in the scatter diagram the probability of occurrence is given so that the annual fatigue damage can be calculated as a weighted average over all sea states. The fatigue life was evaluated by running a 120-minute time-domain simulation to determine the stresses along the entire riser length.

4 Discussion

This section presents the sensitivity analyses performed on the SLWR fatigue life prediction. It should be noted that fatigue lives presented in this section are based on the use of DNV S-N curves (DNV, 2001, 2005)[15, 16]. Given that the fatigue lives do not fully account for the armor wire material properties of any application, they are used only as illustrative aids for fatigue sensitivity analyses and do not reflect the true design life.

4.1 Effects of the vessel motion on fatigue life

The steel lazy wave catenary riser (SLWR) configuration was modified based on vessel offset for both near and far positions. Figure 3 shows the configuration of the SLWR in the mean, near and far positions. Near and far positions are relative to the SLWR vertical plane, and are defined as follows.

Near: Wave, current and wind loading in the plane of the riser where the FPSO is offset towards SLWR touchdown.

Far: Wave, current and wind loading in the plane of the riser where the FPSO is offset away SLWR touchdown.

Table 2 SLWR fatigue lives at TDZ and hang-off

Load case description	Fatigue life (year)	
	TDZ	Hang-off
Mean	110	2040
Near	30	1080
Far	41	812

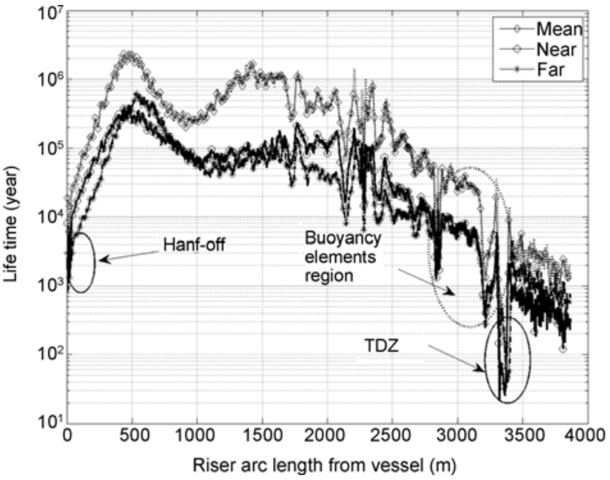

Figure 4 Fatigue lives along the SLWR length.

The fatigue life summary for TDZ and hang-off regions is presented in Table 2. As shown in Figure 4, the touchdown zone (TDZ) and hang-off of the SLWR are two critical fatigue parts. When the vessel is in the near position, the fatigue life of SLWR is smaller than that of far position in the TDZ. It is noted that the SLWR has lower fatigue life at 100 m TDZ around, which moves toward FPSO in the near case. This is illustrated in Figure 5, which shows the fatigue life in a zoom view of TDZ.

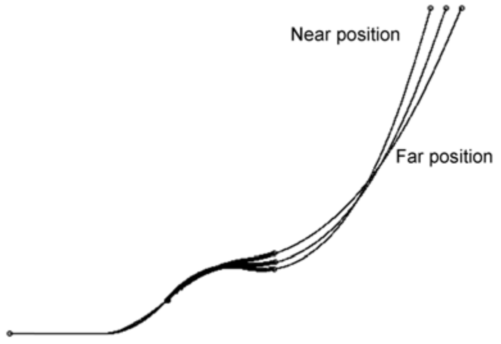

Figure 3 SLWR configurations in the near, mean and far positions.

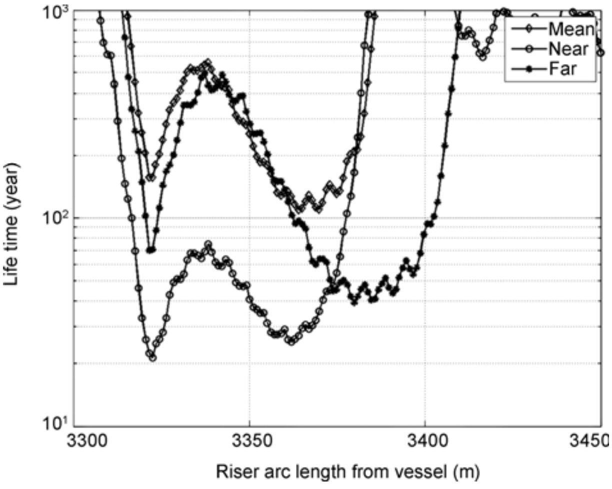

Figure 5 Touchdown zone fatigue lives.

This phenomenon can be explained by the different dynamic behaviors of the SLWR at touchdown zone (TDZ) and hang-off. The contact of the SLWR with the seabed introduces a source of non-linearity in the TDZ. As the vessel moves, the TDZ moves as well. Severe motion of the FPSO may cause a significant compression load on SLWR at the TDZ. The vessel motion can change the configuration of the riser, and then the transition length of the riser at the touchdown point. The reaction forces at the touchdown point further change the riser configuration when the SLWR changes the contact position.

4.2 Sensitivity to hydrodynamic coefficients

Hydrodynamic loading on the SLWR is expressed by Morison formulation as a summation of a drag term and inertia force term. The selection of drag coefficient (C_d) is an essential issue for SLWR analysis. A sensitivity study was conducted to assess the riser fatigue life to variation in hydrodynamic drag coefficient.

The base case analysis was conducted using a C_d value of 1.0. Comparisons were made with C_d values of 0.7 and 1.4 over the entire SLWR length, as shown in Table 3 and Figure 6. The results showed that fatigue response of the system was particularly sensitive to drag coefficient values. Increasing the drag coefficient to 1.4 decreased the fatigue damage at the TDZ. A higher drag coefficient value was used to represent the increase in drag on the riser due to strake. It was noted that by increasing the length of strake could reduce fatigue damage at critical part in SLWR such as TDZ and hang-off.

4.3 Effects of structural damping

Figure 7 shows the sensitivity of the predicted fatigue life to the structural damping used in the analysis. Three damping values were used to study the sensitivity, 0.05%, 0.15% and 0.3%. The predicted fatigue life at TDZ and hang-off are presented in Table 4. As seen from the Figure 7 and Table 4, the structural damping has a strong dependency on the value of the fatigue life.

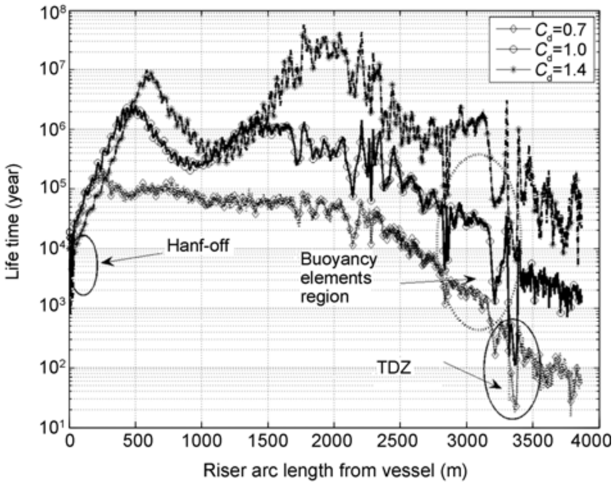

Figure 6 Effects of drag coefficient on fatigue life.

Table 3 Fatigue responses (year): C_d changes

Analysis cases	Fatigue life (year)	
	TDZ	Hang-off
C_d = 0.7	25	2750
C_d = 1.0	110	2040
C_d = 1.4	6166	812

The attenuation of resonant response along the length of the SLWR is primarily controlled by the system damping. Selecting a high structural damping for the analysis should lead to conservative estimates of the fatigue life.

4.4 Sensitivity to seabed soil stiffness

Seabed soil modeling has a significant impact on the predicted fatigue life of SLWR in the touchdown area. The seafloor contact behavior was modeled by nonlinear springs. The vertical and horizontal riser-seabed interactions were considered in this work. The impact of seabed stiffness on the riser fatigue life was assessed for a range of soil conditions, and compared to the base case.

The fatigue life along the length of SLWR near the TDZ for the soft, hard seabed is presented in Figure 8. Table 5 summarizes the fatigue life due to seabed stiffness effect for

Table 4 Fatigue responses (year): Structural damping changes

Analysis cases	Fatigue life (year)	
	TDZ	Hang-off
Damping=0.05%	110	2040
Damping=0.15%	501	7300
Damping=0.3%	1500	9450

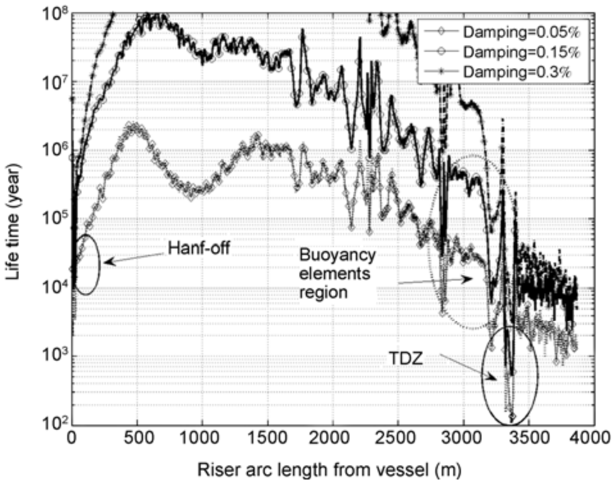

Figure 7 Effects of structural damping.

Table 5 Fatigue responses (year): Seabed stiffness changes

Analysis cases	Fatigue life (year)	
	TDZ	Hang-off
Seabed stiffness −15%	240	2690
Base case	158	1820
Seabed stiffness +15%	110	2040

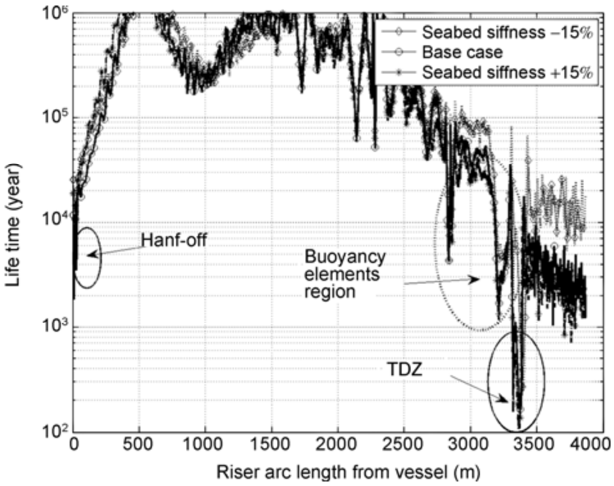

Figure 8 Effects of seabed stiffness.

TDZ and hang-off. The comparisons show that away from the maximum damage location, the damage for the hard seabed is slightly greater than that for the soft seabed. The location of the maximum damage has also shifted significantly towards the FPSO.

Figure 9 is a zoomed view of the TDZ, with results of seabed stiffness changes. The greatest fatigue damage always appears to be concentrated over a small length of the SLWR, typically no more than 100 m or so. It was observed that increasing the seabed stiffness by 15% would decrease the minimum fatigue life in the TDZ from the base case by 158 to 110 years. On the other hand, the TDZ is moved with the seabed stiffness changes. This indicates that the influence of seabed stiffness on fatigue life is significant.

4.5 Sensitivity to internal fluid density

Figure 10 illustrates the sensitivity of fatigue life distributions along the SLWR due to internal fluid density changes. It is clearly seen that the main difference is near the TDZ region, where riser configurations were locally modified. The high internal fluid density induced high stress ranges levels, leading to high fatigue damage, mainly in touchdown zone (TDZ). Table 6 shows the relative fatigue life comparison between the studied cases for different internal fluids. TDZ fatigue lives are smaller than hang-off fatigue lives.

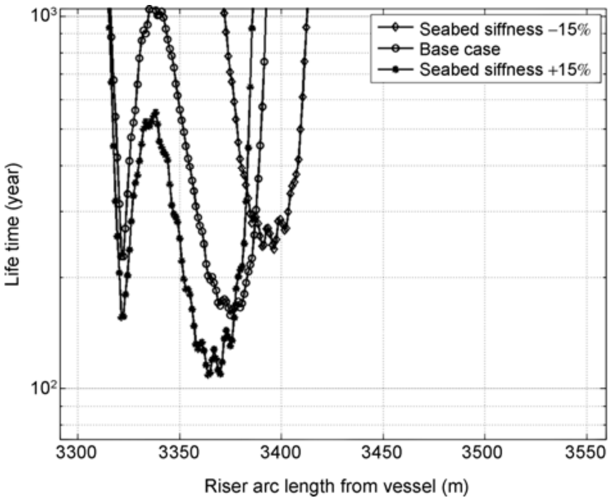

Figure 9 Touchdown zone fatigue lives.

4.6 Effects of S-N curves on fatigue life

The fatigue performance along the SLWR riser length with different S-N curves is shown in Figure 11. The predicted fatigue lives at TDZ and hang-off use different S-N curves, as shown in Table 7. The critical fatigue damage locations are at TDZ and close to the top end. As is seen, the riser configurations have sufficient fatigue life even with E-curve. If the weld quality and pipe matching can be improved, the riser can easily get fatigue life with a margin of safety.

In the previous section the sensitivity of the SLWR fatigue life to a range of parameters have been demonstrated. Since the vortex suppression devices such as strakes were used to disrupt or prevent vortex street formation, VIV induced fatigue damage of the riser was not discussed in this work.

Table 6 Fatigue responses (year): Internal fluid changes

Analysis cases	Fatigue life (year)	
	TDZ	Hang-off
No fluid	316	1740
Gas	110	2040
Oil	60	1780

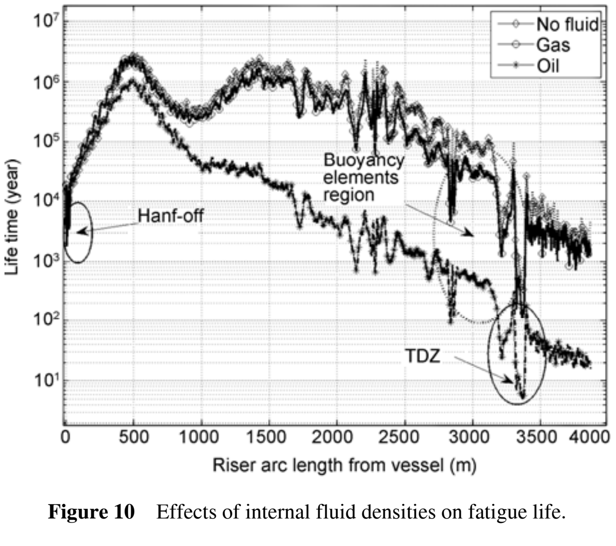

Figure 10 Effects of internal fluid densities on fatigue life.

Table 7 Fsatigue responses (year): S-N curve changes

Analysis cases	Fatigue life (year)	
	TDZ	Hang-off
D-curve	110	2040
C-curve	575	8820
E-curve	66	1148

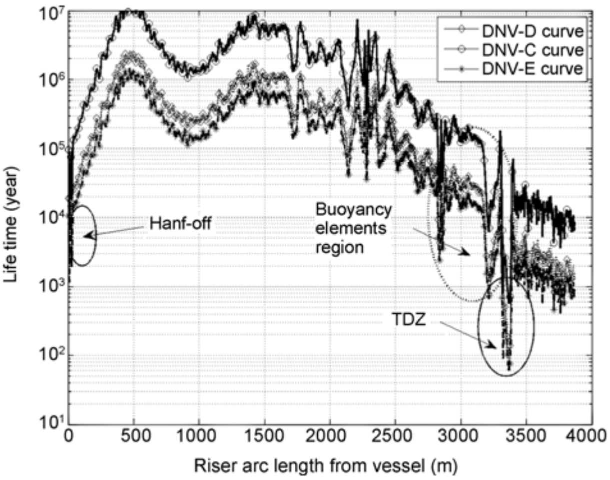

Figure 11 Effects of S-N fatigue curves.

5 Conclusions

The paper presents key results from a comprehensive study on the fatigue life prediction of SLWR. The results illustrate the sensitivity of the riser fatigue to the vessel motions, the drag coefficient along the riser, the structural damping and the seabed stiffness.

Based on the sensitivity studies, the conclusions can be drawn as follows.

1) The motion characteristic of the FPSO has a large influence on the fatigue response of the riser.

2) The hydrodynamic coefficients can have a substantial impact on the fatigue characteristics of the SLWR and therefore need to be carefully selected to represent the design conditions.

3) The greatest fatigue damage of SLWR near its touchdown region is significantly affected by its interaction with the seabed. The results also show that the fatigue damage for a ‘hard’ seabed is slightly higher than the damage for a ‘soft’ seabed. The predicted fatigue damage in touchdown area is therefore dependent upon the level of seabed stiffness.

4) When applying SLWR to deepwater, the assumption for structural damping is a critical issue and can have a significant effect on the riser fatigue performance.

As we move into deeper water and face even more severe fatigue loading, the accurate fatigue analysis method will hopefully benefit future SLWR design. This work was focused on the influence of fatigue life parameters for SLWR attached to FPSO, and much of the findings are general enough to be applicable to other floating platform types. Future work shall be conducted to optimize the overall riser system configuration so as to provide satisfactory levels of safety and reduce the cost of the whole systems.

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