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Fatigue performance of deepwater steel catenary riser considering nonlinear soil

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Abstract. The touch down zone (TDZ) and top connection point of the vessel are most critical part of fatigue damage in the steel catenary riser (SCR). In general, the linear soil model has been used to evaluate fatigue performance of SCRs because it gives conservative results in the TDZ. However, the conservative linear soil model shows the limitation to accommodate real behavior in the TDZ as water depth is increased. Therefore, the riser behavior on soft clay seabed is investigated using a nonlinear soil model through time domain approach in this study. The numerical analysis considering various important parameters of the nonlinear soil model such as shear strength at mudline, shear strength gradient and suction resistance force is conducted to check the adoptability and applicability of nonlinear soil model for SCR design.

Keywords: steel catenary riser; touch down zone; nonlinear soil; vortex-induced vibration; fatigue damage

1. Introduction

Riser structure is one of the significant components in subsea system that transports hydrocarbon production from subsea well to floating platform and exports processed fluid to onshore. From technical and economical perspective, steel catenary riser (SCR), which is cost effective and viable, has been a preferable solution in deepwater oil and gas production, especially for wet-tree production, water/gas injection and oil/gas export. To date, SCRs have been designed and installed on Tension Leg Platform (TLP), Spar and Semi-submersible facilities in the GOM, semi-submersibles offshore Brazil and TLPs offshore Indonesia (Bai and Bai 2005).

For deepwater SCR design, both the touchdown zone (TDZ) and the riser's top connection point of the vessel are the most critical areas for fatigue damage. In general, the top connection point could be controlled artificially by adopting mechanical methods such as the tapered stress joint or flex joint. Therefore, fatigue performance of SCR at TDZ where it comes into contact with seabed has become a concern in design of SCR. Therefore, the SCR's service life is strongly affected by fatigue performance in the TDZ. The fatigue in the TDZ is heavily influenced by the riser-seabed interaction and soil characteristic. Therefore, the greatest uncertainty in the SCR analysis comes from this interaction.

Over the years, several seabed soil models are developed and used in examining fatigue damage of riser at TDZ with respect to soil-riser interaction. Thethi (2001) showed that modelling the seabed as a rigid or linear elastic medium was a conservative approach and Thethi (2001) divided riser-seabed soil interaction into three categories: effect of riser movements on seabed, effect of water on seabed and effect of seabed on riser. Dixon (2009) addressed the prediction of fatigue life of SCR using traditional linear seabed models may result in over-conservative SCR design. From the previous studies, conservative linear soil model shows limitation to accommodate real behaviour in the TDZ as water depth is increased due to the complex phenomenon of the clayey seabed (Shiri and Randolph 2010). Therefore, many researchers considered nonlinear soil model to accommodate the nonlinearity of soil at TDZ. Elosta *et al*. (2014) showed that linear or rigid models are unable to represent actual seabed interaction due to the nonlinearity and geotechnical parameter of seabed. In 2009, Randolph and Quiggin (2009) proposed nonlinear hysteretic seabed model for more accurate seabed interaction.

The trench formation at TDZ affects to fatigue performance of riser. Therefore, many researches in the past utilised different soil model to investigate the influence of trenching. Fontaine (2006) considered soil abrasion model to study trench formation. You *et al*. (2008) used nonlinear load-deflection relationships to represent soil in stimulating trench formation and estimating moments in riser. Rezazadeh *et al*. (2012) used comprehensive nonlinear soil model in combination with vessel slow drift. Some studies

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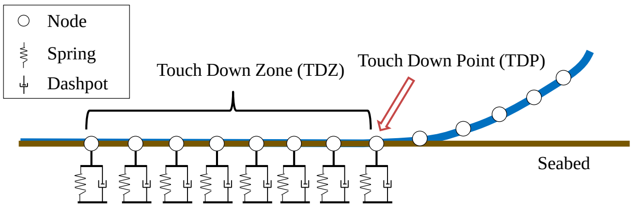


Fig. 1 A simple model describing soil interactions with riser in the TDZ

showed trench formation can cause increase in fatigue damage (Giertsen *et al*. 2004) while others reported reduction in fatigue damage (Clukey *et al*. 2007, Nakhaee 2010).

With regard to the uncertainties in soil model, Li and Low (2012) conducted fatigue reliability analysis of SCR by incorporating soil model uncertainties using variables representing stiffness, suction and trench. In considering the complexity in computational fatigue damage analysis, Shiri and Hashemi (2012) presented a simple and quick calculation method for estimating maximum fatigue damage at touchdown zone based on soil rigidity by using catenary equation and boundary layer solutions. In terms of nonlinear soil behaviours, recent studies are also focusing soil and pipeline interactions (Yu *et al*. 2013, 2015, 2016).

In this study, the effect of nonlinearity in the TDZ considering various environmental loading such as wave-induced forces, vortex-induced vibration (VIV), vortex-induced hull motion (VIM) and wave-induced fatigue (WIF) which cause continuous interaction between the riser and seabed. During the time domain numerical analysis, three critical parameters such as mudline shear strength, shear strength gradient and suction resistance ratio of nonlinear soil model are considered.

2. Numerical model

2.1 Numerical simulation procedure

When a pipe is placed in soil and subjected to oscillatory motion, there are complex interactions between pipe movements, penetration into the soil and soil resistance. A simple configuration representing the soil interactions in the TDZ is shown in Fig. 1.

In the TDZ of the riser, transverse (out-of-plane) motions will occur as a consequence of oscillatory forces caused by transverse waves acting on the free hanging part of the riser and also cross flows induced by in-line currents. A proper description of the pipe-soil interaction is therefore important for accuracy in the calculation of riser fatigue damage. In this study, the hysteretic nonlinear pipe-soil interaction model of Randolph and Quiggin (2009) is used. The nonlinear soil model had been basically developed using four penetration modes such as *Not-in-Contact, Initial Penetration*, *Uplift* and *Repenetration* as shown in Fig. 2. Four behaviour modes have been realized numerically by OrcaFlex (Randolph and Quiggin 2009), which is capable of performing analysis based on time domain including nonlinear effects and coupled analyses such as seabed soil,

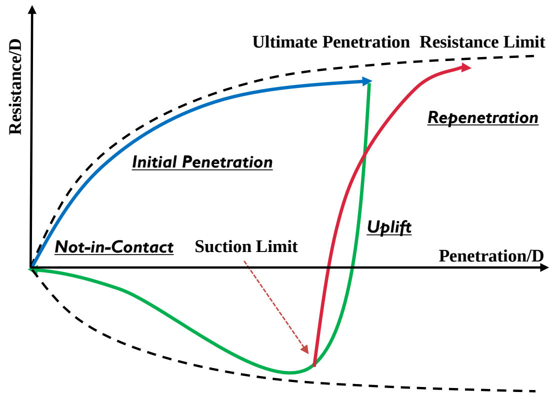


Fig. 2 Nonlinear soil model characteristics with different behaviours (Orcina 2013)

Table 1 Nonlinear soil parameters for the base case

Parameters	Symbol	Value
Saturated soil density (t/m^3)	ρ_{soil}	1.5
Power law coefficient	a	6
	b	0.25
Soil buoyancy factor	f_b	1.5
Normalized maximum stiffness	$K_{\max}$	200
Suction decay parameter	λ_{suc}	6
Repenetration parameter	λ_{rep}	0.25

Table 2 Parameters for the case studies

Parameters	Symbol	Lower	Medium	High
Mudline shear strength (kPa)	s_{u0}	0	1	2
Shear strength gradient (kPa/m)	s_{ug}	0.5	1.5	3.0
Suction resistance ratio	f_{suc}	0.2	0.4	0.6
Soil stiffness (kN/m/m^2)	k_{stiff}	50	100	200

floating system, mooring and riser (Orcina 2013). This study is performed using OrcaFlex (Orcina 2013) by considering the semi-submersible with mooring and nonlinear seabed soil model. The detailed procedure for the fatigue assessment of SCR can be founded at Park *et al.* (2015, 2016).

Typical properties of clay soil in GOM (Randolph and Quiggin 2009) used in the study are shown in Table 1. Three important parameters (s_{u0}, s_{ug} and f_{suc}) in the nonlinear soil model and soil stiffness (k_{stiff}) in the linear model are considered to investigate the sensitivity of the effect on fatigue performance under various environmental load cases such as VIV, WIF and VIM as shown in Table 2.

2.2 Analysis model

To investigate the nonlinear soil model and the approach for practical uses, the SCR design is connected to the semi-submersible with mooring considered as shown in Figure 3. A total of 10 numbers of mooring lines could support to minimize the floater’s offset under extreme environmental conditions. The data has been compiled from various sources (MCS 2005, Antares 2007, HOE 2013).

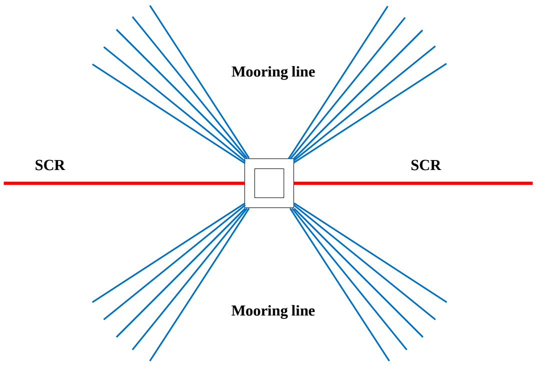


Fig. 3 Plan view of the overall system

Table 3 Mechanical data of riser pipe

Parameter	Value	Unit
Outer diameter	508	mm
Inner diameter	447	mm
Wall thickness	30.7	mm
Riser pipe density	7849	kg/m^3
Ovaility	+0.75/-0.25	%
Material	API X-65	
Young's modulus	204,774	MPa
Shear modulus	78,759	MPa
Tangent modulus	457	MPa
Minimum yield strength	448	MPa
Poisson's ratio	0.3	N/A
Stress concentration factor	1.2	
Internal fluid density	200.2	kg/m^3
Internal fluid pressure	22,408.0	kPa

Table 4 SCR strake data

Parameter	Value	Unit
Density	1150.8	kg/m^3
Section weight in air	72.0	kg/m
Section weight in water	7.9	kg/m
Barrel outside diameter	568.0	mm
Barrel thickness	29.6	mm
Equivalent thickness for hydrodynamic diameter	7.0	mm
Strake height (0.25D)	142.0	mm
Strake pitch (16D)	9087.9	mm

Table 5 Wave data

Types of wave for analysis case	Wave Type	H_s (m)	T_p (s)	γ
Associated wave for 100 yr. loop current	JONSWAP	1.2	3.8	2.4
100 yr. hurricane waves	JONSWAP	15.8	15.4	2.4

Table 6 Wind data

Types of wave for analysis case	Wind Type	1 hr. mean wind speed (m/s)
Associated wind for 100 yr. loop current	NPD spectrum	5.4
100 yr. hurricane winds	NPD spectrum	45.6

Table 7 Current data

100 yr. Eddy/Loop current				100 yr. hurricane currents	
Depth (m)	Velocity (m/s)	Depth (m)	Velocity (m/s)	Depth (m)	Velocity (m/s)
0	2.07	300	0.62	0	1.8
50	2.05	400	0.5	37.8	1.35
60	1.97	500	0.41	75.6	0
70	1.86	600	0.37	2000	0
80	1.76	700	0.33	-	-
90	1.66	800	0.29	-	-
100	1.53	900	0.25	-	-
150	1.12	1000	0.21	-	-
200	0.89	1500	0	-	-
250	0.72	2000	0	-	-

Two SCRs are designed for the export line of hydrocarbons and connected to the semi-submersible under 2,000 m of water depth. The separation at the hang-off location (HOL) of the SCR is assumed as 6 m with 12 degrees of hang-off angle. The strake design is considered to avoid vibration due to vortex induced oscillations; coverage ranges are 80% over the riser length to the TDP based on the Independence Hub design data (Calvin and Hill 2007). Platform hydrodynamics such as response amplitude operators (RAOs) and wave drift Quadratic Transfer Function (QTF) data are compiled from reference (HOE 2013) and this semi-submersible is modelled as an imaginary platform that corresponds to existing platform data. The details of structural and material properties of the SCR and strakes for analysis are presented in Tables 3 and 4, respectively.

In the design for offshore structures under various environment loads, short-term and long-term conditions are assessed for fatigue performance or strength design in terms of wave loading, floater motion and current loading. In this study, extreme cases (i.e., short term) are considered 100 years. Eddy/Loop current for VIV/VIM and 100 years of hurricanes combined with associating winds, waves and currents as shown in Tables 5 to 7.

Short-term time domain simulations were carried out to study the dynamic response interacting in SCR pipes in the TDZ thus verifying the effects of the nonlinear soil model on fatigue performance. Time duration of exposure to the extreme conditions were set to 10,800 sec (3 hours) in the case of WIF and VIM. However the fatigue damages for VIV were computed for 1,200 sec because the results between the 3-hour and 1,200 sec simulations showed similar tendency.

The purpose of this study is to verify the effects of the nonlinear soil model on fatigue performance in order to design SCRs under VIV, WIF and VIM in time domain and not to calculate accurately the amount of fatigue damage. The fatigue VIV analysis uses a vortex tracking model, which is based on the underlying physical equations of the boundary layer theory and the Navier-Stokes equation. This model is capable of introducing physical realism that is absent from the wake oscillator models (Sarpkaya and

Table 8 VIV parameters of vortex tracking model

Parameter	Value
Strake coverage length	1885 m
In-line force factor[(1)]	1.17
Transverse force factor[(2)]	0.1

Note: [(1)]Drag amplification factor, i.e., the ratio of drag coefficient between straked pipe and bare pipe. In the case of bare pipe it equals to the value of 1.0; [(2)]Straked section of the riser could reduce transverse amplitude and corresponding force. In the case of bare pipe it equals to the value of 1.0.

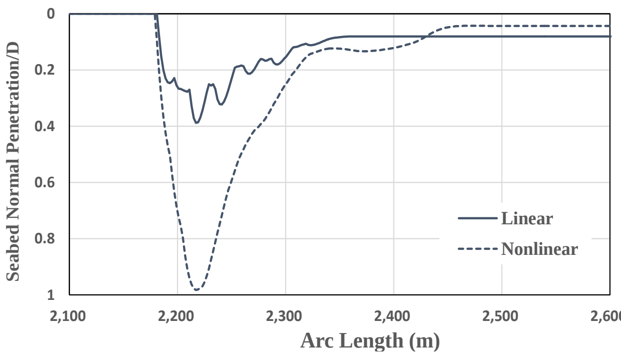


Fig. 4 Seabed normal penetration/D of linear (k_{stiff}=100 kN/m/m^2) and nonlinear (s_{u0}=2.0 kPa) soil

Shoaff 1979). Other parameters involved in the calculation of fatigue damage are used for the analysis as shown in Table 8. The in-line force factor and transverse force factor are adapted as a result of the discussion with Orcina.

The analysis is post-processed to obtain the time histories of stress along the overall riser. Fatigue damage is then calculated by performing rainflow counting and S-N damage accumulation calculations. The choice of the design curve depends on the location of potential failure and girth welding types. Usually, the curves corresponding to the pipe welds in seawater with cathodic protection are used for the risers (DNV 2010). The 'E-curve' represented in the DNV is selected for the calculation of fatigue damage. The more result of the S-N curve effect on fatigue damage of SCR was covered by Kim *et al*. (2015).

3. Numerical simulation results

3.1 Effect of nonlinear soil model under various loading conditions

The result of time domain analysis for the case of wave induced forces depicts the biggest difference in penetration depth of the soil models, which caused the formation of a trench at the TDZ as shown Fig. 4. The result from the WIF analysis also shows that fatigue damage of the linear model is more significant than the nonlinear soil model as shown in Fig. 6. The nonlinear soil model however, gave only 4% reduced value compared to the linear soil model in the view point of strength design whereas fatigue damage of the nonlinear model decreased by 15% of the linear model. In

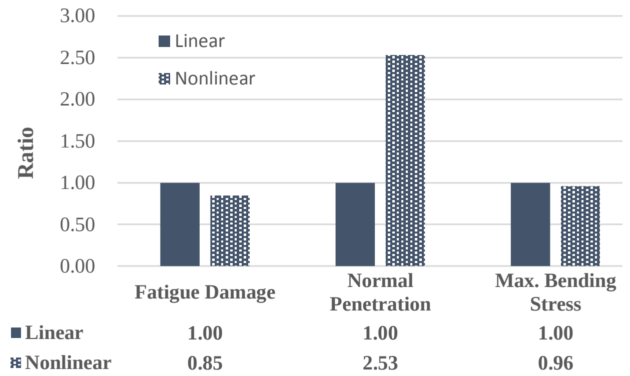


Fig. 5 WIF Fatigue damage linear (k_{stiff}=100 kN/m/m^2) and nonlinear (s_{u0}=2.0 kPa) soil

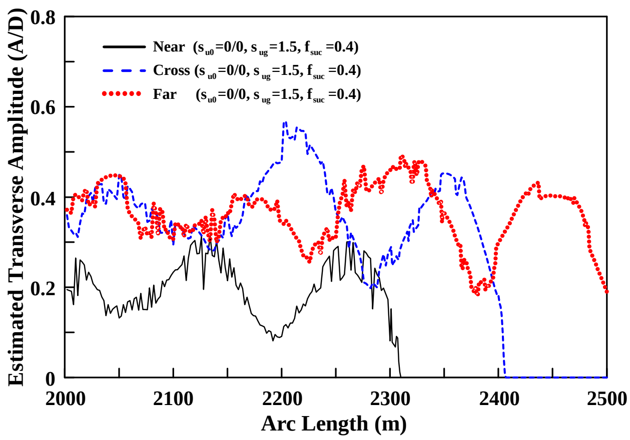


Fig. 6 Transverse A/D with respect to loading directions

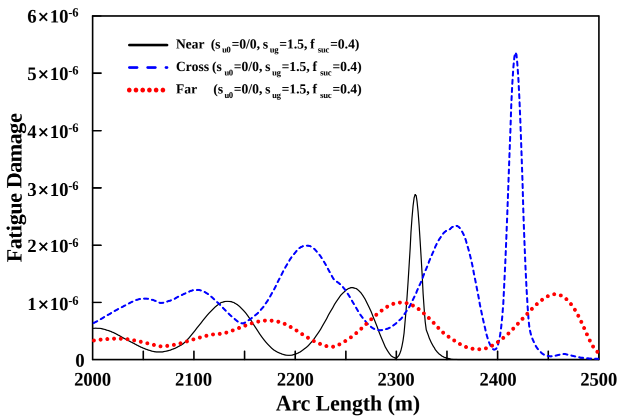


Fig. 7 Fatigue damage with respect to loading directions

general, the fatigue damage of HOL is almost insensitive with respect to the seabed-soil interaction model because tapered stress joint using titanium steel used at HOL. Therefore, numerical simulation results at HOL are not shown in this study

It should be noted that both models have the same value for the location in which maximum penetration occurs despite the nonlinear model having about 5 times deeper penetration than the linear model as shown in Fig. 4.

Global analysis of VIV is performed with 1,200 sec of simulation time mainly in the cross-flow direction. The SCR installed in the cross direction of the current is shown

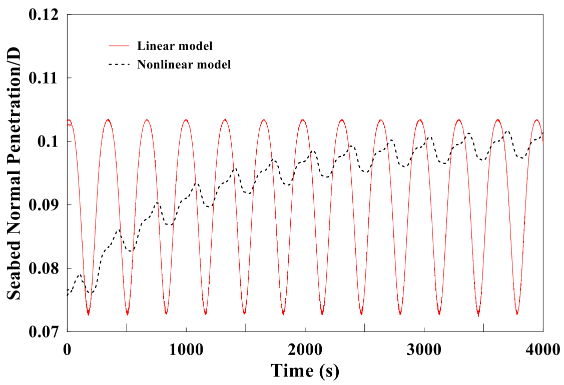


Fig. 8 Seabed normal penetration/D in the TDZ (t=0 to 4,000 s)

to experience larger transverse amplitude and ultimately has more fatigue damage as shown in Figs. 6 and 7, respectively.

The VIM analysis is also performed for the cross-flow direction with respect to the 100 year Eddy/Loop current with associated wave and wind, which is the same environment condition for the VIV analysis. Under the cross-flow direction, amplitude of sway motion for the semi-submersible was found from the natural period of certain motion. VIM analysis result clearly shows soil suction and degradation, which are remarkable characteristics of the nonlinear soil model, affecting the penetration in the TDZ as shown in Fig. 8. The linear soil model does not include soil degradation characteristics, whereas the nonlinear soil model reflects the degradation of soil and causes the gradual hysteretic penetration in the process of time. From the behaviour in the TDZ, it could be understood that the nonlinear soil model presents more realistic soil-riser interactions phenomena.

3.2 Sensitivity analysis of nonlinear soil model parameters

For the sensitivity analyses of nonlinear soil seabed model proposed by Randolph and Quiggin (2009) is considered. Three main parameters of soil are selected and compared to the stiffness of the linear seabed soil model. The three parameters of nonlinear seabed soil models selected are the mudline shear strength, shear strength gradient, and soil suction, which were all applied to the analyses of VIV, VIM and WIF.

The undrained shear strength in the mudline, s_{u0} and shear strength gradient, s_{ug} of the clayey soil determine the main characteristics of the soil in terms of its strength and bearing capacity, which are capable of resisting penetration under external loads. The linear undrained shear strength would increase with increased depth, which also causes the increase of shear strength with increased depth (Valent *et al.* 1988). The accuracy of the undrained shear strength profile is important, particularly for the pipeline penetration depth (Shiri and Randolph 2010). This property of soil can be expressed by Eq. (1)

$$s_u(z) = s_{u0} + s_{ug} \cdot z \tag{1}$$

where, $s_u(z)$ is the undrained shear strength in the depth of z, s_{u0} is the mudline shear strength and s_{ug} is the shear strength gradient.

These parameters contribute to the formation of the backbone curve shape as it forms the ultimate resistance limit represented by the blue curve as shown in Fig. 3. The ultimate penetration asymptotic limits are given by Eq. (2).

$$P_u(z) = N_c(z/D) \cdot s_u(z) \cdot D \tag{2}$$

where, z is penetration depth, D is pipe diameter, $N_c(z/D)$ is the bearing factor that is a function of z and D.

Cohesive soils will develop adhesion in contact with almost any materials such as riser pipes. This adhesion would affect the vibration of the pipe and trench penetration in the TDZ (Vesic 1969). Thus the suction resistance ratio is investigated to study its effects on fatigue damage, strength and penetration induced cyclic loading.

The factor of suction resistance ratio, which is the range of the suction limit, controls the ultimate suction resistance in the green curve as shown in Fig. 3. A lower value gives less suction, whereas a higher value gives more suction. Soil suction, f_{suc}, controls the suction asymptotic limit, $P_{u\text{-}suc}$, as given by Eq. (3).

$$P_{u-suc}(z) = -f_{suc} \cdot P_u(z) \tag{3}$$

The repenetration resistance in the uplift mode is also controlled by soil suction as given by Eq. (4).

$$P(z) = P_0 - H_{UL}(\zeta_0 - \zeta)(P_0 - P_{u-suc}(z)) \tag{4}$$

where, $H_{UL}(\zeta_0-\zeta)$is a hyperbolic factor.

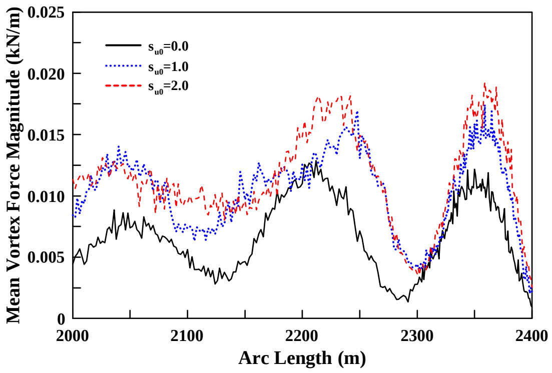
$$\zeta = \frac{z}{D/K_{\max}} \tag{5}$$

$$\zeta_0 = \frac{z_0}{D/K_{\max}} \tag{6}$$

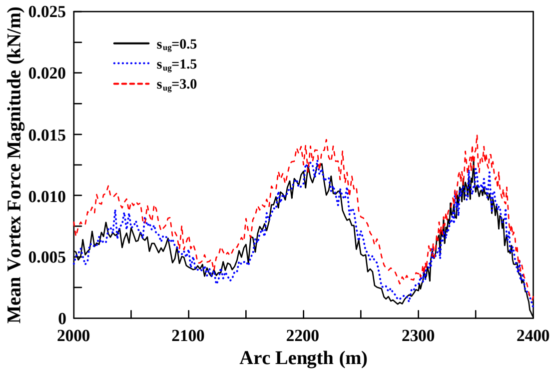
where, ζ is the penetration given by non-dimensionalised unit of $(D/K_{\max})$, ζ_0 is the non-dimensionalised penetration in which the latest episode of the contact mode started, $K_{\max}$ is the normalized maximum stiffness.

In the VIV analysis, vortex induced forces are the main contributor for fatigue damage. The submerged bluff body for example the SCR, experiences oscillation caused by alternative vortices around the surface of the structure as its natural frequency approaches the Strouhal frequency. Vortex induced forces occurring in that condition also accumulates the stress on the riser, i.e., random cyclic loads that cause fatigue damage. Vortex induced forces from the VIV analysis is therefore used to compare the effect to the fatigue damage as shown in Fig. 9. The results shows that the transverse vortex force along the riser in the vicinity of TDZ becomes large with increased shear strength, strength gradient and suction as shown in Figs. 9(a) to (c), in respectively.

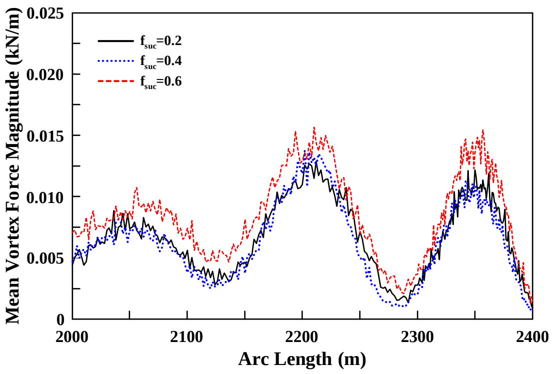
The tendency of the vortex force corresponding to soil parameters related to the stiffness in the nonlinear seabed soil almost conformed to the seabed stiffness in the linear soil model as shown in Fig. 9(d). The results are also true with the commonly accepted concept such that stiff seabed



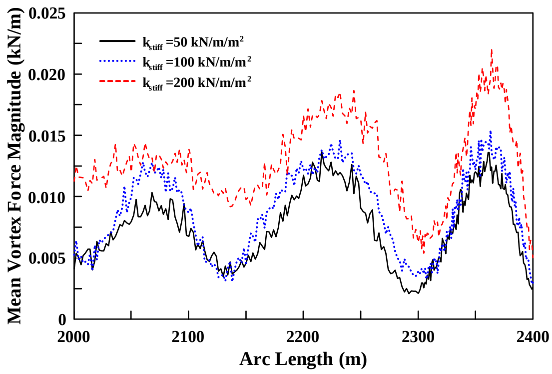
(a) mudline shear strength



(b) shear strength gradient

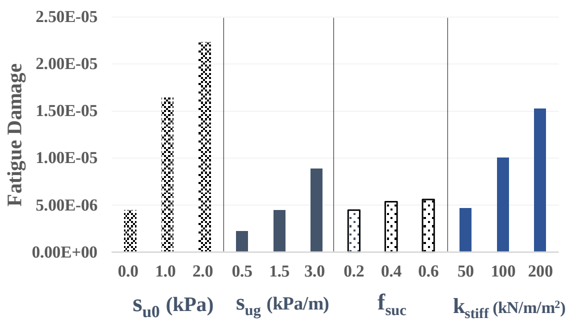


(c) suction resistance ratio

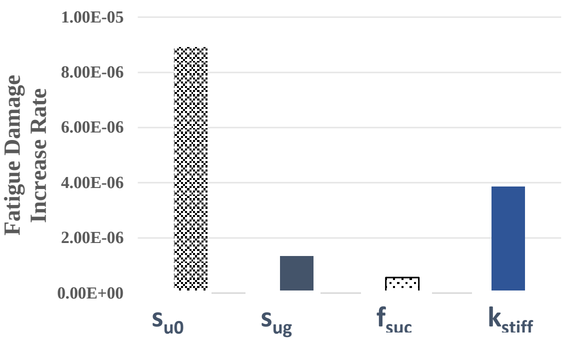


(d) soil stiffness

Fig. 9 Mean vortex force magnitude corresponding to soil parameters



(a) fatigue damage



(b) increase rate of fatigue damage

Fig. 10 Fatigue damage sensitivity corresponding to soil parameters in VIV

conditions give negative effects to fatigue damages. It should be noted that the suction force in clayey soil could contribute to large vortex forces, which ultimately increase fatigue damages as shown in Fig. 9(c).

Fig. 10(a) shows the maximum fatigue damage calculated from the VIV analysis with nonlinear soil and linear soil parameters. From comparison with the increased rate of fatigue damage based on factored soil parameter values, the mudline shear strength and seabed soil stiffness are the most sensitive factors to fatigue damage in the VIV analysis as shown in Fig. 10(b). The end condition of the riser at the TDP could be of most importance because it gives discernible effects to the structure’s natural frequency. Therefore, the mudline shear strength should be considered more carefully rather than the shear strength gradient in the case of VIV analysis.

Riser motion could occur due to floater VIV induced by current loading, named VIM. VIM occurs on any bluff body such as Spars, semi-submersibles, TLPs and buoys exposed to currents; provided the vortex shedding frequency is close or equal to the natural period of the floating body. Longer periods of motions, i.e., low frequency motions of the vortex induced vibrations of floating structures are more commonly referred to as VIM. As noted, current direction is considered for surge direction so that the floater VIM could be moved in a sway direction, which gives maximum fatigue damages to the riser. The riser at the touchdown point (TDP) ultimately moves in same direction as in the case of wave motion analysis shown in Fig. 11.

The periodical motion in the sway direction is caused by vortex shedding on the hull leading to the movement of the TDP location with coincident frequency as shown in Fig.

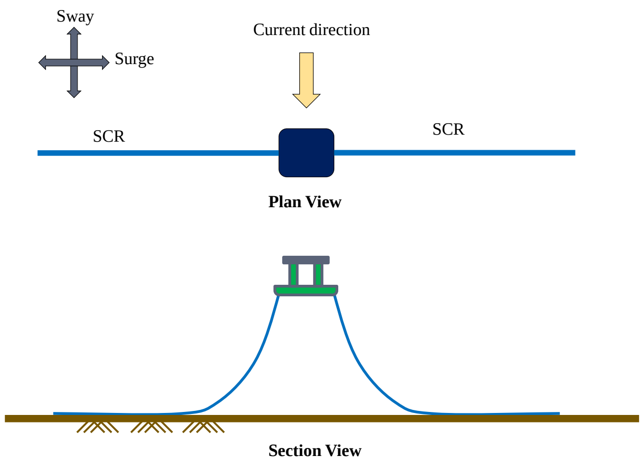


Fig. 11 Plan and section view for the concept of vortex induced motion

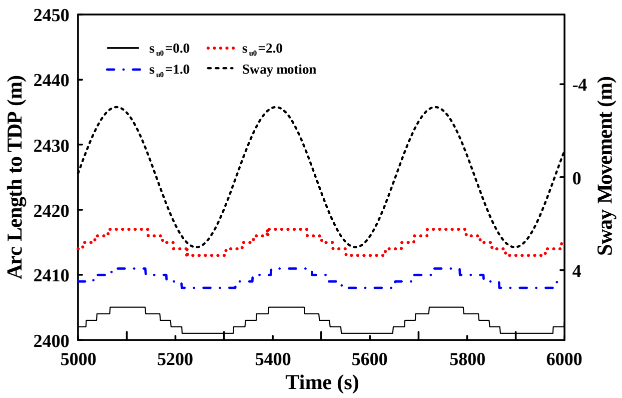


Fig. 12 Sway movement and TDP location change corresponding to mudline shear strength

12. The low frequency motion in the TDP could help to investigate the effects of parameters relating to suction force. First of all, different mudline shear strengths only change the TDP location with the same configuration regardless of the degree of strength. It is commonly accepted for TDP to move forward with the semi-submersible when soil stiffness becomes stronger. The result of the shear strength's effect on the TDP location supports this phenomenon. The suction forces have enough time to affect seabed-riser interactions at the TDP due to the behaviour of the TDP with relatively low frequency in the VIM analysis. Figure 13 shows stronger suction forces that make it difficult for the pipe to lift upwards when the TDP is moving forward to flowline, i.e., the far direction. On the contrary, it firstly starts the movement backwards to the near position.

Maximum fatigue damages are calculated from the VIM analysis with each nonlinear soil and linear soil parameters as shown in Fig. 14(a). The mudline shear strength is shown to give the most negative effects on fatigue damage in view of sensitivity, which are similar results with the VIV analysis. The sensitivity of suction resistance is relatively larger than that of the VIV analysis as shown in Fig. 14(b). The reason is that suction forces contribute to the behaviour of the TDP. As a result, suction forces should be carefully

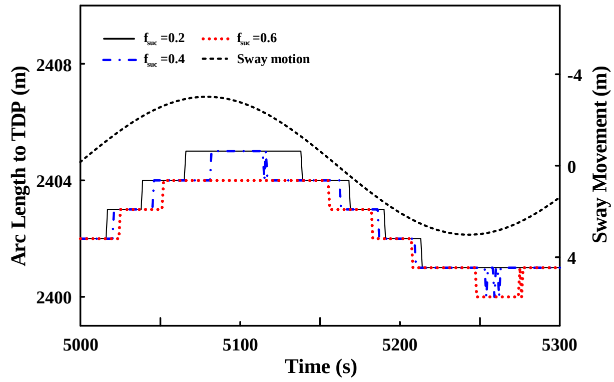
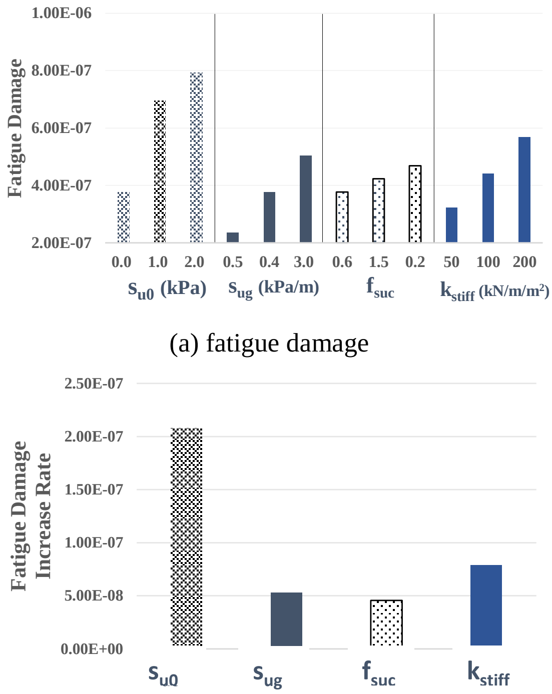


Fig. 13 Sway movement and TDP location change corresponding to suction resistance ratio



(a) fatigue damage

(b) increase rate of fatigue damage

Fig. 14 Fatigue damage sensitivity corresponding to soil parameters in VIM

considered when nonlinear seabed soil model is adopted for VIM analysis.

Wave induced loads on the floater and the motion induced by its loads are the key issues for the riser design because the floater motion would affect significantly to the riser fatigue. For this study, wave load is applied to the design for WIF including associated current and wind.

Dynamics response of the riser in the wave induced forces analysis is subject to first order and second order wave loads. First order wave loads are the cause of well-known first order motions with wave frequencies. Therefore, oscillating displacements of the structure at certain frequencies are corresponding to those of the waves, i.e., wave-frequency region. There are also drift forces that are caused by non-linear (second order) wave potential effects. The mean slow drift offset of individual sea states should therefore be considered as these offsets can have

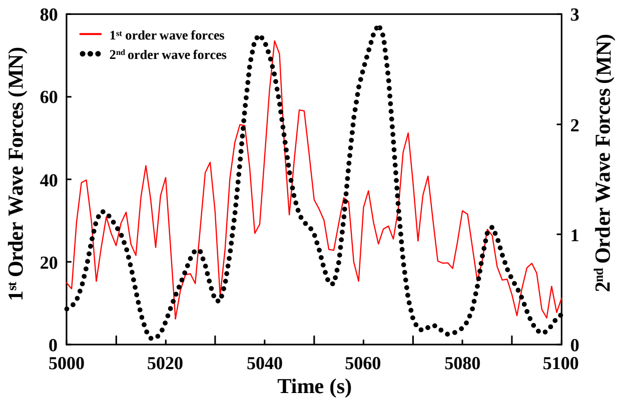


Fig. 15 First and second order wave forces applied to the semi-submersible

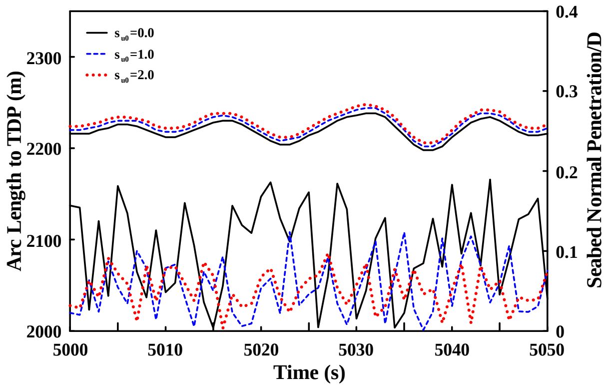
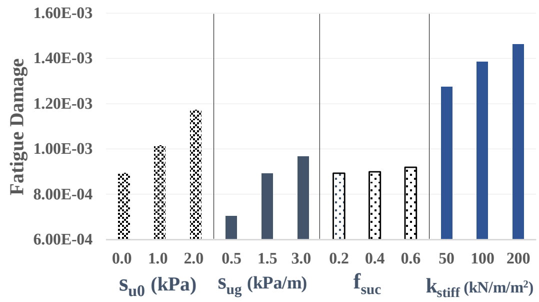


Fig. 16 TDP locations and normal penetration in WIF

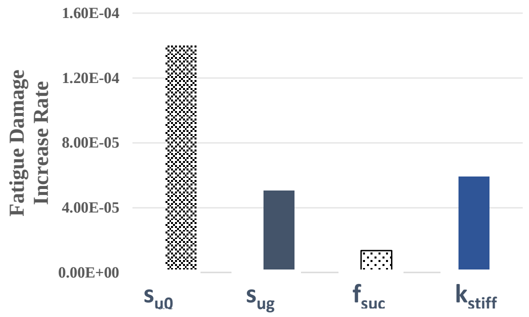
significant influence on the TDP's fatigue damage distribution. Drift forces lead to oscillating displacements of the structure at frequencies that are much lower than those of the waves. Generally, a moored floater has low natural frequency in its horizontal modes of motion as well as very little damping at such frequencies. Very large motion amplitudes can then result in resonance; a major part of the floater's dynamic displacement can be caused by these low-frequency excitations. In addition, slowly varying components of drift motions provide further contributions to the total riser fatigue damage. This study is performed by considering these wave forces to investigate the effect of soil on the fatigue damage for practical approaches. Figure 15 shows the first and second wave forces of a semi-submersible used in the model.

The TDP location and the seabed normal penetration change differently according to the corresponding mudline shear strength as shown Figure 16. From these results, the arc lengths become shorter with stiff soil. However, the responding frequency of the change of TDP location is relatively fast than the frequency of VIM cases due to high frequency external loads of the wave forces. And the penetration depth with less stiff soil is shallower than stiff soil in static analysis.

WIF analyses present results such that all the linear soil model with stiffness (k_{stiff}) ranges from 50 kN/m/m^2 to 200 kN/m/m^2 as shown in Fig. 17(a). From the results of SCR analysis for wave induced fatigue, it can be concluded that



(a) fatigue damage



(b) increase rate of fatigue damage

Fig. 17 Fatigue damage sensitivity corresponding to soil parameters in WIF

SCR designs with linear seabed-pipe response model give negative effect on fatigue life and would ultimately become a conservative approach design. In the case of nonlinear soil models, the shear strength at the mudline is the most significant parameter for fatigue damage based on the sensitivity analysis; on the other hand, the suction resistance ratio relatively gives less effect to fatigue damage. Accordingly, parameters related to the soil strength should be carefully considered if a nonlinear soil model is applied for the SCR design.

4. Conclusions

The main contribution of this study is to present the effects of a nonlinear soil model to fatigue performance in SCR designs, which are commonly performed by using the VIV, VIM and WIF analyses. The investigation results of these effects will assist in checking adoptability and applicability for the nonlinear soil model when performing SCR designs.

This paper investigates the nonlinear soil effect on fatigue performance of SCRs in the TDZ and sensitivity for key designs of the SCR such as VIV, WIF and VIM based on the Metocean data of Central GOM. The main conclusions are as follows:

- Based on the WIF analysis, the fatigue damages of the linear soil model are calculated more conservatively than the nonlinear soil model, however the penetration depth is shallower in the linear soil model. HOL is not significantly affected by the soil models. The strength designs are also not sensitive to the soil models.
- Nonlinear soil models give negative effects on the

fatigue performance in the TDZ in the cases of VIV and VIM analyses that focus on the cross direction of currents. Cross direction does not affect much the final penetration depth under cyclic loads but the trench configurations are rather affected by the static penetration. The VIV phenomena are fundamentally sensitive to the end conditions of HOL and TDP. Given the end condition of HOL, the shear strength at the mudline gives effect on the natural frequency of the riser thus ultimately affects the VIV fatigue performance relatively rather than affecting soil strength degradation or soil suction forces. The vortex force magnitudes from VIV are also significantly affected by the shear strength at mudline.

• Nonlinear soil models are capable of including soil suction forces; it shows different penetration behaviours corresponding to time in VIM analysis and can be used in the approach to design the TDZ considering real phenomena of soil. Cyclic motions from VIM will have the riser move during penetration and uplift with lower frequency in the vertical plane compared to VIV and WIF. The soil suctions therefore have enough time to give effect to the fatigue performance. The soil suction during cyclic and hysteretic interactions between riser and seabed gives negative effects on the fatigue performance in VIM analysis.

• As a result of sensitivity analysis, the mudline shear strength is the most sensitive factor to fatigue damage in VIV, VIM and WIF analysis. Seabed soil stiffness is the following parameter that gives large sensitivity but the degree of the effect is the largest in VIV analysis. Soil suction force is the parameter giving lowest sensitivities among the parameters investigated in this study but the degree of the effect is relatively large in VIM analysis.

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Abbreviations & Nomenclatures

CARISIMA	=	catenary riser soil interaction model for global analysis
DNV	=	Det Norske Veritas
GOM	=	Gulf of Mexico
HOL	=	hang-off location
SCR	=	steel catenary riser
STRIDE	=	steel riser in deepwater environments
TDP	=	touchdown point
TDZ	=	touchdown zone
VIM	=	vortex-induced hull motion
VIV	=	vortex-induced vibration
WIF	=	wave-induced fatigue
WIM	=	wave-induced hull motion
D	=	outer diameter
f_b	=	soil buoyancy factor
f_{suc}	=	suction resistance ratio
$H_{UL}(\zeta_0-\zeta)$	=	hyperbolic factor
$K_{\max}$	=	normalized maximum stiffness
k_{stiff}	=	soil stiffness
N_c	=	bearing factor
P_u	=	the ultimate penetration asymptotic limits
$P_{u\text{-}suc}$	=	the suction asymptotic limits
s_{u0}	=	mudline shear strength
s_{ug}	=	shear strength gradient
ρ_{soil}	=	saturated soil density
λ_{suc}	=	suction decay parameter
λ_{rep}	=	repenetration parameter
ζ	=	non-dimensionalised penetration
ζ_0	=	non-dimensionalised penetration when the latest episode of the contact mode started