Nonlinear hysteretic seabed response to vibrations of slugging steel catenary risers

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ABSTRACT
Fatigue analysis of steel catenary risers (SCR) in the touchdown zone (TDZ) is extremely challenging because of complex mechanisms between the riser, seabed soil, seawater, and internal fluid. In this paper, an advanced numerical model was developed with complex modules including a) a DISP subroutine to simulate the vessel motions under realistic environmental loads, b) a user defined element (UEL) subroutine to model the nonlinear hysteretic riser-seabed interaction in the TDZ, c) a structural model of SCR and riser hydrodynamics, and d) MPC/DLOAD subroutines to simulate the slug regime and transportation inside the SCR. Two groups of comprehensive parametric studies were conducted to explore the impacts of seabed soil and slug models on the responses of slugging SCR. The results showed that the nonlinear seabed model might significantly affect the slug-induced stress variation distribution and consequently the fatigue of SCR.

RÉSUMÉ
L'analyse de la fatigue des risers caténaires en acier (SCR) dans la zone de toucher des roues (TDZ) est extrêmement difficile en raison des mécanismes complexes entre la colonne montante, le sol du fond marin, l'eau de mer et le fluide interne. Dans cet article, un modèle numérique avancé a été développé avec des modules complexes comprenant a) un sous-programme DISP pour simuler les mouvements du vaisseau sous des charges environnementales réalistes, b) un sous-programme UEL pour modéliser l'interaction hystérétique non montante TDZ, c) un modèle structurel de l'hydrodynamique SCR et de la colonne montante, et d) des sous-programmes MPC / DLOAD pour simuler le régime des limaces et le transport à l'intérieur du SCR. Deux groupes d'études paramétriques exhaustives ont été menés pour explorer les impacts des modèles de sols et de limaces du fond marin sur les réponses de SCR. Les résultats ont montré que le modèle de fond marin non linéaire pourrait affecter de manière significative la distribution de la variation de contrainte induite par les limaces et, par conséquent, la fatigue du SCR.

1 INTRODUCTION

Steel Catenary Risers (SCR) are widely used in offshore industry for transportation of oil and gas. Due to the slim and hanging nature of the structure, SCR suffers from the vibrations and oscillations induced by dynamic, cyclic loads. Fatigue damage of SCR has been a concern and efforts have been made to evaluate the fatigue especially for the critical area, the touchdown zone (TDZ) of SCR, where the SCR touches the seabed. However, the evaluation is quite challenging since complex mechanisms contribute to the loads, inducing riser oscillations in the TDZ including wave and low-frequency vessel motions, vortex induced vibrations, and slugging. In this paper, slugging was investigated as a key factor to the accumulated fatigue damage (Kansao et al. 2008, Ortega et al. 2012). In addition to this, observations in subsea surveys and exploration projects indicate the complexities of the mechanisms in riser-seabed-seawater interactions. These complexities result in cyclic soil stiffness degradation, suction force mobilization during the riser uplift, and eventually a trench formation underneath the SCR in the touchdown zone. Nonlinear seabed models are required to be developed to model the seabed soil response to the complex coupled mechanisms. The advanced nonlinear hysteretic riser-seabed interaction models have been developed and evaluation of wave and current-induced fatigue loads of the SCR has been widely studied in the literature (Nakhaee and Zhang 2008, Shiri 2010, Shiri and Randolph 2010, Shiri and Esmaeilzadeh 2011, Hashemi 2011, Shiri and Hashemi 2012, Rezazadeh 2012, Shiri 2014, Kimiaei and Liao 2015, Clukey et al. 2017). However, the effect of these significant mechanisms and the nonlinear seabed soil response on slug-induced fatigue loads of SCR have never been investigated until now.

In this study, the impact of the nonlinear hysteretic seabed response and its consequences on slug-induced loads of the SCR was comprehensively investigated as an important knowledge gap. An advanced numerical model was developed using ABAQUS with several subroutines (e.g., user-defined element (UEL), multi-point constraints (MPC), and user-defined boundary conditions (DISP)) developed in FORTRAN and linked to the main analysis model to simulate slugging regimes, nonlinear hysteretic riser-seabed interaction, and various vessel excitation modes (including wave and low-frequency motions) under the act of environmental loads.

2 LITERATURE REVIEW

The influence of seabed soil evolution on wave and current-induced fatigue damage of SCR have been well investigated in the literature (Shiri 2010, Shiri and Randolph 2010, Clukey et al. 2017, Dong and Shiri 2017, Dong and Shiri 2018), but it has never been studied in slug-induced fatigue. Slug-induced vibrations have been explored for the hanging part of the SCR but in most models the seabed end of the riser was considered as pinned and thus oscillation of SCR in the TDZ was absent from the analysis. Bordalo et al. (2008) examined the effects of two phase flow patterns (slug, intermittent and annular) and flow rates of contents on the induced loads and riser responses by developing a laboratory-scale model. But in this research the seabed end was set as pinned and thus the responses in TDZ were absent in these tests. Pollio and Mossa (2009) compared two simple models of slug flow (with and without elastic seabed models) in a long flexible marine riser. The results showed the bending moment variation was significantly different in cases with and without the elastic seabed model. Gundersen et al. (2012) used commercially available global and local riser analysis software (e.g., RIFLEX and BFLEX) and explored the remnant fatigue life of a lazy-S flexible riser under the combined effects of wave and slug. The riser was simulated as hinged at hang off and analysis was entirely focused on the hanging part. Results showed the slug dominated the dynamic top angle response and significantly reduced the riser fatigue life during a relatively calm sea condition. Ortega et al. (2012) analyzed the dynamic responses of a lazy wave riser under slugging by coupling the slug flow tracking code (SLUGGIT) and riser structure code (RISANANL) together. The results presented the irregularities in riser structure responses to slugging and indicated the importance of considering the effects of slug flow in the fatigue analysis. However, the seabed end of riser was considered as pinned and riser responses under slugging in TDZ were not included. Ortega et al. (2013) conducted a fully-coupled analysis to examine the combined effects of slug loads and wave loads on the dynamic responses of a catenary riser. It was presented that internal slug flow generated irregular deformation time histories when the regular waves resulted in typical deformations of the riser structure. However, the riser responses in TDZ were not analyzed with the seabed end of riser considered as pinned. Chatjigeorgiou (2017) investigated the combined effects of harmonic motions of the vessel and the internal slug flow on the responses of the hanging part of the riser by incorporating the slug flow terms into the structural dynamic model formerly built by Chatjigeorgiou (2010a, 2010b). It was shown that the magnitudes of dynamic components were amplified due to the existence of internal slug flow. Bordalo et al. (2018) incorporated a slug flow load model to a 3D pipeline dynamics simulator. The simulation of slugging SCR in the case study showed that large oscillations might be induced when the slug frequency was close to any of the natural frequencies of the riser. However, the seabed interface was not the focus of the paper.

To fill the knowledge gap, in this paper, a nonlinear soil model was embedded into the advanced numerical model to consider the effects of the seabed evolution process on slug-induced vibrations. In SCR design codes, linear springs have been used to present the pipe-soil interaction. With further observations in subsea surveys and exploration projects, more sophisticated nonlinear models were needed to better represent the mechanism of riser-seabed interaction (Phifer et al., 1994; Theti and Moros, 2001; Campbell, 1999). Based on full-scale harbor tests and some existing models, Bridge et al. (2004, 2007) developed a model capturing some of nonlinear aspects of soil behavior, except for the degradating soil stiffness and riser embedment into the seabed. Jiao (2007) proposed the degradating soil model which could capture the cyclic softening of soil in the re-loading process but not in the unloading process. This disadvantage was overcome in new models proposed later (Aubeny and Biscontin 2009, Nakhaee and Zhang 2010). Randolph and Quiggin (2009) developed a new nonlinear seabed model for the calculation of reaction force in different penetration modes of the oscillating riser. Shiri and Randolph (2010) explored the fatigue analysis of SCR by developing a numerical model in ABAQUS with the R-Q soil model adopted in the user-defined element. Zargar et al. (2015) conducted a comparative study of two existing riser-soil interaction models (Aubeny and Biscontin 2009, Randolph and Quiggin 2009) and identified their pros and cons for future developments. SCR fatigue was further investigated and reported with newly proposed trench models (Randolph et al. 2013, Shiri 2014a, Shiri 2014b) or different case studies (e.g., different loading histories, complex riser excitations etc.) (Elliott et al. 2013, Kimiaei and Liao 2015, Clukey et al. 2017). Authors emphasized the significance of nonlinear riser-soil interaction models and their needs for further improvement of fatigue analysis of SCR in TDZ. Dong and Shiri (2017) comprehensively investigated the performance of the R-Q model (Dong and Shiri 2017, Dong and Shiri 2018). The R-Q model was found to have strong features and may be an appropriate approach for modelling the nonlinear riser-seabed interaction. But some improvements may be needed since it was observed by the authors that the model was unable to explicitly simulate trench formation. In addition, the model doesn't capture the four sub-episodes of riser-soil interaction that were observed in experimental studies (Hodder and Byrne 2009). However, the advantages of this model in automotive simulation of cyclic soil stiffness degradation and trench creation has made it a popular model. In this study, the R-Q model was coded in the UEL subroutine and implemented into the global SCR model in ABAQUS to incorporate the effect of nonlinear hysteretic seabed on slug-induced fatigue loads.

3 NUMERICAL MODEL

3.1 Global Model

A global SCR model was developed in ABAQUS. Slug loading, nonlinear hysteretic riser-seabed interaction, and the wave/current-induced vessel motions were coded in MPC/DLOAD, UEL, and DISP subroutines respectively. To facilitate the comparison of results from slug-induced, wave-induced, and combined wave/slug-induced analysis, the global SCR configuration was adopted from Dong and Shiri (2018).

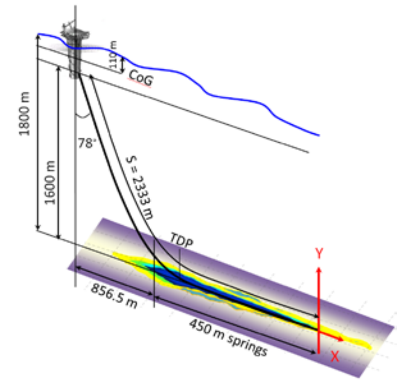

Figure 1. The global geometry of SCR modelled by ABAQUS.

3.2 Modelling of SCR Slugging

As illustrated in Figure 2, the slugging or separation of the flow to a film zone, and a slug liquid zone usually occurs in moderate flow velocities (Kansao et al. 2008).

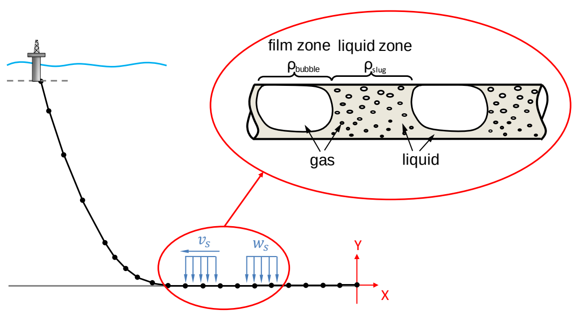

Figure 2. The slug flow regime.

A pre-defined distributed load representing the weight of the slug was executed on the SCR by coding the DLOAD subroutine in FORTRAN. The key steps inside DLOAD were outlined in the flowchart as shown in Figure 3.

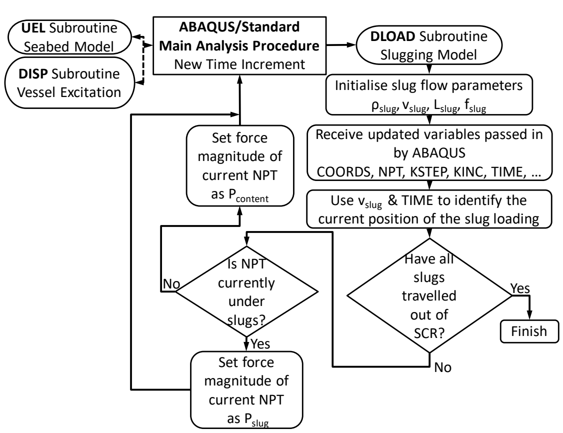

Figure 3. DLOAD subroutine internal flowchart.

The ABAQUS Multi-point constraints (MPC) user subroutine was coded to create a moving tie constraint interface modelling the moving slug. The main step in MPC is to determine and eliminate the dependent DOF of the slave node and transfer the information of the derivatives of the constraint function (A, see Figure 3) to ABAQUS for the redistribution of loads from the dependent DOF to other DOFs.

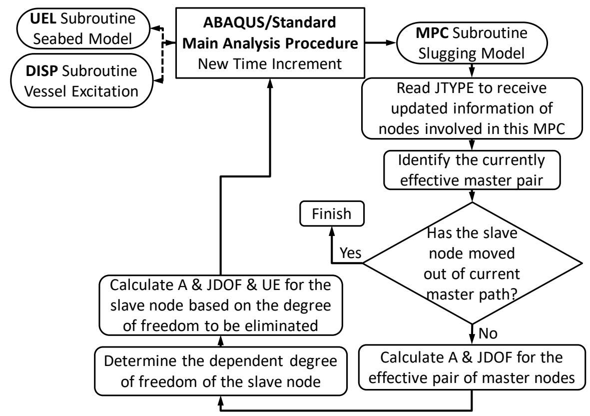

Figure 4. MPC subroutine internal flowchart.

3.3 Modelling of Seabed Soil

In this study, one of the most popular riser-seabed interaction models (Randolph and Quiggin 2009) have been coded in a UEL subroutine in ABAQUS to capture the effect of the nonlinear seabed on slug-induced oscillation and fatigue. The R-Q model was first coded by Shiri and Randolph (2010) in a user-defined element (UEL) to investigate the influence of seabed soil stiffness degradation and trench creation on wave-induced fatigue response of SCR. Figure 5 illustrates the analysis flowchart of the UEL subroutine incorporated in ABAQUS.

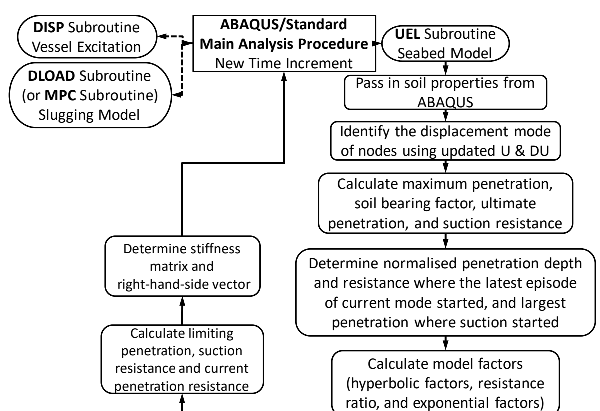

Figure 5. UEL subroutine internal flowchart.

3.4 Modelling of wave-induced vessel motions

A user-defined DISP subroutine was coded in FORTRAN and linked to the global SCR model in ABAQUS to incrementally update the vessel location through modelling two translations (surge and heave) and one rotation (pitch) through 2D displacement-controlled analysis. A similar methodology was originally proposed by Shiri and Randolph (2010). Figure 6 illustrates the schematic flow chart of DISP subroutine and its linkage with the main analysis procedure.

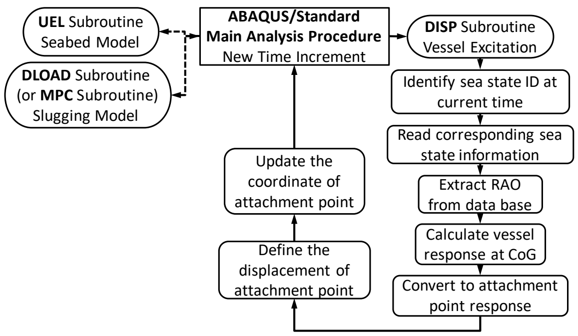

Figure 6. DISP subroutine flowchart.

4 PARAMETRIC STUDY

Comprehensive parametric studies were conducted to investigate the influence of cyclic seabed soil stiffness degradation and gradual SCR penetration into the seabed on slug-induced vibrations in the touchdown zone. The properties of SCR were given in Table 1. Effects of slug-induced, wave-induced and slug/wave-induced excitations were examined at the TDP respectively. Then slug/wave induced vibrations were further examined by conducting two groups of parametric studies. Slug parameters were examined both on the linear elastic seabed and the nonlinear hysteretic seabed using Table 7. Default parameter settings for the linear elastic seabed and nonlinear hysteretic seabed were given in Table 3 and Table 2. An estimated equivalent soil stiffness of 300 kPa was used to represent the elastic seabed (Randolph et al. 2013). Various nonlinear soil model parameters were examined to evaluate the impact of soil model parameters on system response to slugging, using Table 8 with the default slug parameters given in Table 4. Sea state information given in Table 5 was embedded in the numerical model and sea state #30 was selected and repeated for 10 cycles in all case studies. The hydrodynamic coefficients adopted in simulation are listed in Table 6.

Table 1. Riser pipe properties.(Dong and Shiri 2018)

Parameter	Symbol	Value	Unit
Outer diameter	D_o	0.324	M
Wall thickness	t	0.0205	m
Second moment of area	I	2.26×10^{-4}	m^4
Steel Young's Modulus	E_{steel}	2.07×10^{11}	N/m^2
Steel density	ρ_s	7850	kg/m^3
Fatigue S-N curve	$\bar{a}$	1.05×10^{12}	-
DNV (2008)	m	3.0	-
E Class weld	SCF	1.13	-

Table 2. Default parameters of R-Q soil models.

Parameter	Symbol	Valu	Unit
Mudline shear strength	s_{u0}	0.65	kPa
Shear strength gradient	ρ	1.5	kPa
Power law parameter	a	6	-
Power law parameter	b	0.25	-
Normalized maximum stiffness	K_{max}	200	-
Suction ratio	f_{suc}	0.3	-
Suction decay parameter	λ_{suc}	0.5	-
Re-penetration parameter	λ_{rep}	0.5	-

Table 3. Default elastic seabed parameters.

Elastic seabed	Equivalent vertical strength (kPa)	Equivalent shear strength (kPa)
Default	300	10

Table 4. Default slug flow parameters.

Parameter	Symbol	Value	Unit
Slug density	ρ_{slug}	600	kg/m^3
Bubble density	ρ_{bubble}	100	kg/m^3
Flow velocity	v_{slug}	10	m/s
Slug length	L_{slug}	30	m
Slug frequency	f_{slug}	180	/hr

Table 5. Wave scatter diagram for a 30-year operational life (GoM).

Sea State				
Bin #	H (m)	T (s)	Omni (1 year) p (-)	Omni (30 year) p (-)
1	0.5	4.2	600376	18011291
2	1	4.6	2379015	71370445
3	1.5	5	1614987	48449608
4	2	5.4	839595	25187856
5	2.5	5.8	450978	13529335
6	3	6.1	249122	7473660
7	3.5	6.5	102683	3080495
8	4	6.9	54367	1631014
9	4.5	7.3	19459	583770
10	5	7.7	12124	363725
11	5.5	8	3823	114700
12	6	8.4	1123	33676
13	6.5	8.5	564	16907
14	7	8.7	362	10864
15	7.5	8.9	181	5421
16	8	9.1	113	3389
17	8.5	9.3	100	3011

Sea State				
Bin #	H (m)	T (s)	Omni (1 year) p (-)	Omni (30 year) p (-)
18	9	9.5	61	1822
19	9.5	9.7	46	1395
20	10	9.9	36	1070
21	10.5	10.1	42	1246
22	11	10.2	19	566
23	11.5	10.4	31	928
24	12	10.6	18	544
25	12.5	10.7	27	813
26	13	10.9	24	712
27	13.5	11	29	877
28	14	11.2	9	262
29	14.5	11.3	11	343
30	15	11.5	14	420

Table 6. Hydrodynamic coefficients.

Drag (C_D)	Inertia (C_I)	Added mass (C_A)
0.7	1.5	1.0

Table 7. Parametric study map 1-slug parameters.

Case study	Input slug model parameter					
	ρ_{slug} (kg/m^3)	P_{bubble} (kg/m^3)	v_{slug} (m/s)	L_{slug} (m)	f_{slug} (/hr)	Seabed (E/N)
CS-1	D	D	D	D	D	E
CS-2	D	D	D	D	D	N
CS-3	700	D	D	D	D	E
CS-4	700	D	D	D	D	N
CS-5	D	150	D	D	D	E
CS-6	D	150	D	D	D	N
CS-7	D	D	25	D	D	E
CS-8	D	D	25	D	D	N
CS-9	D	D	D	50	D	E
CS-10	D	D	D	50	D	N
CS-11	D	D	D	D	100	E
CS-12	D	D	D	D	100	N
Note	D refers to "Default" values for slug model as described in Table 4. From CS-1 to CS-12, soil parameters in Table 2 were adopted for nonlinear seabed models and soil parameters in Table 3 were adopted for elastic seabed models.					

Table 8. Parametric study map 2-nonllinear seabed parameters.

Case study	Input soil model parameters				
	s_u	ρ	f_{suc}	λ_{suc}	λ_{rep}
CS-13	0.35	D	D	D	D
CS-14	0.95	D	D	D	D
CS-15	D	0.5	D	D	D
CS-16	D	1.0	D	D	D
CS-17	D	D	0.5	D	D
CS-18	D	D	1	D	D
CS-19	D	D	D	0.2	D
CS-20	D	D	D	1.0	D
CS-21	D	D	D	D	0.2
CS-22	D	D	D	D	0.8
Note	D refers to "Default" values for soil model as described in Table 2. From CS-13 to CS-22, slug parameters given in Table 4 were adopted for slug model.				

5 RESULTS

To give a direct view of the effects of wave and slug on SCR responses, time history outputs at TDP were investigated under vibrations induced by the slug, wave, and slug-wave respectively as predefined in CS-2 (see from Figure 7 to Figure 11). As shown in Figure 7 and Figure 8, the amplitude of resultant oscillations showed scattered results and the wave-induced oscillation amplitudes may be amplified or mitigated by the slug-induced oscillations depending on the oscillation phase angle.

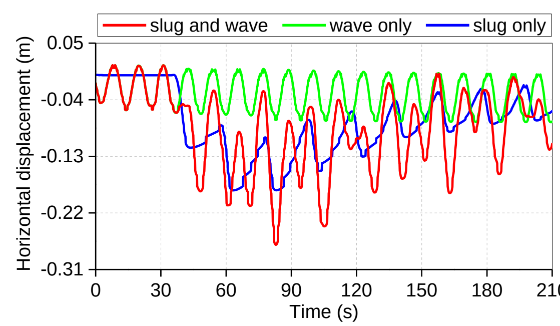

Figure 7. Time history of horizontal displacement at TDP.

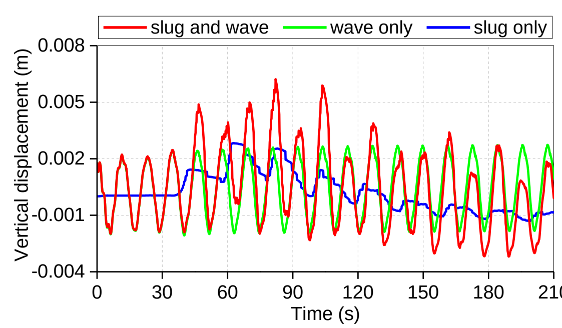

Figure 8. Time history of vertical displacement at TDP.

As shown in Figure 9 to Figure 11, there was a sharp increase in the amplitudes of bending moment, shear force, and maximum von Mises stress when the liquid slugs arrived at TDP. The resultant amplitudes changed every time and the maximum amplitudes showed approximately when the wave only case and the slug only case came to extreme values at almost the same time. For instance, in Figure 11, the peak amplitude of maximum von Mises stress at TDP occurred when the wave and slug phase angles met at about 100s.

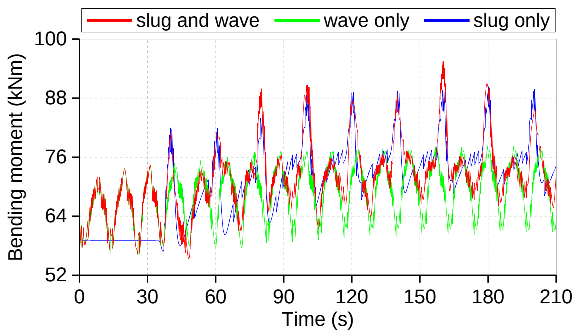

Figure 9. Bending moment of the TDP.

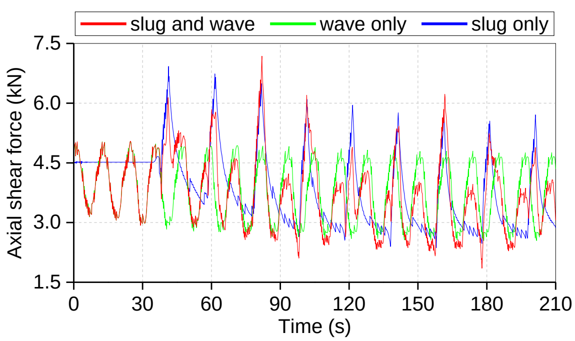

Figure 10. Shear force at TDP.

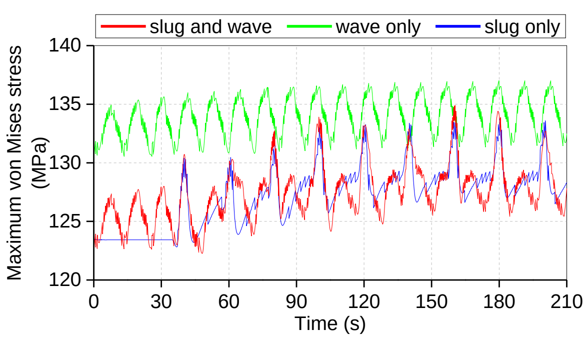

Figure 11. Maximum von Mises stress at TDP.

Two groups of parametric studies have been conducted as described in Section 4. The influence of the slug parameters was compared on the linear seabed model and the nonlinear seabed model in parametric study group 1 (see Table 7). Influence of nonlinear seabed soil parameters was compared in parametric study group 2 (see Table 8). Final riser profiles after 115 s slugging were given in Figure 12 to Figure 14. As shown in Figure 12, maximum penetration location is very dependent on the slug parameters. Slug density was investigated to have the most significant impact on the depth of penetration (see CS-4 in Figure 13). Changes in the value of soil parameters also resulted in significant differences among the final SCR profiles (e.g., CS-2, CS-13, change in mudline shear strength of soil, see Figure 14).

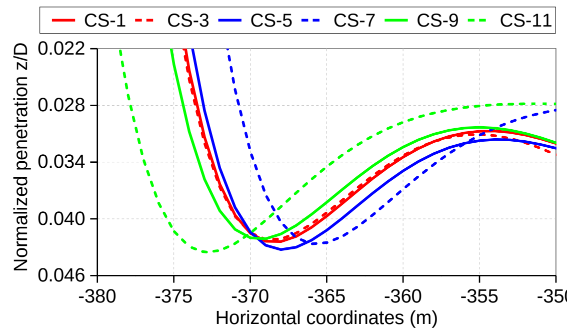

Figure 12. Final riser profiles from CS-1 to CS-11.

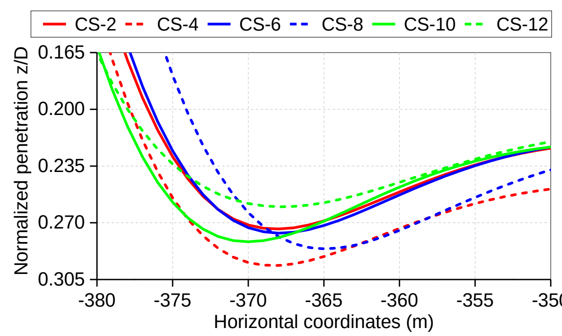

Figure 13. Final riser profiles from CS-2 to CS-12.

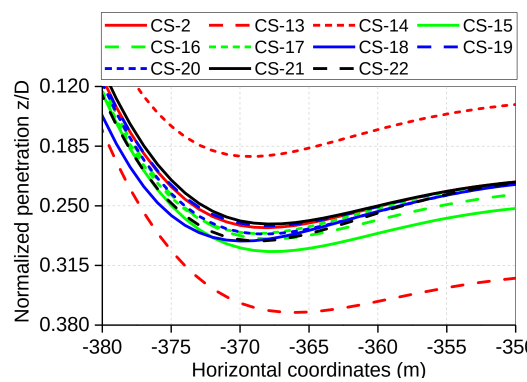

Figure 14. Final riser profiles from CS-13 to CS-22.

Variation of the von Mises stress is the key parameter for the fatigue damage evaluation of SCR. To explore the impact of slugging and nonlinear soil parameters on the trends of fatigue, distribution of maximum von Mises stress ranges were plotted in different case studies as shown in Figure 15 to Figure 17. Compared with the slight differences induced by the changes in soil parameters as examined in parametric study (see Figure 17), greater influences of slug parameters were observed, especially the slug density (see Figure 15). However, the results on elastic seabed and plastic seabed showed minor differences (see Figure 15 and Figure 16). This is because the stationary von Mises stress is mainly governed by the catenary configuration and bending curvature instead of the seabed soil model.

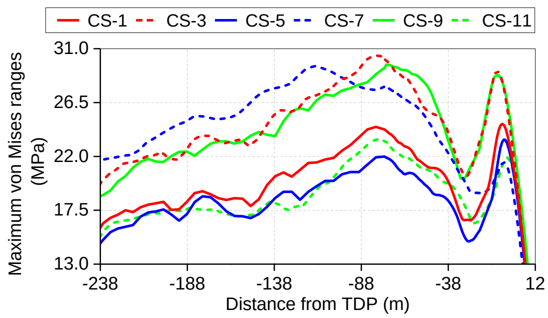

Figure 15. Effects of slug parameters on the distribution of the maximum von Mises stress ranges along SCR on elastic seabed.

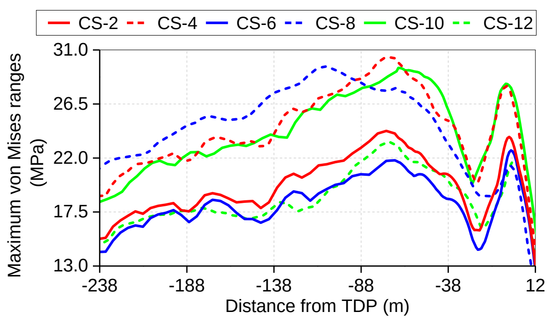

Figure 16. Effects of slug parameters on the distribution of the maximum von Mises stress ranges along SCR on nonlinear hysteretic seabed.

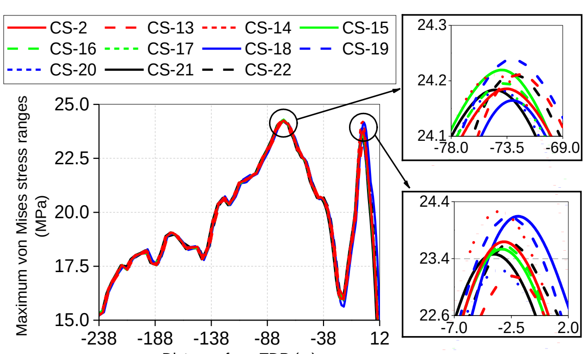

Figure 17. Effects of nonlinear soil parameters on the distribution of the maximum von Mises stress ranges along SCR on nonlinear hysteretic seabed

6 SUMMARY AND CONCLUSION

An advanced numerical model was developed to fill the knowledge gap in exploring the influence of complex nonlinear hysteretic riser-seabed interaction on slugging SCR. The model consists of slugging SCR, nonlinear hysteretic seabed, and the vessel excitation under the impact of environmental loads. A summary of the key conclusions can be listed as follows:

- The slug-induced oscillation and wave-induced oscillation show scattered results. Depending on the phase angles of oscillations, the slug-induced oscillation may amplify or mitigate the wave-induced oscillation at different times.
- Slug-induced oscillation significantly contributes to riser penetration into the seabed when it is coupled with wave-induced oscillation. This shall be further investigated for incorporation in any trench profile model.
- Final riser profiles on the elastic seabed and the nonlinear seabed with the same slug parameters show a difference in penetration depth. This may be caused by the capability of nonlinear seabed to consider the accumulation of penetration.
- The peak value point of the maximum von Mises stress range is located in the area close to the TDP. With a different slug model and soil model, the maximum point may fall on a different side of the TDP.
- The slug-induced fatigue damage of SCR on the nonlinear seabed is most likely to be slightly less than on the conventional elastic seabed as indicated by the distribution of the von Mises stress ranges. Therefore, it is conservative and less expensive to utilize the linear elastic seabed model in design.

7 ACKNOWLEDGEMENTS

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