# THE INFLUENCE OF SLUG CHARACTERISTICS ON OSCILLATION OF STEEL CATENARY RISERS IN THE NON-LINEAR HYSTERETIC SEABED

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## ABSTRACT

Steel catenary risers (SCR) are widely used in the development of offshore fields and are exposed to severe fatigue loads generated by environmental and operation loads. Slugging can induce SCR oscillations in the touchdown zone (TDZ) and cause the cyclic degradation of seabed soil. In this study, the influence of slug characteristics on SCR oscillation in the TDZ was comprehensively investigated by developing numerical models in ABAQUS with FORTRAN interfaces. The slugging characteristics such as density, length, velocity etc. have been examined together with the influence of non-linear hysteretic riser-seabed interaction, and complex vessel excitations. The study revealed several important trends of SCR response to slug-induced oscillations in the non-linear hysteretic seabed and consequently on accumulated fatigue damage in the TDZ.

## RÉSUMÉ

Les colonnes montantes de caténaires en acier (SCR) sont largement utilisées dans le développement de champs offshore et sont exposées à des charges de fatigue sévères générées par des charges environnementales et opérationnelles. Les slugging peuvent induire des oscillations de RCS dans la zone de toucher des roues (TDZ) et provoquer la dégradation cyclique des sols des fonds marins. Dans cette étude, l'influence des caractéristiques des bouchons sur l'oscillation de la RCS dans le TDZ a été largement étudiée en développant des modèles numériques dans ABAQUS avec des interfaces FORTRAN. Les caractéristiques de slugging telles que la densité, la longueur, la vitesse, etc. ont été examinées, ainsi que l'influence de l'interaction non linéaire hystérétique entre le riser et le fond marin et les excitations complexes des navires. L'étude a révélé plusieurs tendances importantes en matière de réponse SCR aux oscillations induites par les bouchons dans le fond marin hystérétique non linéaire et, par conséquent, aux dommages de fatigue accumulés dans le TDZ.

## 1 INTRODUCTION

Steel Catenary Risers (SCRs) are designed to deliver hydrocarbons from the sea floor and floating facilities with a catenary configuration. The subsea recordings show that the SCR penetrates into the seabed and creates a trench several diameters deep in the early stages after the installation. Several complex mechanisms contribute to the cyclic soil stiffness degradation and the gradual penetration of the SCR into the seabed. This has made the SCR fatigue assessment in the touchdown zone (TDZ) to be one of the most challenging issues in design practice. Various external loads contribute to the oscillation of SCR in the touchdown zone such as wave action (high-frequency), wind and surficial current action (low-frequency), and vortex induced vibrations. The SCR slugging is a common source of internal loads that contribute to the riser oscillations in the touchdown zone and consequently the fatigue life (Kansao et al. 2008, Ortega et al. 2012). Also, the slug-induced oscillation amplitudes may sum up to or subtract from wave-induced oscillations depending on the phase difference. Rigid or simple elastic springs are usually used as a simplified model of seabed soil in practice. However, comparing with the observations of complex riser-seabed-seawater interactions in the conducted subsea surveys, this approach is oversimplifying the riser-seabed interaction. These mechanisms 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.

In the literature, advanced nonlinear hysteretic riser-seabed interaction models have been proposed to explore the influence of these mechanisms on the wave and current-induced fatigue loads of the SCR (Shiri and Randolph 2010, Shiri 2014, Nakhaee and Zhang 2008, Kimiaei and Liao 2015, Clukey et al. 2017). However, the effect of the nonlinear hysteretic seabed soil response on slug-induced stress oscillations has never been investigated before. In this study, the impact of the nonlinear hysteretic seabed response and its consequences on slug-induced responses and potential fatigue of the SCR were comprehensively investigated as an important knowledge gap. Also, the model parameters and equations are not fully accessible in the commercial software with built-in slugging and soil models. Therefore, an advanced numerical model was developed using ABAQUS to address a series of severe nonlinearities in model geometry, material behaviour, environmental, and functional loads. Several user-defined subroutines (e.g., UEL, MPC, and DISP) were developed in FORTRAN and linked to the ABAQUS to model slugging regimes, nonlinear hysteretic riser-seabed interaction, and various vessel excitation modes (including wave and low-frequency motions) under the act of environmental loads. Cyclic seabed soil stiffness degradation and consequently the trench formation in the touchdown zone were greatly influenced by the slug-induced oscillations of SCR. The necessity of the accurate modelling of the plastic seabed response in slug-induced fatigue analysis of SCRs was also indicated in the results of parametric studies. With full administration to customize plastic seabed soil condition, vessel excitation, and complex slugging regimes, the numerical model developed in this study was found to be a robust tool for advanced slug-induced fatigue analysis of SCR.

Considering a full examination of slug parameters, the system response to the nonlinear seabed has been entirely investigated in terms of the SCR cyclic profile changes and the maximum von Mises stress ranges in the TDZ with different slug patterns. However, to facilitate reading the paper, a summary of the developed numerical model was also included in this paper. Before discussing the developed model and the analysis results, it is worth reviewing the published key research works conducted on modelling of the slugging SCRs and also the riser-soil interaction that will be presented in the next section.

## 2 LITERATURE REVIEW

The slugging contributes to the vertical oscillation of SCR in the touchdown zone, where the riser comes to cyclic contact with the seabed soil. This cyclic contact causes the progressive soil stiffness degradation and gradual penetration of the SCR into the seabed. The slugging-induced oscillations may be combined with other kinds of motions such as wave and low-frequency vessel motions and vortex-induced vibrations. The gradual softening of the seabed soil and the trench creation affect the cross-sectional stress oscillation range and consequently the fatigue life in the touchdown zone. The influence of cyclic soil softening on the wave and current-induced fatigue damage of SCR has been well explored in the literature (Shiri and Randolph 2010, Clukey et al. 2017, Dong and Shiri 2018, Dong and Shiri 2019a). However, there is no published work to investigate the effect of seabed soil stiffness degradation on slug-induced vibrations.

Bordalo et al. conducted a laboratory-scale model test to explore the dynamic response of catenary part of the riser to the internal two-phase flow. With seabed end considered as pinned, the tests were conducted with different flow patterns (slug, intermittent and annular) and flow rates (Bordalo et al. 2008). It was concluded that magnitude of whipping increased when a transition is presented between the slug and intermittent patterns or between the intermittent and annular patterns. Besides, when the air flow rates increased, the magnitudes of whipping and variation of the sustaining force at the top increased. Pollio and Mossa compared two simple models of slug flow in a long flexible marine riser (with and without elastic seabed model) (Pollio and Mossa 2009). The riser-seabed interaction was considered with a simplified normal reaction force as a function of the relative displacement and the friction force in the opposite direction of the nodal velocity. The results showed that irregular inner stress responses might be generated by the slug flow with variable frequency, while the tension and moment variations were found to be more regular under the flow with a constant frequency. The authors observed a significant difference in variation of the bending moment in the seabed existence case and seabed absence case. The greater magnitude of bending moment variation and greater probability of higher stress in riser were induced by the slug flow with variable frequency. Gundersen et al. conducted a case study on the remnant fatigue life of flexible risers in lazy-S configuration subjected to combined wave and slug-induced motions (Gundersen et al. 2012). Commercially available global and local riser analysis tools (i.e., RIFLEX and BFLEX) were coupled to build the adopted model. They observed that the slugging dominated the dynamic top angle response and significantly reduced the riser fatigue life during a relatively calm sea condition. Ortega et al. investigated the influence of slug loading on the dynamic responses of a flexible riser in lazy wave configuration (Ortega et al. 2012). The authors coupled two distinct codes for slug flow tracking (SLUGGIT) and riser structure (RISANANL). With seabed end of SCR assumed as pinned, the results showed that depending on the characteristic of slug flow, irregular deformation time histories might be generated. This indicated the importance of considering the effects of slug flow in the fatigue analysis. A fully-coupled analysis was conducted later by Ortega et al. to examine the response of catenary flexible riser to the combined effect of slugging and wave loads (Ortega et al. 2013). It was shown that the internal slug flow might result in irregular deformation time histories. Chatjigeorgiou established an analytical approach and examined the combined effects of harmonic motions of the vessel and the internal slug flow on the dynamic response of catenary pipelines (Chatjigeorgiou 2017). The slug flow terms were incorporated into the model formerly built by Chatjigeorgiou with the seabed end considered as pinned (Chatjigeorgiou 2010). It was shown that the magnitudes of dynamic components may be amplified due to the existence of internal slug flow. Bordalo et al. incorporated a slug flow model into a 3D pipeline dynamics simulator (Bordalo et al. 2018). 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.

As mentioned earlier, the literature review shows that the effect of the cyclic seabed stiffness evolution on slug-induced stress oscillations has not been explored before. This might be due to the need for simultaneous modelling of several complex aspects related to different engineering disciplines including the nonlinear hysteretic riser-seabed interaction, slug loading, and vessel motions. However, this is an important knowledge gap and the current study has tried to explore it and fill the gap. In the next section, the previous efforts on the development of cyclic seabed soil stiffness degradation and its impact on the wave and current-induced fatigue damage will be briefly reviewed to facilitate reading the paper.

The riser-seabed interaction in design codes is usually modelled by traditional linear springs. After first experience of SCR technology in the Auger field of the Gulf of Mexico (Phifer et al. 1994), the STRIDE and CARISIMA JIPs (1999-2001) were the first studies to investigate the need for more sophisticated nonlinear riser-seabed interaction models (Theti and Moros 2001, Campbell 1999). A model was developed by Bridge et al. to simulate various nonlinear aspects of soil behaviour through full-scale harbour tests Bridge et al. (Bridge et al. 2004, Bridge et al. 2007). It was similar in form to the hyperbolic pipe-soil interaction curve proposed by Hardin and Drnevich that was originally established for clay by Kondner (Hardin and Drnevich 1972, Kondner 1963). However, the model was unable to sequentially simulate the gradual seabed soil softening and riser embedment to the seabed. Jiao proposed two nonlinear non-degradating and degradating spring models for soils beneath the SCR (Jiao 2007).The degradating model works well in simulating cyclic softening of the soil but only through the re-loading paths. Based on the work conducted by Jiao, a new model was proposed by Aubeny and Biscontin to simulate the nonlinear hysteretic soil behaviour under the riser, which was further improved by Nakhaee and Zhang (Aubeny and Biscontin 2009, Nakhaee and Zhang 2010). The model overcame the shortcomings of Jiao's model, but still adopted the non-uniform set of equations. Another nonlinear model was developed by Randolph and Quiggin (hereinafter referred to as R-Q model) with more unified sets of equations to define the hysteretic soil behaviour interacting with a riser under vertical oscillations using a combination of hyperbolic and exponential functions (Randolph and Quiggin 2009). Shiri and Randolph developed a finite element model and a user-defined element in ABAQUS to conduct series of fatigue studies using the R-Q model (Shiri and Randolph 2010). A series of centrifuge tests was conducted by Elliott et al. and the soil response to complex riser excitations was examined (Elliott et al. 2013). The results of these tests will be used as a key reference in achieving the first and third short-term objectives of this program. A new trenching model was proposed by Randolph et al. to study SCR fatigue, which was an important step in developing simplified fatigue assessment methods (Randolph et al. 2013). Different time loading histories on SCR fatigue response in a nonlinear seabed were examined by Kimiaei and Liao (Kimiaei and Liao 2015). Authors identified the most influential components of vessel motions on fatigue life. Liu et al. developed a new user-defined subroutine to implement the nonlinear seabed response to SCR fatigue analysis (Liu et al. 2016). Clukey et al. (2017) reported the state of knowledge of riser-soil interaction and its impact on fatigue assessment (Clukey et al. 2017). Authors emphasized on significance of nonlinear riser-soil interaction models and need for further improvement of these models for fatigue analysis of steel catenary risers in the touchdown zone. Dong and Shiri comprehensively investigated the performance of R-Q model (Dong and Shiri 2018, Dong and Shiri 2019a). The R-Q model was found to have strong features and potentially an appropriate approach for modelling the nonlinear riser-seabed interaction. However, it was observed that the model needed further improvement to explicitly model the trench formation and resolve some nodal inconsistencies. The advantages of this model in automotive simulation of cyclic soil stiffness degradation and SCR penetration into the seabed have made it a popular model.

In this study, considering the limited access to the model parameters in commercial software, the R-Q model was coded in UEL subroutine and implemented into the global SCR model in ABAQUS to incorporate the effect of nonlinear hysteretic seabed on slug-induced fatigue loads. The emphasis is made on the influence of slug patterns on the response of the riser. Various slug parameters have been explored using the parametric study.

## 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. The global SCR configuration was adopted from Dong and Shiri (2018) (see **Figure 1**).

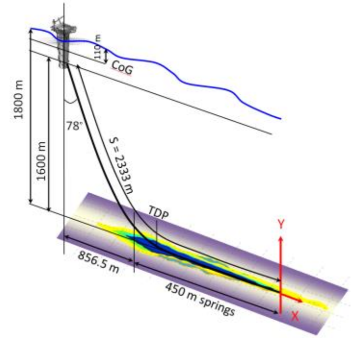


Figure 1. The global geometry of SCR modelled by ABAQUS.

### 3.2 Modelling of SCR Slugging

As illustrated in **Error! Reference source not found.**, 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). The MPC/DLOAD subroutine coded in FORTRAN is frequently called by the main code to execute the slugging by capturing the frequency, velocity, weight, and length of the slug flow.

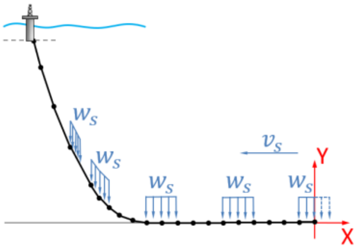
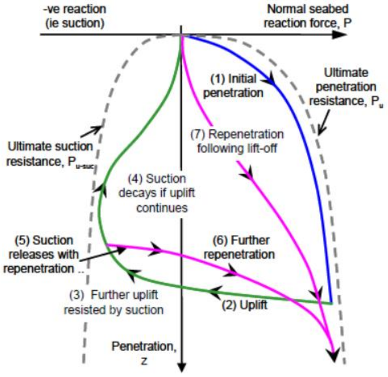


Figure 2. Slug characteristics capture.

## 3.3 Modelling of non-linear seabed

In this study, the nonlinear riser-seabed interaction is coded in UEL subroutine according to the interaction models proposed by Randolph and Quiggin (Randolph and Quiggin 2009) 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 wave-induced fatigue response of SCR. Initial penetration, uplift, break out, and re-penetration have been considered as 4 main episodes in the subroutine (see Figure 3).



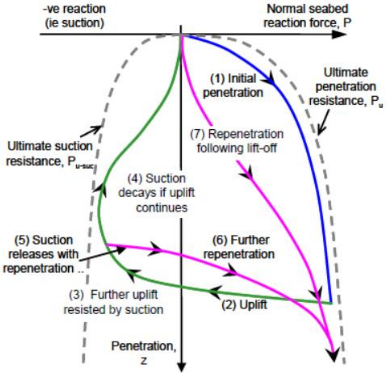


Figure 3. R-Q soil model for different modes (Randolph and Quiggin 2009)

## 3.4 Modelling of wave-induced vessel motions

A user-defined DISP subroutine was coded in FORTRAN for the SCR vessel-end motion excited by the waves. Information of waves are transferred to the excited motions and the displacement controlled motion will then be executed to the at the vessel end of the SCR. A similar methodology was originally proposed by Shiri and Randolph (2010).

## 4 MODEL SETTINGS

The slug-induced vibrations of SCR in TDZ with different slug patterns were explored using parametric study. The properties of SCR were given in Table 1. Vibrations induced by slug/wave or wave only on elastic seabed and nonlinear seabed have been examined respectively to show the different vibration modes and influence of seabed properties. Properties for the linear elastic seabed and nonlinear hysteretic seabed could be found in

Table 3 and Table 2. The influence of slug density, flow velocity, length and slug frequency were explored respectively on the nonlinear hysteretic seabed according to Table 7. Sea state information given in Table 5 was embedded in the numerical model using DISP subroutine developed using FORTRAN code. Sea state #30 was selected and repeated for 10 cycles in all case studies as the excitation for vessel end motions. The hydrodynamic coefficients are listed in Table 6.

Table 1. Riser pipe properties**Error! Reference source not found.**(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 | $2.26\times10^{-4}$ | $m^4$ |
| Steel Young's Modulus | $E_{steel}$ | $2.07\times10^{11}$ | $N/m^2$ |
| Steel density | $\rho_s$ | 7850 | $kg/m^3$ |
| Fatigue S-N curve | $\bar{\alpha}$ | $1.05\times10^{12}$ | - |
| DNV (2008) | m | 3.0 | - |
| E Class weld | SCF | 1.13 | - |

Table 2. Default parameters of R-Q soil models. (Dong and Shiri 2019b)

| 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 | $\lambda_{suc}$ | 0.5 | - |
| Re-penetration parameter | $\lambda_{rep}$ | 0.5 | - |

Table 3. Default elastic seabed parameters. (Dong and Shiri 2019b)

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

Table 4. Default slug flow parameters. (Dong and Shiri 2019b)

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Slug density | $\rho_{slug}$ | 600 | kg/m$^3$ |
| Bubble density | $\rho_{bubble}$ | 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 |
| 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. (Dong and Shiri 2019b)

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

Table 7. Parametric study-slug patterns. (Dong and Shiri 2019b)

| Case study | Input slug model parameter | | | | | |
|---|---|---|---|---|---|---|
| | $\rho_{slug}$ (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 | N |
| CS-4 | D | 150 | D | D | D | N |
| CS-5 | D | D | 25 | D | D | N |
| CS-6 | D | D | D | 50 | D | N |
| CS-7 | 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-7, soil parameters in Table 2 were adopted for nonlinear seabed models and soil parameters in Table 3 were adopted for elastic seabed models. | | | | | |

## 5 RESULTS

Stress variations ranges from CS-2 to CS-7 are plotted in Figure 4. During load cycles, the variation range of the von Mises stress is the main parameter for the calculation of SCR fatigue life. The slug characteristics show a significant impact on von Mises stress distribution, particularly the slug density (highest value is obtained in CS-3 with heaviest slug density). Also, the slug characteristics affect the location of the peak von Mises stress ranges. The peak point in CS-4 occurred on the right hand of the peak point in CS-2, while in CS-5 the peak point is obtained on the left hand of the peak point in CS-2.

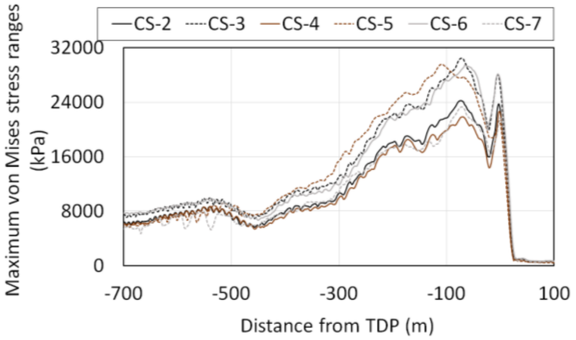


Figure 4. Influence of slug parameters on the von Mises stress.

Compared Figure 5 and Figure 6, the difference in penetration depths of wave/slug combined-induced vibration and of slug induced vibration could hardly be identified. However, in Figure 7 and Figure 8, the difference in penetration depth can be clearly observed due to the accumulation ability of non-linear seabed. Wave-induced vibration has contributes to the deeper penetration of SCR into the non-linear seabed especially at the region around TDP.

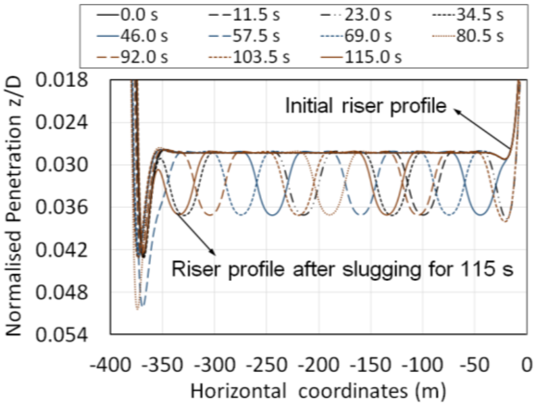


Figure 5. CS-1-wave/slug combined.

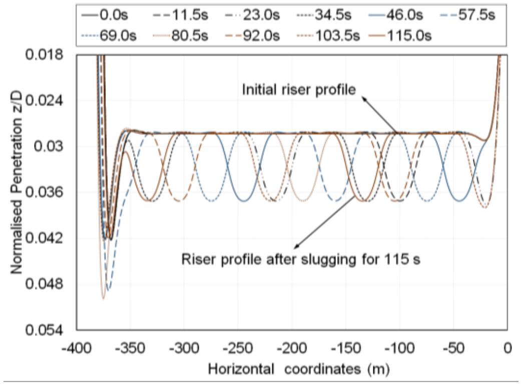


Figure 6. CS-1-slug induced.

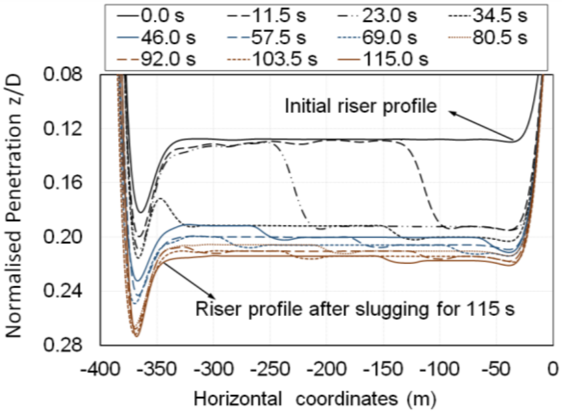


Figure 7. CS-2-wave/slug combined.

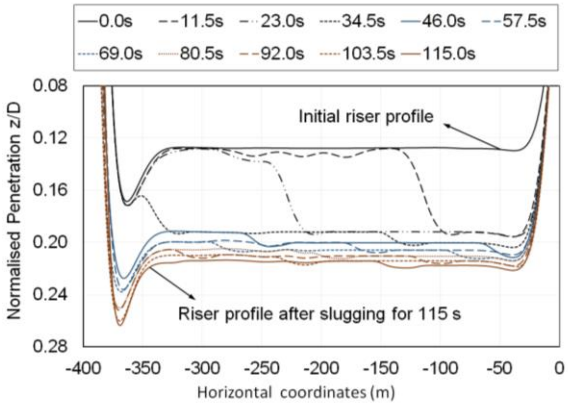


Figure 8. CS-2-slug induced.

As shown in Figure 9, Figure 10, and Figure 11, the location of the peak value of maximum shear force during the fatigue loads cycles are determined mainly by the slug induced vibrations. In the wave induced vibration, the peak value showed on the right side of the TDP (see point $P_b$ in Figure 9). While the peak in slug induced vibration is located on the left side of the TDP (see $P_a$ in Figure 10).

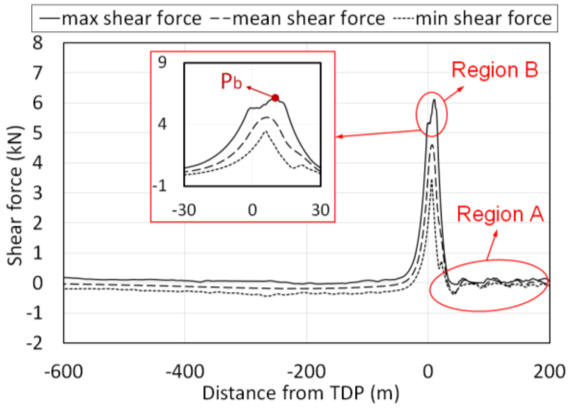


Figure 9. CS-2-wave induced.

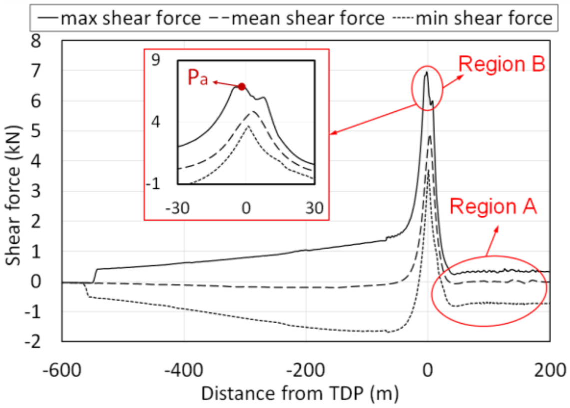


Figure 10. CS-2-slug induced.

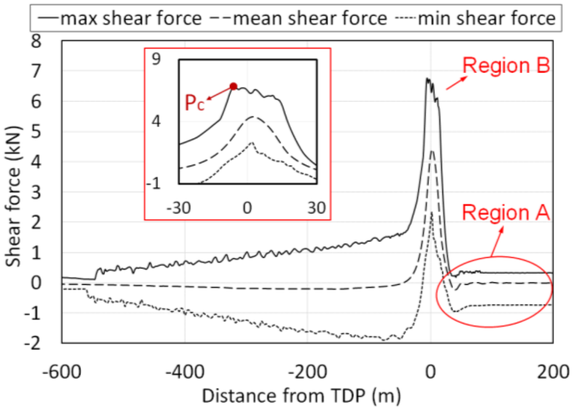


Figure 11. CS-2-wave/slug combined.

As shown from Figure 12 to Figure 16, riser profiles were recorded in case studies with different slug parameters. When slug density was increased, the normalised penetration at bottom point increased from 0.274 (CS-2, see Figure 7) to 0.296 (CS-3, see Figure 12) at 115 s. By increasing the density of gas, slight deeper penetration could be found (CS-4, see Figure 13) while the initial normalised penetration in the middle region (horizontal coordinates between -300 m and -100 m) can be clearly observed to increase from 0.128 (CS-2, see Figure 7) to 0.134 (CS-4, see Figure 13). When the velocity of slug was increased from 10 m/s (CS-2, see Figure 7) to 20 m/s (CS-5, see Figure 14), longer portion at the right section of riser has deep penetration and the normalised penetration at bottom point increased from 0.231 (CS-2, see Figure 7) to 0.249 (CS-5, see Figure 14) at 46.0 s. But this increase may be caused by the time picked up for plotting.

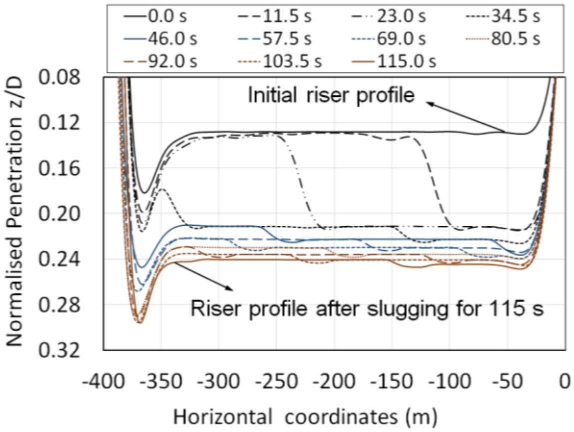


Figure 12. CS-3.

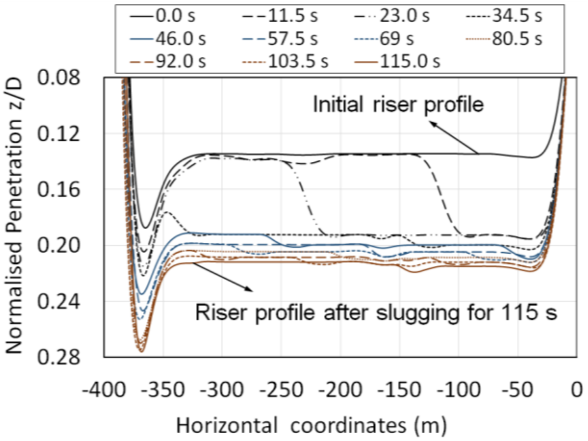


Figure 13. CS-4.

In CS-6, slug was set with longer length and this could be observed in Figure 15 and noting that the largest normalised penetration in CS-6 (Figure 15) increased comparing with CS-2 (Figure 7). Compared riser profiles in Figure 7 and Figure 16, higher frequency of slug flow will effect the vibration modes of the SCR in TDZ but rarely affect the penetration depth of SCR into the seabed. Within same period, longer oscillation distance is obtained when the slug frequency is higher, that is, more slugs travelled through the SCR due to the shorter interval between generation of slugs.

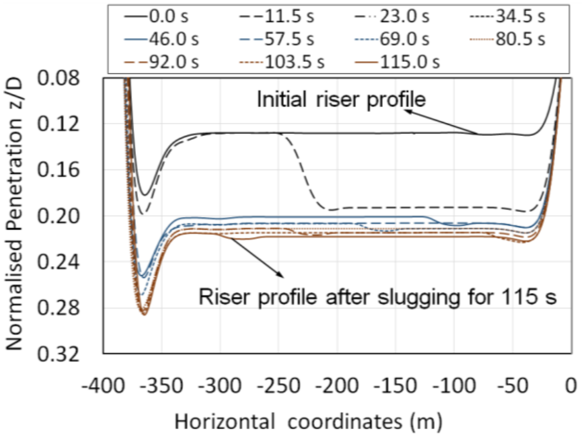


Figure 14. CS-5.

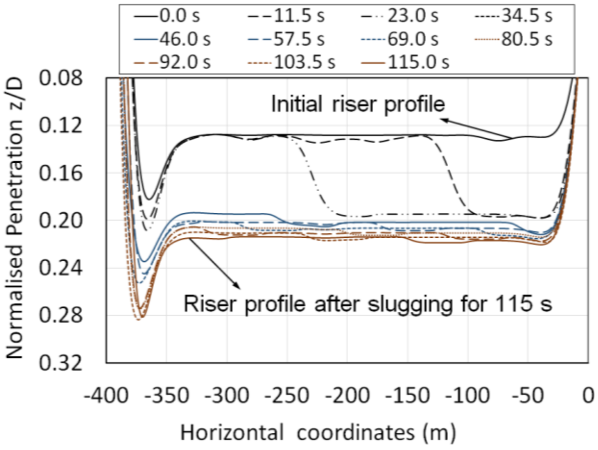


Figure 15. CS-6.

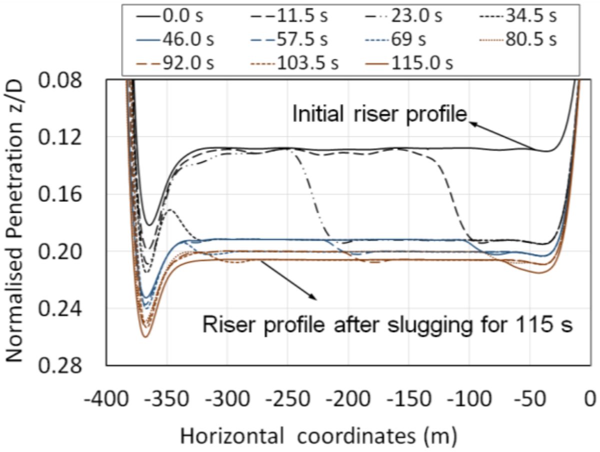


Figure 16. CS-7.

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## 6 SUMMARY AND CONCLUSION

Aa parametric study was performed using the developed numerical model in Abaqus. Various slug parameters (slug density, length, velocity and frequency) have been fully examined for the SCR laid on non-linear hysteretic seabed with vessel end excited by wave. The key conclusions can ba highlighted as follows:

- The study showed that the fluctuations of SCRs induced by slugging together with non-linear seabed soil degradation might have a significant influence on stress variation distribution along SCRs and decrease the fatigue life.
- 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.
- The slug density and length were found to have a significant impact on oscillations.
- It was observed that the slug frequency and velocity affect the oscillation modes particularly when they are combined with wave-frequency vessel motions. This may be caused by the capability of nonlinear seabed to consider the accumulation of penetration.
- The seabed soil properties showed a significant influence on slug-induced oscillations.
- The study revealed several important trends of SCR response to slug-induced oscillations in the non-linear hysteretic seabed and consequently on accumulated fatigue damage in the TDZ.

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## 8 REFERENCES

Aubeny, C.P., Biscontin, G. 2009. Seafloor–riser interaction model, *Int J Geomechanics*, 9: 133-141.

Bordalo, S.N., Morooka, C.K., Cavalcante, C.C.P. 2008. Whipping phenomenon caused by the internal flow momentum on the catenary risers of offshore petroleum fields, in: *Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering*, Estoril, Portugal, OMAE 2008-57351.

Bordalo, S.N., Morooka, C.K. 2018. Slug flow induced oscillations on subsea petroleum pipelines, *Journal of petroleum science and engineering* (In press, accepted manuscript).

Bridge, C., Laver, K., Clukey, E., Evans, T. 2004. Steel catenary riser touchdown point vertical interaction models, in: *Offshore Technology Conference*, OTC16628, Houston, Texas.

Bridge, C., Howells, H. 2007. Observations and modeling of steel catenary riser trenches, in: *17th International Offshore and Polar Engineering Conference*, ISOPE2007, Lisbon, Portugal.

Campbell, M. 1999. The complexities of fatigue analysis for deepwater risers, in: *Proceedings of the 2nd International Deepwater Pipeline Technology Conference*.

Chatjigeorgiou, I.K. 2010a. Three dimensional nonlinear dynamics of submerged, extensible catenary pipes conveying fluid and subjected to end-imposed excitations, *International Journal of Non-linear Mechanics* , 45: 667-680.

Chatjigeorgiou, I.K. 2010b. On the effect of internal flow on vibrating catenary risers in three dimensions, *Engineering structures*, 32: 3313-3329.

Chatjigeorgiou, I.K. 2017. Hydroelastic response of marine risers subjected to internal slug-flow, *Applied Ocean Research* , 62: 1-17.

Clukey, E.C., Aubeny, C.P., Zakeri, A., Randolph, M.F., Sharma, P.P., White, D.J., Sancio, R., Cerkovnik, M. 2017. A Perspective on the state of knowledge regarding soil-pipe interaction for SCR fatigue assessments, in: *Offshore Technology Conference*, Houston, Texas, OTC27564-MS.

Dong, X., Shiri, H. 2018. Performance of non-linear seabed interaction models for steel catenary risers, part I: Nodal response, *Journal of Ocean Engineering*, 154: 153-166.

Dong, X., Shiri, H. 2019a. Performance of non-linear seabed interaction models for steel catenary Risers, part II: Global response, *Applied Ocean Research,82:* 158-174.

Dong, X., Shiri, H. 2019b. The influence of nonlinear hysteretic seabed interaction on slug-induced stress oscillations in steel catenary risers. *Applied Ocean Research,82:* 175-190.

Elliott, B.J., Zakeri, A., Barrett, J., Hawlader, B., Li, G., Clukey, E.C. 2013. Centrifuge modeling of steel catenary risers at touchdown zone Part II: Assessment of centrifuge test results using kaolin clay, *Ocean Engineering*, 60: 208-218.

Gundersen, P., Doynov, K., Andersen, T., Haakonsen, R. 2012. Methodology for determining remnant fatigue life of flexible risers subjected to slugging and irregular waves, in*: Proceedings of the ASME 2012 31st Int Conf on Ocean, Offshore and Arctic Engineering*, OMAE 2012, July 1-6, Rio de Janeiro, Brazil.

Hardin, B.O., Drnevich, V.P. 1972. Shear modulus and damping in soils: Measurement and parameter effects (Terzaghi Lecture). Journal of the Soil Mechanics and Foundations Division; 98 (6): 603-624.

Jiao, Y. 2007. Non-linear load-deflection models for Seafloor Interaction with Steel Catenary Risers. Texas A&M University, College Station, USA. Master of Science, 2007.

Kansao, R., Casanova, E., Blanco, A., Kenyery, F., Rivero, M. 2008. Fatigue life prediction due to slug flow in extra long submarine gas pipelines, in: *Proceedings of the ASME 2008 27th Int Conf on Offshore Mechanics and Arctic Engr*, OMAE2008, Estoril, Portugal, 3: 685-692.

Kimiaei, M., Liao, J. 2015. Effects of different loading time histories on fatigue design of steel catenary risers using nonlinear riser-soil interaction models, in*: Frontiers in Offshore Geotechnics III*, Norway, Trondheim.

Kondner, R.L. 1963. Hyperbolic stress-strain response; cohesive soils. Journal of the Soil Mechanics and Foundations Division; 89 (1): 115-143.

Liu, J., Kimiaei, M., Randolph, M. 2016. A new user defined element for nonlinear riser-soil interaction analysis of steel catenary riser systems. In: ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2016.

Nakhaee, A., Zhang, J. 2008. Effects of the interaction with the seafloor on the fatigue life of a SCR, in: *Int Offshore and Polar Engr Conf*, Vancouver, BC, Canada.

Nakhaee, A., Zhang, J. 2010. Trenching effects on dynamic behavior of a steel catenary riser, *Ocean Engineering*, 37(2–3):277–288.

Ortega, A., Rivera, A., Nydal, O.J., Larsen, C.M. 2012. On the dynamic response of flexible risers caused by internal slug flow, in: *Proceedings of the ASME 2012 31st Int Conf on Ocean, Offshore and Arctic Engineering*, OMAE2012, Rio de Janeiro, Brazil, 5: 647-656.

Ortega, A., Rivera, A., Larsen, C.M. 2013. Flexible riser response induced by combined slug flow and wave loads, in: *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, OMAE2013, Jun 9-14, Nantes, France.

Phifer, E.H., Kopp, F., Swanson, R.C., Allen, D.W., Langner, C.G. 1994. Design and installation of Auger steel catenary risers, in: *Offshore Technology Conference*, OTC7620, Houston, Texas.

Pollio, A., Mossa, M. 2009. A comparison between two simple models of a slug flow in a long flexible marine riser, Thesis.

Randolph, M.F., Quiggin, P. 2009. Non-linear hysteretic seabed model for catenary pipeline contact, in: *28th International Conference on Ocean, Offshore and Arctic Engineering*, OMAE 2009, Honolulu, Hawaii, USA.

Randolph, M., Baht, S., Jain, S., Mekha, B. 2013. Modeling the touchdown zone trench and its impact on SCR fatigue life, in: *Offshore Technology Conference*, Houston, OTC23975.

Shiri, H. 2014. Influence of seabed trench formation on fatigue performance of steel catenary risers in touchdown zone, *Journal of Marine Structures*, 36: 1-20.

Shiri, H., Randolph, M.F. 2010. Influence of seabed response on fatigue performance of steel catenary risers in touch down area, in: *29th International Conference on Ocean, Offshore and Arctic Engineering*, Shanghai, China, 5: 63-72.

Theti, R., Moros, T. 2001. Soil interaction effects on simple-catenary riser response, *Pipes and Pipelines Int.*; 46 (3): 15-24.