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An Influence of Trench Formation on Steel Catenary Risers Based on a Hysteretic Nonlinear Seabed Model

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Abstract

A steel catenary riser (SCR) attached to a floating platform at its upper end encounters fluctuations in and near its touchdown zone (TDZ), which causes the interaction with the seabed. Subsea surveys and the analysis of SCR's indicated that the greatest stress and highest damage occurred near the touchdown point (TDP), where the SCR first touches the seabed. Nowadays, the linear seabed spring is carried out, and it is assumed as a flat seabed. Improved nonlinear hysteretic seabed models have recently been proposed, which simulate the different stiffness in the seabed response in the TDZ. In this study, an advanced hysteretic nonlinear SCR-seabed soil interaction model has been implemented to simulate the exact behavior of the riser in the vicinity of the touchdown zone. This paper focusses on the seabed trench, which develops progressively under the SCR due to repeated contact. Also, different important parameters such as water depth and material of riser have been investigated based on the Caspian Sea environmental conditions. This paper highlights the impact of trenches of different depths on the fatigue performance of riser at TDZ.

Keywords: Steel Catenary Riser, Riser Response, Riser-Soil Interaction, Hysteretic Seabed Model

1. Introduction

Steel catenary risers (SCR's) have been associated with floating platforms since the mid-1990's and were first used as export risers for the Auger TLP (Phifer et al., 1994). Since then, they have been used progressively for more severe applications. They have been used as export risers for semisubmersibles and as production risers for FPSO's (Serta and Mourelle, 1997). SCR's are the subject of much ongoing research, particularly with respect to interaction with the seabed, fatigue, and vortex induced vibration (VIV) (Edwards et al., 1999). The remote operating vehicles (ROV) survey results show that trenches with a depth as deep as several riser diameters can be developed beneath the steel catenary risers. Therefore, an important question with respect to the riser–seabed interaction is about the riser trench formation effects on the riser fatigue performance in the touchdown zone (TDZ) (Bridge and Howells, 2007). Nowadays, the linear seabed spring is carried out, and it is assumed as a flat seabed. Improved nonlinear hysteretic seabed models, which simulate the different stiffness in the seabed response in the touchdown zone, have recently been proposed. Recent research studies have focused on improving the

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riser-soil interaction. The nonlinear seabed interaction model considers the cyclic loading, riser embedment, and the mechanism of the soil suction. Furthermore, it emphasizes the level of conservatism which exists in the current linear model. Elosta et al. (2013a) developed a SCR–soil interaction mechanism to provide a realistic technique to predict the dynamic response and the structural behavior of the SCR in the TDZ. Shiri and Randolph (2010) indicated that the nonlinear hysteretic seabed model is able to generate deep trenches by adopting the extreme values of the model parameters such as the re-penetration delay (λ_{suc}) and maximum suction parameter (f_{suc}). Moreover, the study of Elosta et al. (2013b) indicated that the probability of failure is associated with the fatigue analysis of a catenary pipeline in the TDZ due to the uncertainty in seabed response model and geotechnical parameters. Bai et al. (2015) investigated the significance of riser-soil interaction on the fatigue damage of SCR's for deepwater developments and confirmed the dynamic response of an SCR by using the nonlinear time domain analysis. Wang et al. (2013) indicated that the trenching development is caused by the decreasing the fatigue damage near the touchdown point (TDP). The study of Nakhaee and Zhang (2010) indicated that trenching development gives lower bending moment variation in the touchdown zone. In addition, due to cyclic loading, the results show that the trenching is gradually developed on the seabed.

In this study, a more realistic approach is developed for simulating the interaction between a SCR and the seabed. This paper focusses on the seabed trench, which develops progressively beneath the SCR due to repeated contact. The significance of the geometry of SCR, wave and current directions, and SCR-seabed soil interaction are discussed using the OrcaFlex finite element program for a nonlinear time domain simulation with a robust meshing technique. The numerical results of the SCR's response, which are fully coupled with a semisubmersible with considering a critical point in the TDZ, are presented. The nonlinear hysteretic seabed model extracted with Randolph and Quiggin (2009) is implemented into the seabed enabling the automatic simulation of different stiffness in the seabed response through the touchdown zone and the gradual embedment of riser. In addition to the application of a *P*–*y* curve (where *P* represents the supporting force of the soil, and *y* is the vertical penetration of the pipe in to the soil) to simulating the seabed displacement during its interaction with the pipe, Aubeny and Biscontin (2009) consider the trench formation caused by the continuous contact of a pipe on the soil and its continuous effect on the changes of the bending moment in the riser. This research spotlights the effect of trenches of various depths on the fatigue performance of SCR's in the TDZ. The findings indicate that the trenching formation on the seabed may lead to a decrease in the maximum variation of bending moment of a steel pipe near its touch down zone. Since the variation of bending moment ordains the fatigue behavior of the SCR, the results based on this approach show that the formation of the trench at the seabed is likely to increase the fatigue life of the riser. Therefore, it may have a crucial application in the design of marine risers. Additionally, different important parameters such as water depth and material of riser have been investigated based on the Caspian Sea environmental conditions.

2. Nonlinear riser–seabed interaction model approach

Recent SCR models are implemented so as to estimate the interaction between the soil and steel catenary risers. The nonlinear seabed model is more complicated than the simple linear model which simulates the nonlinear hysteretic interaction of the soil in the vertical direction, including the consideration of soil suction effects. A nonlinear mathematical model was introduced by Randolph and Quiggin (2009) for the cyclic riser–soil interaction in the contact area (TDZ), which is based on hyperbolic secant stiffness formulation, similar to those introduced by Bridge et al. (2004) and Aubeny and Biscontin (2009). The soil stiffness changes along the contact zone by a nonlinear hysteretic soil model due to the cyclic displacement amplitude. The model is implemented in OrcaFlex and uses data such as the seabed density, pipe diameter, and the soil shear strength along the depth. As shown in Figure 1, there are four various penetration modes in this contact zone, namely Not in Contact, Initial Penetration, Uplift, and Re-penetration modes. Different mathematical formulas are used for these models, and the related parameters are updated as a penetration reversal happens.

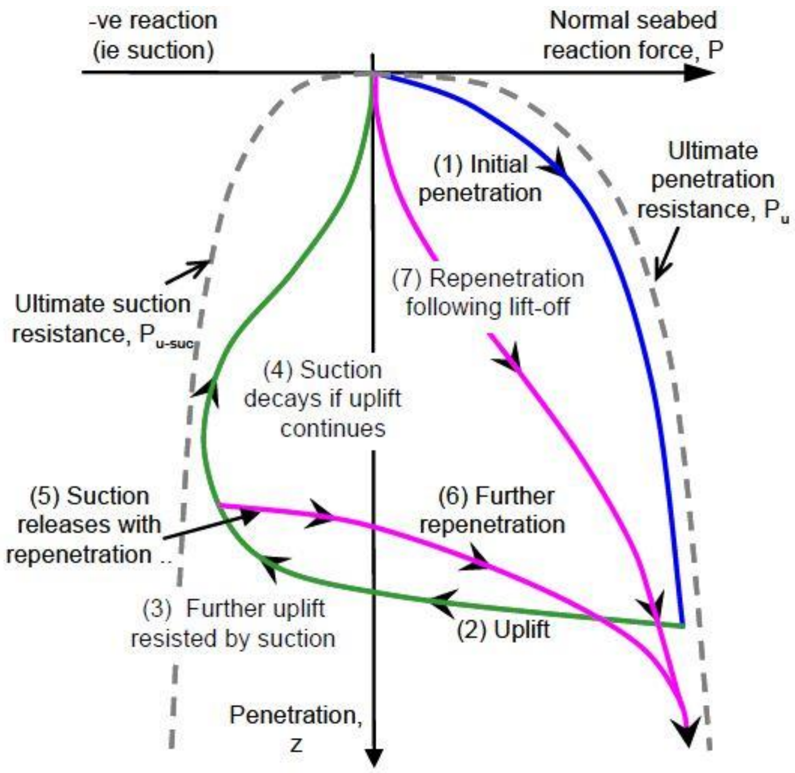

Figure 1
Seabed soil model characteristics (Randolph and Quiggin 2009).

3. Numerical simulation

The nonlinear seabed model presented by Randolph and Quiggin (2009) is selected and shown in Figure 1 with the main features given below:

(1) The seabed normal resistance is simulated using four penetration modes, i.e. Not in Contact, Initial Penetration, Uplift, and Re-penetration model. (2) In each case, the seabed reaction force per unit length, *P(z)*, is modeled using a function of the non-dimensional parameter of penetration *z/D*, where *z* is the penetration depth and *D* is the riser diameter. (3) For each mode, the resistance *P(z)* asymptotically approaches the seabed soil ultimate penetration resistance $P_u(z)$ or ultimate suction resistance $P_{u-suc}(z)$. This check is performed while the penetration *z* increases or decreases from its value when the penetration or uplift is started. The ultimate asymptotic limits are described by:

$$P_u(z) = N_c S_u(z) D \tag{1}$$

$$P_{u-suc}(z) = -f_{suc} p_u(z) \tag{2}$$

where, $s_u(z)$ is undrained shear strength at penetration z. This is given by $s_u(z) = s_{uo} + s_{ug} z$, where s_{uo} is the undrained shear strength at the mudline, and s_{ug} is the undrained shear strength gradient, both of which are specified in the seabed soil properties data.

D is penetrator contact diameter or SCR diameter, and $N_c\left(z/D\right)$ represents bearing factor. For $z/D \geq 0.1$, this is modelled using the power law formula $N_c\left(z/D\right) = a\left(z/D\right)^b$, where a and b are the non-dimensional penetration resistance parameters of the model, as specified in the soil model parameters.

The finite element model is used to model the steel catenary riser. The riser is divided into a series of massless segments so that each of them has a node on the end. The static shape of SCR is created, and then the non-linear dynamic analysis is carried out. The SCR situation and tension are calculated at each time step by an iterative procedure, and the dynamic responses are calculated using the forward Euler explicit method.

4. Case study

4.1. Environmental and floating conditions

Wave condition can either be described by a deterministic design or by applying wave spectra. Most spectra are described in terms of significant wave height (Hs), spectral peak period (Tp), spectral shape, and direction. According to the dominant spectra wave in the Caspian Sea, the JONSWAP will be used in the analyses of this paper. The resulting spectrum is given by:

$$s(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} e^{-1.25\left(\frac{f_p}{f}\right)^4} \gamma^a \tag{3}$$

where,

$$a = e^{-\left[\left(f - f_p\right)^2 / 2\sigma^2 f_p^2\right]}$$

$\sigma = 0.07$ when $f < f_p$

$\sigma = 0.09$ when $f \geq f_p$

In Equation 3, γ typically has values ranging from 1.6 to 6, but the value of 3.3 is recommended for general usage; f_p is the peak frequency, and α is the coefficient ranging between 0.0008 to 0.08 (Sorensen 2006; McCormick 2010).

For design purposes, the SCR is designed for a 100-year wave condition combined with a 10-year current profile, which is defined as a severe condition by the det norske veritas and American petroleum institute (DNV 2010; API 2009). For the Caspian Sea, a 100-year return period is defined by:

$Hs = 8\ m$

$Tp = 12.47\ s$

The corresponding 10-year current profile is shown in Table 1.

Table 1
Current speed and water depth.

Depth (m)	Speed (m/s)
0 at mean sea level	0.66
700	0

4.2. Model description

The primary parameters of the seabed model are undrained shear strength profile (linear variation with depth) and the soil density. Other parameters (Table 2) control the specific details of the model, including the maximum normalized stiffness of the seabed response after the reversal of the motion, the magnitude of suction developed during the uplift, and the incremental embedment during the cycles of the uplift and re-penetration. The nonlinear soil model includes complex mathematical expressions and its detailed formulation can be found in the original paper published by Randolph and Quiggin (2009).

Table 2

Nonlinear seabed soil model parameters.

Parameters	Symbol	Value
Mudline shear strength (median range)	S_{uo}	2.6 kPa
Shear strength gradient (median range)	S_{ug}	1.25 kPa/m
Saturated soil density	ρ_{soil}	1.5 t/m^3
Power law parameters	a	6.15
Power law parameters	b	0.15
Normalized maximum stiffness	K_{max}	200
Suction ratio	f_{suc}	0.7
Suction decay parameter	λ_{suc}	0.6
Re-penetration parameter	λ_{rep}	0.3
Soil buoyancy factor	f_b	1.5

The marine riser descends from a semisubmersible in a simple hanging catenary shape transitioning to a flow-line after 700 m, which is connected to the floating at a mean top angle of 20 degrees toward the vertical direction (Figure 2). The yield stress of this riser is considered to be 448 MPa. The outside diameter is 461 mm (18 in), and the wall thickness is 21 mm (0.825 in); the riser length is 2500 m .The inertia coefficient C_M used in this analysis is 2.0, and the drag coefficient is 1.2. The model parameters and the characteristics of the SCR are presented in Table 3.

Table 3

Riser pipe parameters.

Parameters	Symbol	Value
Outer diameter	D_o	461 mm
Wall thickness	t	21 mm
Pipe wall modulus	E	207 GPa
Yield stress	σ_y	448 MPa
Steel density	ρ	7850 kg/m^3

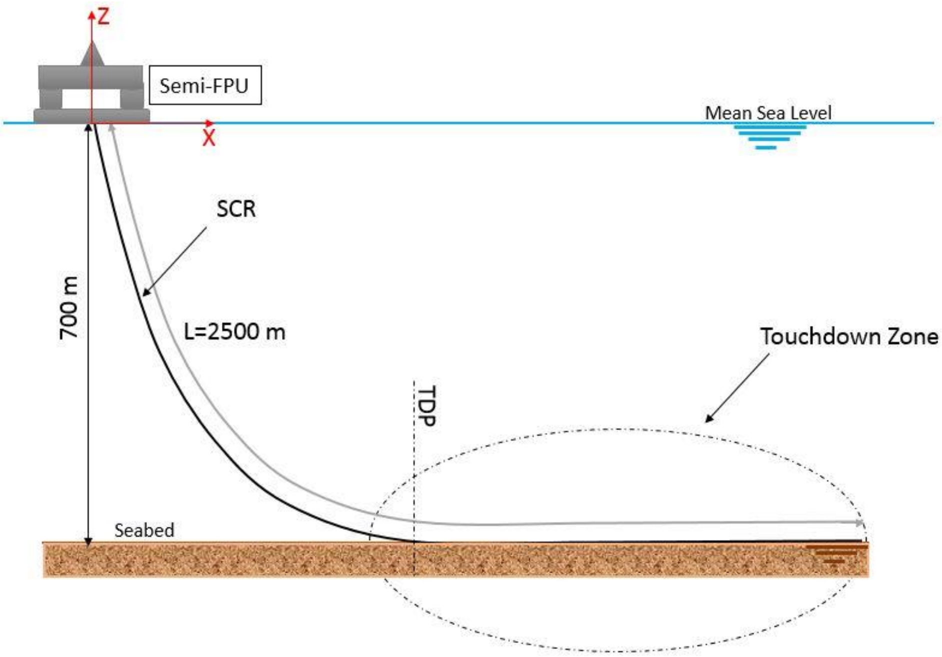

Figure 2
Global geometry of modeled SCR.

5. Results and discussion

5.1. Nonlinear hysteretic SCR–seabed contact model response

The dynamic riser–seabed soil penetration is introduced as seabed penetration/D (Figures 3), and the dynamic seabed contact resistance is introduced as seabed resistance/D (Figures 4). The early penetration of 0.022D corresponds to a seabed contact force of 4.37D ($k = 4.37 / 0.022 \approx 199\, kPa$). The maximum envelope of the riser increases to a penetration of 0.16D at an arc length with respect to the TDP of 949 m during the vertical cyclic motions. The seabed resistance approaches a local maximum of 10D (almost twice as much as the static value of 4.37D) compared to seabed resistance with a value of 3.37D kPa and 63D kPa when the models of linear and rigid seabed are performed respectively. However, the minimum soil suction resistance/D approaches a value of −7.37D kPa.

The initial dynamic TDP is shown at an arc length of about 907 m, which is measured from the top end of the SCR at the semisubmersible for the 180° wave and current direction. Figures 5 and 6 highlight the cyclic response at an arc length of 920 m in the contact area during some cyclic motions. The nonlinear seabed hyperbolic model produces a gradual penetration of the riser from an initial penetration of 0.03D to a maximum value of 0.16D at an arc length of around 949 m. It is concluded from Figure 6 that soil cyclic degradation (which is caused by the change of seabed stiffness) allows for the penetration, re-penetration, and soil suction effects.

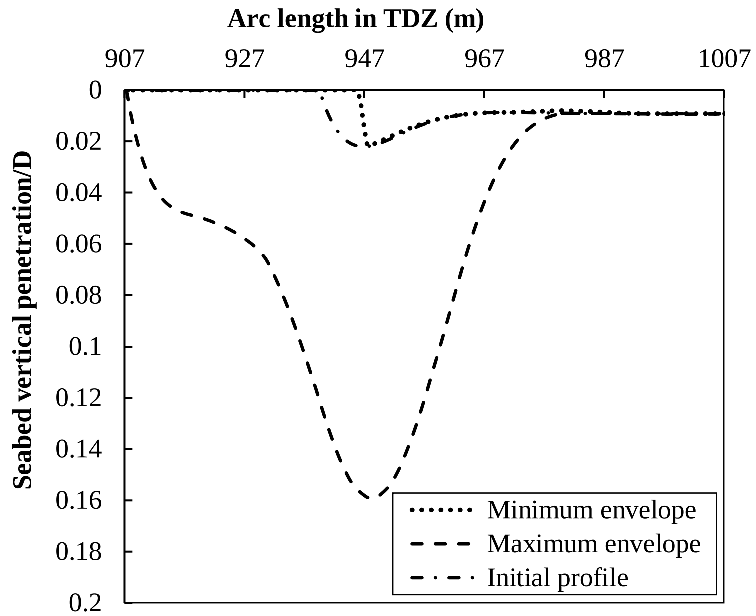

Figure 3
Dynamic riser penetration.

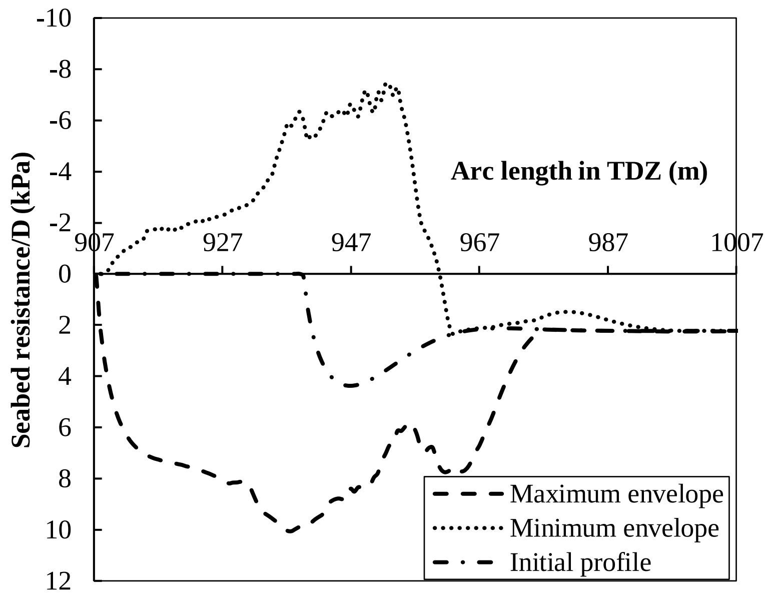

Figure 4
Dynamic riser–seabed resistance.

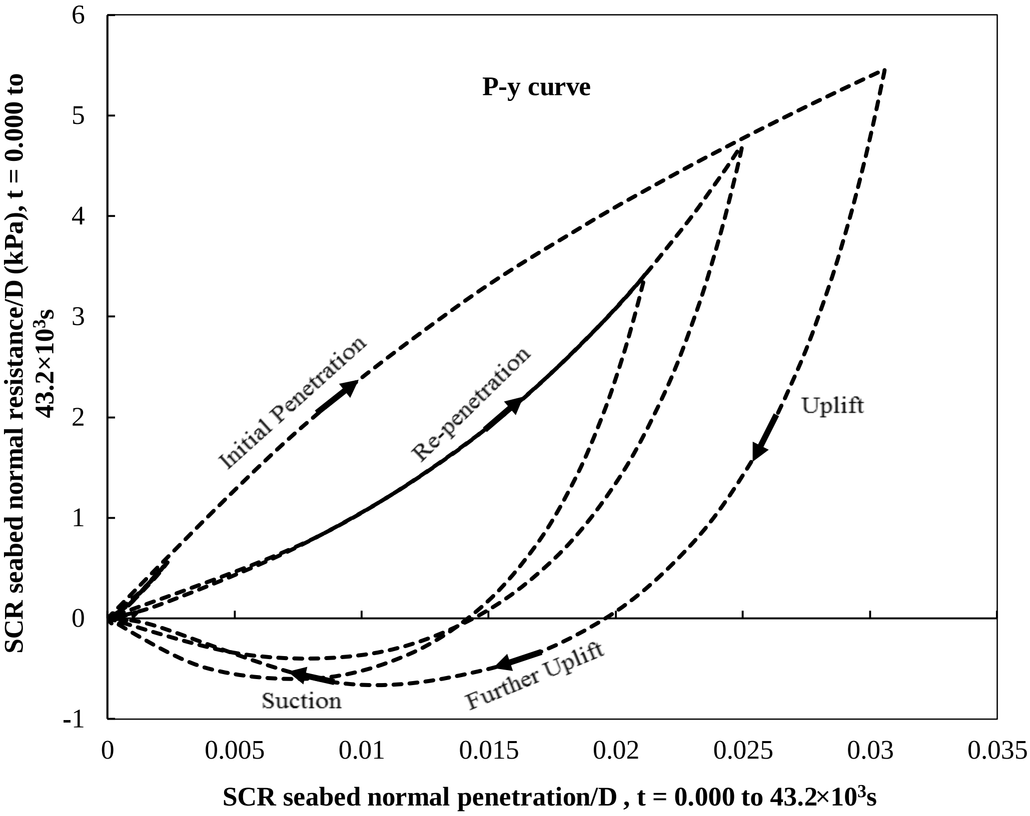

Figure 5

Riser–seabed interaction response at the TDZ at 920m arc length.

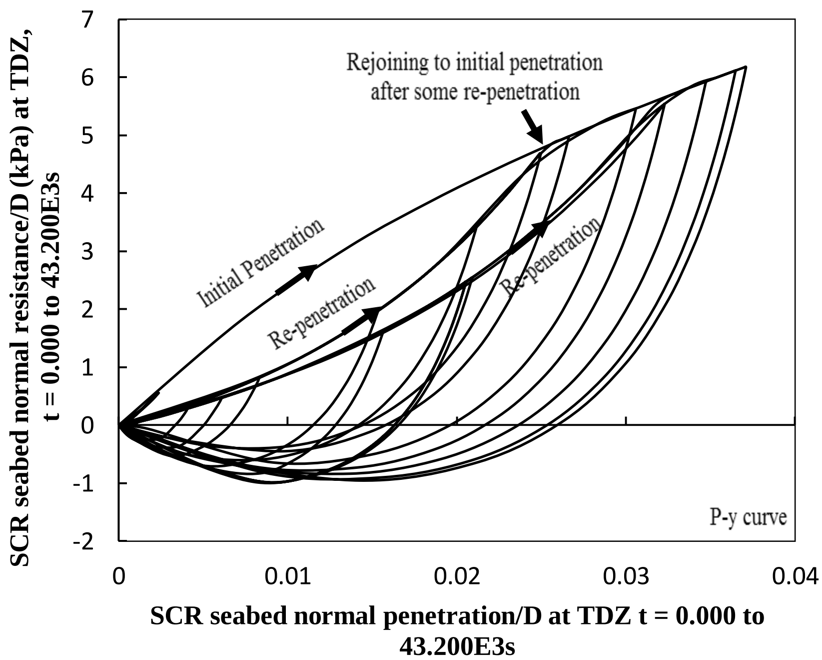

Figure 6

Proceeding of decreased seabed stiffness due to the vessel cyclic motion based on hysteretic nonlinear seabed model.

The soil stiffness degradation due to cyclic undulations has an important influence on the structural dynamic performance of the marine risers in the TDZ. After the seabed soil reaches its maximum strength, it leads to the plastic trenching and replacement during the cyclic loadings. This soil stiffness degradation mechanism is represented by the nonlinear hysteretic seabed model which is obtained through experimental results and consists of the uplift, suction, separation, and the re-penetration process.

The riser–soil interaction in the TDZ performs the general characteristics of nonlinear soil performance and finally leads to the limiting resistances curves $P_u(z)$ and $P_{u-suc}(z)$ as shown in Figure 6. The penetration parameter *z* for the ultimate resistance limits increases in the case of penetration motion and decreases conversely. The magnitudes of the ultimate penetration and suction resistance limits are obtained by $P_u(z) = N_c S_u(z) D$ and $P_{u-suc}(z) = -f_{suc} P_u(z)$ respectively.

After 3, 6, 9, and 12 hours of analysis, trenching development at different depths are obtained as shown in Figure 7. From the validation model, it is concluded that the riser-seabed interaction event can be well simulated by the proposed seabed soil parameters. Figure 7 shows the gradual growth in the trench depth beneath the riser as a function of the number of loading cycles. The cyclic loading was obtained from a periodic heave of amplitude of 3.6 m and a period of 30 s at the upper end of the steel catenary risers. It is found out that the rate of trench formation is initially relatively quick, but slows down after many cycles. Although the rate of trenching decreased from 3 hrs (900 cycles) to 12 hrs (3,600 cycles), the trenching formation still remained observable. It is also very important to note that the trenching at the early stages is nearly symmetric with respect to the center of the TDZ (located at an arc length of 949 m in Figure 7). After 3 hrs of cyclic loading, the deepest point of the trench (located at an arc length of 948 m in Figure 7) moves gradually towards the right end of the TDZ (near the anchor region of the SCR).

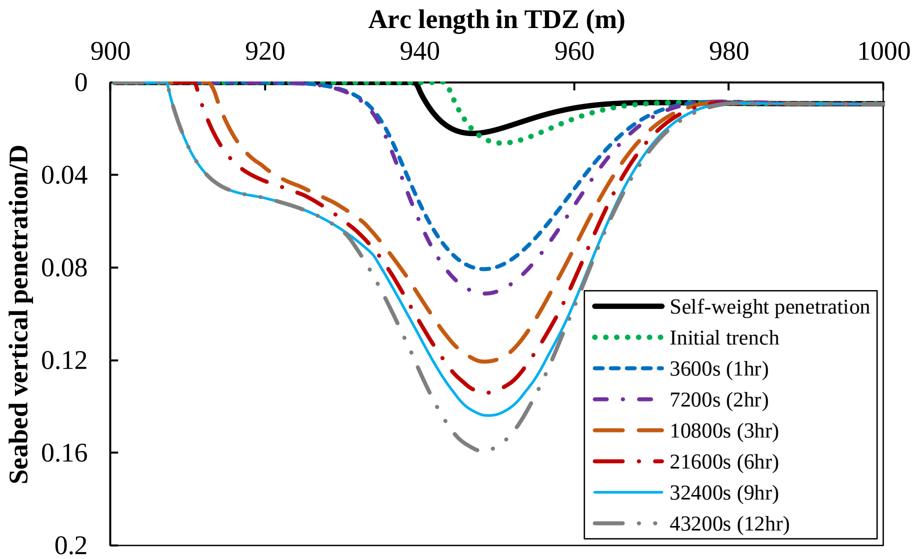

Figure 7
Trench development.

Figure 8 depicts the bending moment based on the maximum variation at the contact area. This figure shows that this maximum variation gently decreases due to the trenching development. This resulted in a trench gently deepening in the seabed smooths curvature of riser near its TDZ and in turn decreasing the maximum variation of bending moment near the touchdown zone.

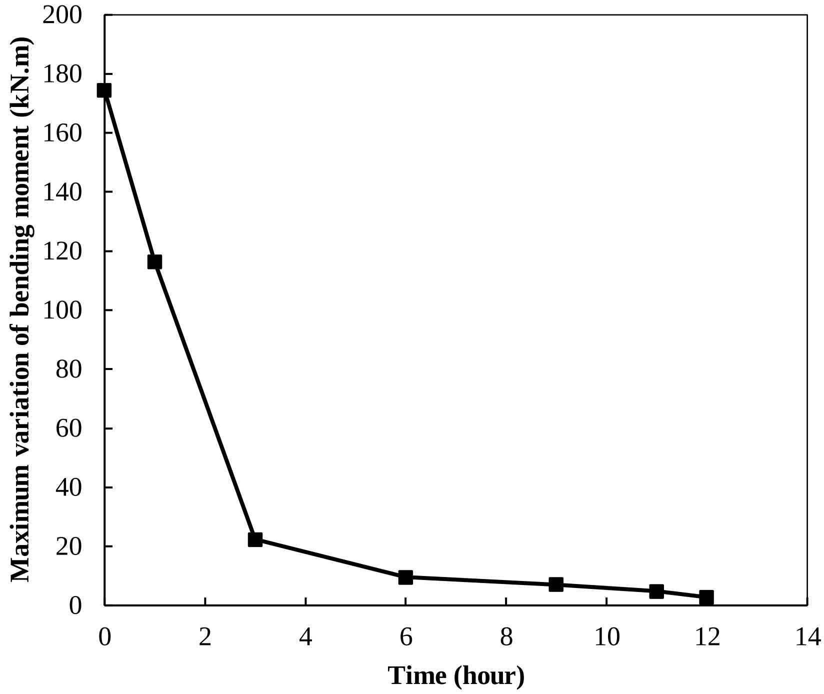

Figure 8
Maximum variation of bending moment along riser in TDZ in the vertical interaction.

It is concluded that the dynamic behavior of the riser is clearly influenced by the vertical hysteretic soil model. The soil interaction model can affect the accuracy of SCR dynamic responses. In this research, an attempt was made to adopt a novel methodology for riser–soil interaction modelling, which is a nonlinear seabed soil model based on the Caspian Sea environment. The better characterization of the riser–soil interaction model, with an accurate simulation of soil stiffness and riser penetration, enables us to obtain the behavior of riser dynamics and the fatigue assessment of SCR in the TDZ with reasonable accuracy. It is concluded that the trench formation decreases the maximum bending variation of a riser near the contact zone. Because the bending variation governs the fatigue life of the riser, it may have a significant application in the design of marine risers. Also, the results of this approach show that the trenching development in the vertical direction can decrease the fatigue damage of the riser.

6. Parametric studies

6.1. Water depth

Water depth is one of the critical environmental parameters for the marine riser response. A steel catenary riser base case is investigated at different water depths. Dynamic results are presented in Figures 9-12.

SCR base case is as follows:

- Wall thickness is 21 mm;
- Simulation length at each depth is 10800 s;
- Material is steel with a Young’s modulus of 207 GPa;
- Water depths are 500, 600, 700, 800, 900 and 1000 m.

A nonlinear seabed model is performed to simulate the vertical riser–soil interaction at considered different water depths. The sag-bend and flow-line of the riser is simulated by a coarse element length, and the contact area is modeled by a finer mesh. The maximum effective tension across the riser arc length is influenced by the vertical riser-seabed resistance model. Figure 10 presents the effective tension along SCR. The effective tension is given by $T_{eff} = T_w - P_i A_i + P_o A_o$ where T_w is the wall tension in the riser pipe, and P_i is the internal pressure; P_0 is the external pressure, and A_i and A_0 are the inner and outer areas respectively. The riser-soil interaction influences the axial strain of the riser. The riser wall tension is a function of the total axial strain; hence, the riser movement on the seabed can affect the riser tension.

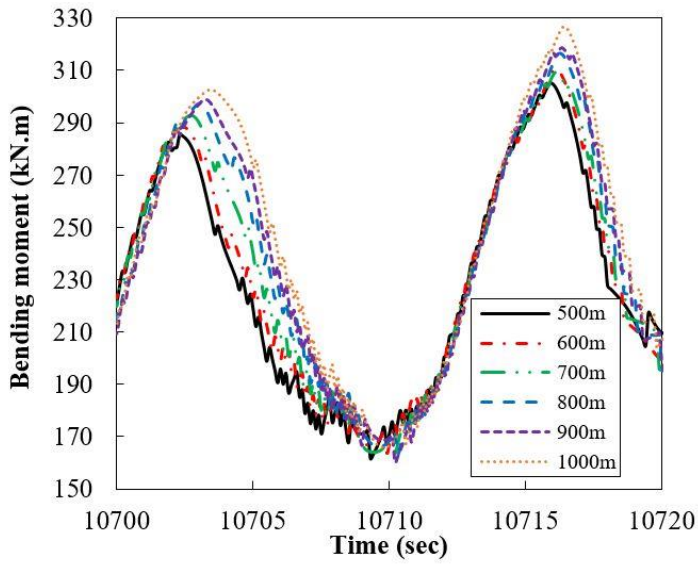

Figure 9
Bending moment with respect to water depth (18 hours of simulation).

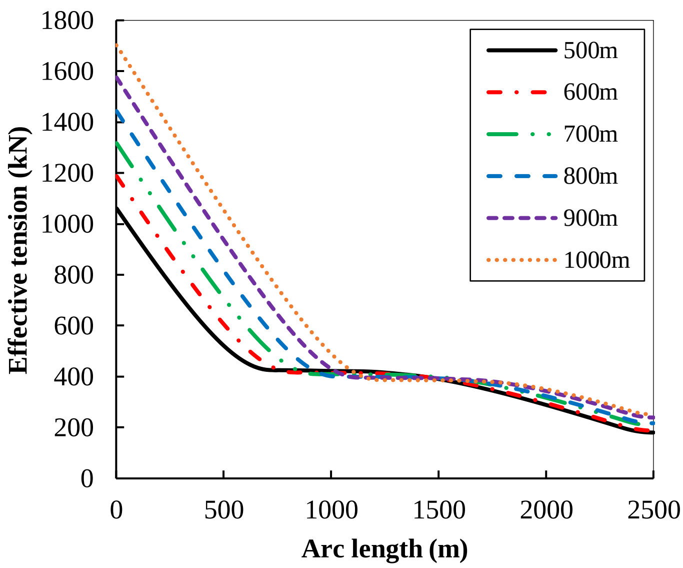

Figure 10
Effective tensions with respect to water depth.

In addition, the riser vertical cyclic fluctuation has an important effect on the seabed soil stiffness in the touchdown zone. The influence of the water depth on the riser embedment is shown in Figures 11 and 12. It is shown that the riser pipe penetration into the seabed is gradually increased with respect to an increase in water depth. Also, the seabed resistance is increased at larger water depths as shown in Figure 12.

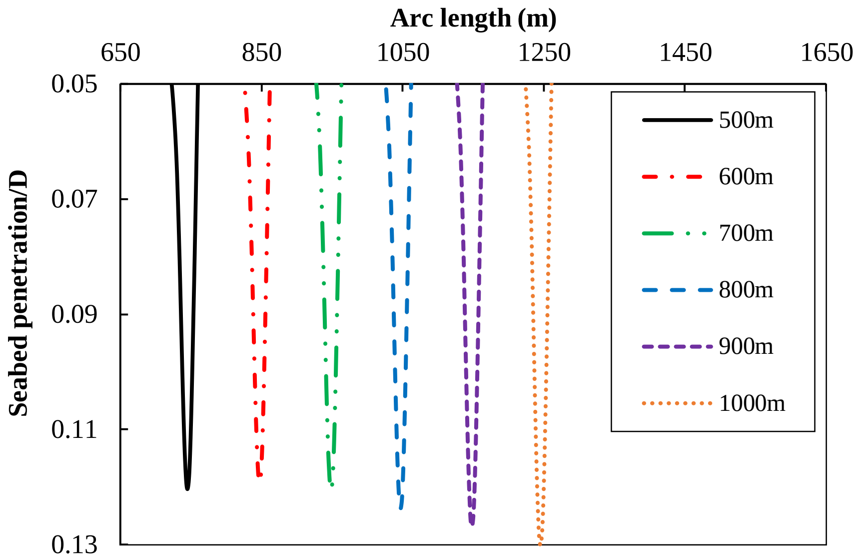

Figure 11
Seabed penetration with respect to water depth.

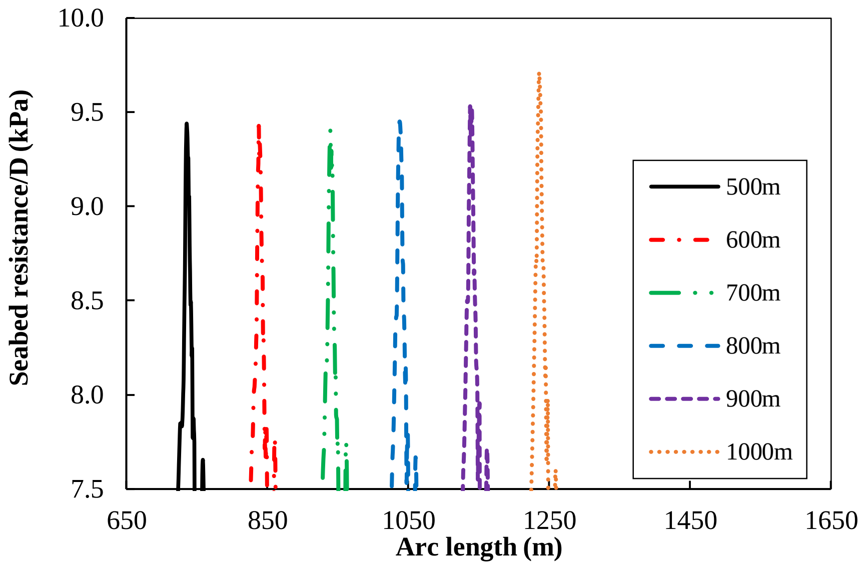

Figure 12
Seabed resistance with respect to water depth.

Figure 13 shows the maximum bending moment variation near the TDZ of riser at different water depths after they experience vertical forces due to wave and current. This figure shows that the maximum bending moment variation near the TDZ at a smaller water depth (500 m) gradually increases at larger water depths (1000 m**)** due to the environmental and hydrostatic water forces, and this enables us to obtain dynamic global riser behavior in the TDZ with higher accuracy. Since the bending moment variation govern the fatigue life of the riser, according to this approach, the results illustrate that increasing water depth may increase the fatigue damage of the riser, so it may have a significant application in the design of a riser.

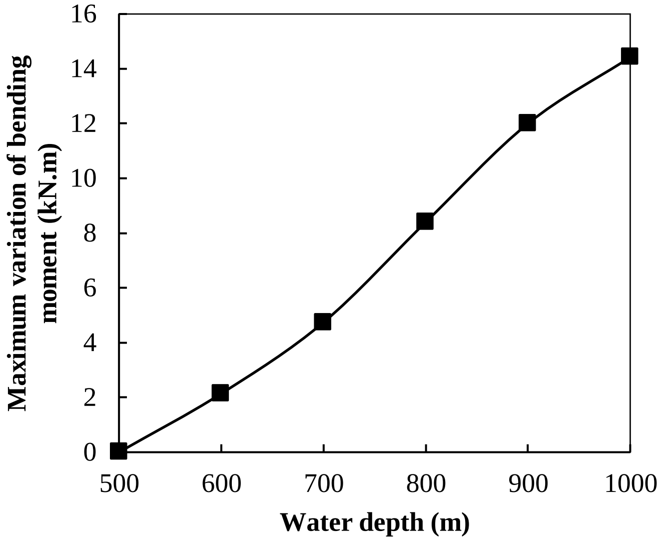

Figure 13
Maximum variation of bending moment with respect to water depth.

6.2. Riser material selection

Material selection is one of the critical SCR parameters for the system response. A steel catenary riser base case composed of different materials is investigated. Bending moment seems more sensitive to material selection than tension forces. Dynamic results are presented in Figures 14-16.

SCR base case is as follows:

- Wall thickness is 21 mm;
- Top hang off angle is 20°;
- Simulation length for each material is 10800 s;
- Water depth is 700 m;
- Materials are steel, titanium, and aluminum.

The influence of the material type on the SCR penetration is shown in Figure 14. It is shown that the SCR penetration into the seabed is decreased when the riser material type is changed. As shown in Figures 14-16, aluminum and titanium is lighter due to their flexibility and low weight, so it is concluded that the aluminum and titanium has lower stresses at the TDP of riser compared with steel. However, during processing, titanium absorbs oxygen and hydrogen which will degrade mechanical properties; moreover, they are expensive material. It would be a costly solution to use titanium over large areas.

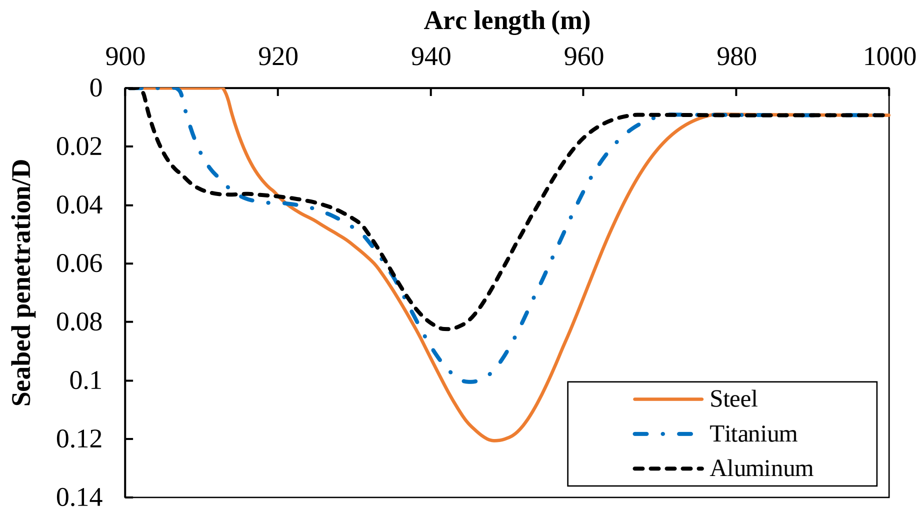

Figure 14
Seabed penetration with respect to material type.

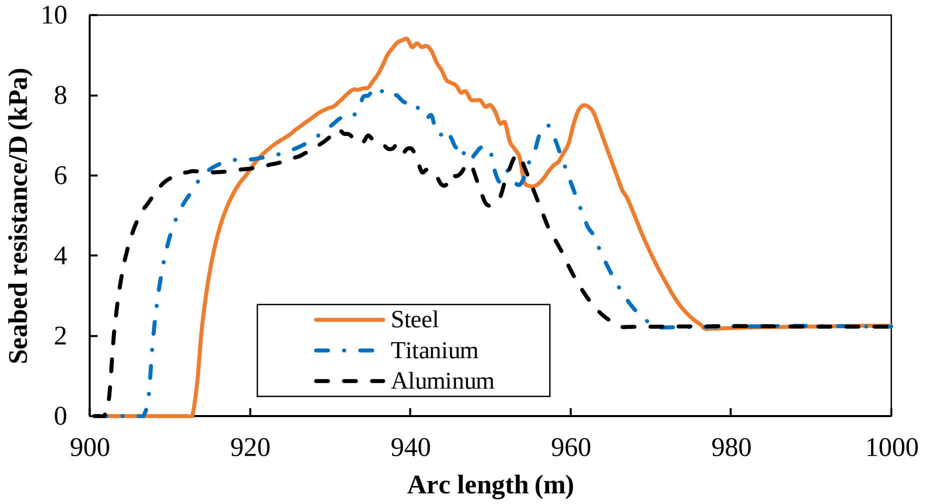

Figure 15
Seabed resistance with respect to material type.

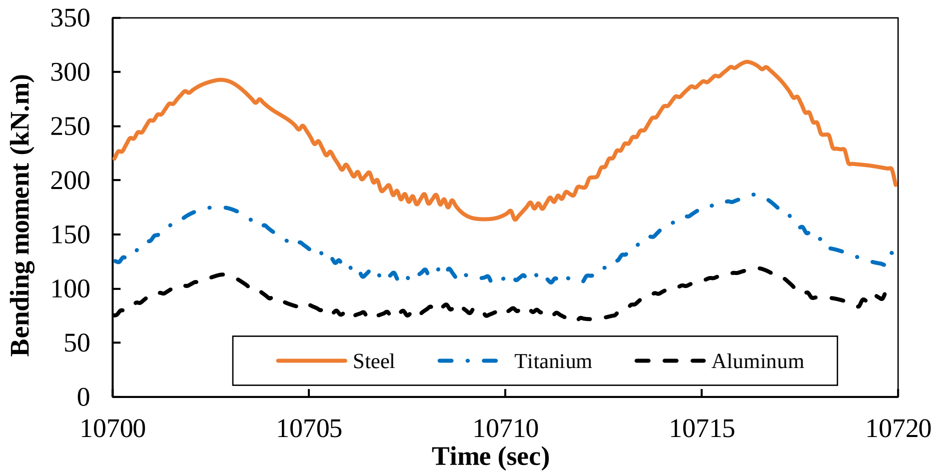

Figure 16
Bending moment with respect to material type (9 hours of simulation).

7. Conclusions

This research provides a comprehensive analysis of the SCR connected to a semisubmersible in the Caspian Sea at a water depth of 700 m in an extreme condition. The importance of the riser–soil interaction on the global dynamic behavior of SCR is investigated. In this study, the vertical embedment of the riser in the contact area is verified. During the dynamic analysis, the seabed soil is simulated by a hysteretic model in the vertical direction. Furthermore, the nonlinear seabed model simulates the varying soil stiffness and soil cyclic degradation, thereby evaluating the effects of re-penetration, uplift, and suction. The maximum dynamic vertical seabed resistance/D is 10kPa, which is approximately twice as much as the static value. It was shown that the TDZ responses result in decreasing the seabed stiffness and give a general overview of the dynamic riser interaction in the contact area due to cyclic loading.

It is concluded that deeper trench leads to the smaller variation of bending moment at the contact area. It shows that a trench is gently deepened at the seabed smooth curvature of riser pipe and in turn decreases the maximum (spatial) change rate of bending moment near the TDZ. The findings indicate that the trench formation may lead to a decrease in the maximum variation of the bending moment of SCR in the contact area. Additionally, it is shown that the maximum variation of bending moment near the TDZ at lower water depths gradually increases at larger water depths. Since the variation of bending moment governs the fatigue life of the SCR, the results of this approach conclude that the formation of seabed trench and the decrease of water depth may lead to an increase in the fatigue life of the riser; hence, it may have a crucial application in the design of a SCR. Increasing the water depth indicated that the vertical embedment and seabed soil resistance are increased; hence, deeper depths cause higher stress at TDP of the riser. Furthermore, different materials commonly used for SCR’s are evaluated, and it is concluded the aluminum and titanium have lower stresses at the TDP of riser compared with steel; nevertheless, since aluminum and titanium are costly solutions, the application of steel is a logical solution compared to the others.

Acknowledgements

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Nomenclature

FPSO	: Floating production storage and offloading
FPU	: Floating production unit
RAO	: Response amplitude operator
ROV	: Remote operating vehicles
SCR	: Steel catenary riser
TDP	: Touchdown point
TDZ	: Touchdown zone
TLP	: Tension leg platform
VIV	: Vortex induced vibration

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