Effect of Riser-Seabed Interaction on the Dynamic Behavior of Risers

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ABSTRACT

In recent years, the production of oil and gas has been developed in deep water depths which exceed 500m. Deep water developments are being followed strongly in different parts of the world (Caspian Sea, Gulf of Mexico, etc.). The movement of floater causes severe stress at the touchdown point (TDP) in steel catenary risers (SCR). The main objective of this study was to simulate the exact behavior of the riser in the vicinity of the touchdown zone (TDZ) by implementing linear SCR-seabed interaction model. Hence, present study attempted to investigate the riser-seabed interaction during lateral cyclic pipe movements and also the influence of seabed evolution around the TDZ based on the vertical cyclic movements. Moreover, The significance of the soil types in the response of riser pipeline at TDP was analyzed based on the vertical and lateral interaction. The fully non-linear time domain finite element model was utilized to simulate the riser behavior.

1. Introduction

In recent years, the production of oil and gas has been taking place in water depths which exceed 500m. Deep water developments are being followed strongly in different parts of the world (e.g. Caspian Sea, Gulf of Mexico, etc.).

The Sardar-e Jangal gas field is an Iranian natural gas field which is located in the Geographical coordinates 50.46 longitudinal and 37.7 latitudinal. The total proven reserves at this field are noticeable. Therefore, doing a study in this area, according to the environmental conditions of the Caspian Sea is increasingly essential [1]. Riser system is a key element in providing safety in all phases from drilling, completion/workover, production/injection to export. The main function of riser is to transport fluids or gas from seabed to a host platform. Steel Catenary Riser (SCR) is one of the direct alternatives to flexible riser. It may be used at larger diameters, higher pressures and temperatures and may be produced more easily. SCR can be suspended in longer lengths, removing the need for mid-depth buoys. Steel lines are cheaper than flexible and may be used in greater water depths without a disproportionate increase in cost. At the seabed, the need of riser base, stress joint or flex joint have been eliminated. This reduces the complexity of riser system and cost savings are made as a result of simplified riser system [2].

A SCR attached to a floating at its upper, encounters fluctuations in and near its Touchdown Zone (TDZ) under different environmental conditions. In other words, the riser is continuously subject to oscillatory environmental loads. ROV observations of installed SCRs have shown deep trenches cutting into the seabed in the TDZ [3]. Therefore, it is important to develop better understanding and modeling of the SCR–soil interaction mechanism to provide a realistic technique for determining dynamic response and strength performance in the TDZ. Oil and gas fields fluctuate in geology and environments, and the result of these differences are the different designs of the riser systems. SCRs are subjected to various types of loads and deformations that range from the routine to the extreme or accidental. The purpose of SCRs design is to design a riser system that can tolerate load effects throughout its expected lifetime. The design is safe if the resistance is more than response and the ratio of response over resistance shall be less than the acceptance criteria or allowable factor. Safety factor shall be incorporated in the design check in order to account for various uncertainties due to natural variability, inaccuracy in analysis procedures and the control of load effects and uncertainties in structural resistance. Siahtiri and Taheri [1] analyzed all of the possible loads which can affect the SCR, for instance hydrostatic and propagation collapse, and obtained the structural parameters of SCR such as wall thickness and riser pipe diameter according to the standard design guidelines [2, 4] based on the Caspian sea severe environmental condition with 100 return period for wave and 10 return period for current and wind.

Recent studies have focused on elaborating the SCR–seabed interaction. Aubeny and Biscontin [5] considers the riser-seafloor interaction problem in terms of a pipe resting on a bed of springs, the stiffness characteristics of which are described by nonlinear load-deflection P-y curves.

Also, Wang et al. [6] conducted the laboratory tests to investigate the SCR-seabed interaction during lateral cyclic riser movements and the influence of seabed evolution around the TDZ on the following vertical cyclic pipe movements. Hejazi and Kimiaei [7] proposed an equivalent linear soil stiffness instead of nonlinearly modelled seabed soil. They showed the design procedures for SCRs based on the linear soil models for the seabed are not only simple but also it usually leads to conservative results. The riser-soil interaction consists of seabed stiffness and equivalent friction to represent the soil resistance to movement of the pipe. The equivalent friction resistance is based on the coulomb friction for non-cohesive soil, cohesive soil or a combination of the two (silt, sand). Therefore, it is important to predict the soil contact pressure, equivalent friction and soil stiffness [8]. The numerical results for the assessment of the SCR's global response at the critical point in the TDZ are presented, so that the seabed is modeled using a linear seabed model in the vertical direction [9], and Coulomb friction soil models in the lateral seabed direction [10-11].

The main objective of this study was to simulate the exact behavior of the riser in the vicinity of the touchdown zone by implementing linear SCR-seabed interaction model. Most previous studies have focused on riser-seabed interaction in the vertical direction at the TDZ. Therefore, present study attempted to investigate the riser-seabed interaction during lateral cyclic pipe movements and the influence of seabed evolution around the TDZ based on the vertical cyclic movements. Moreover, the significance of the soil types in the response of riser pipeline at TDP was analyzed based on the vertical and lateral interactions. The fully non-linear time domain finite element model was used to simulate the riser behavior.

2. Numerical modeling of riser-seabed interaction

The dynamic analysis is a time simulation of the motions of the model over a specified period of time, starting from the position derived by the static analysis. Based on dynamic force equilibrium equation, one specifies a constant time step for the numeric integration scheme. Force equilibrium is achieved in each time step by iteration. Typical numerical integration methods include Newmark-β, Wilson method, etc. OrcaFlex also employs Generalized-α implicit integration scheme and Forward Euler Explicit integration scheme [12].

Even though the riser is submerged, it is still affected by surface forces, as these create motions on the floater which translates directly to the riser itself. Because SCR does not have tensioner systems, it relies on self-weight to keep the tension. Increased vertical motion gives reduced tension, which can cause buckling and instability. Since the system is all connected, both the motion and offset of the floater constitute a source of static and dynamic loading on the riser. The main data needed for riser designs are: Static offset (mean offset due to wave, wind and current) and Wave frequency motions (First-order wave induced motions) [4]. Floating Production Unit (FPU) can be subjected to the large static displacements. The static vessel offset regarding the operating extreme response analysis is 10% of water depth for intact mooring and 12% for one mooring line failure condition. These displacements are in the plane and out of plane of a SCR. A generic configuration of an SCR attached to a floating platform system has been considered as shown in Figure 1.

It is believed that the riser dynamics has important contributions to fatigue life, so the dynamic effects of the riser including the drag, inertia and added mass were included for a more realistic investigation. The system has been studied through displacement-controlled, quasi-static and dynamic analyses with the floating excitation based on the generic approximated RAOs from Caspian Sea. No hydrodynamic software is needed to extract vessel RAO under environmental loads, which is usually a common practice in load-controlled analyses [13].

In this study, a semi-submersible vessel was used as shown in Figure 2. Hence, Response Amplitude Operators (RAOs) for semi-submersibles were applied as shown in Figure 3. This RAO was integrated into the model used in OrcaFlex.

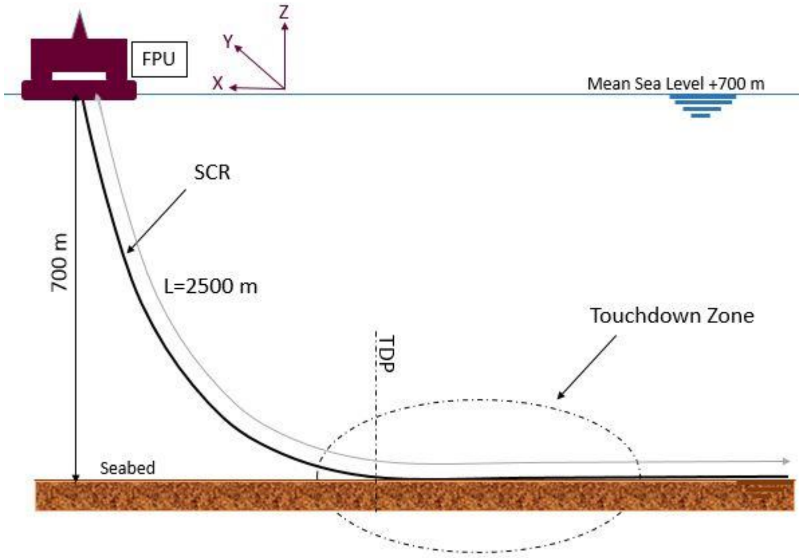


Figure 1. Static configuration of SCR under floating offset

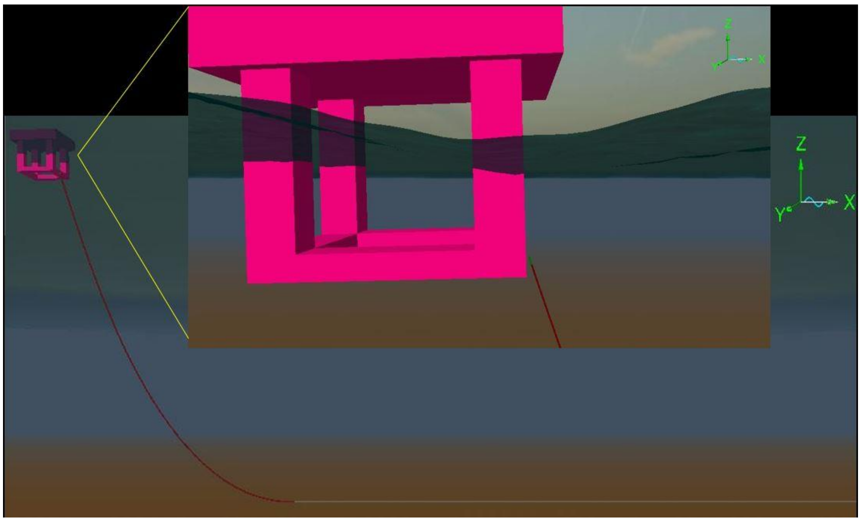


Figure 2. Semi-FPU and SCR modeling in OrcaFlex software

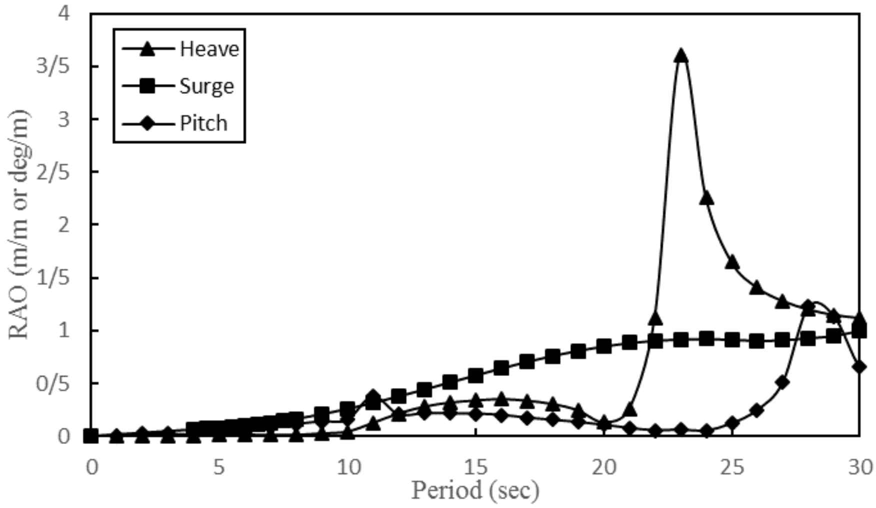


Figure 3. Approximation FPU RAO in head seas, wave heading = 0°

The main factors to control the magnitude of bending stress in the riser pipe are riser characteristics, environmental criteria and touchdown zone (TDZ) characteristics. The movement and oscillation of the SCR in the TDZ will cause severe stress and dynamic embedment of the SCR into the seabed. A typical schematic illustration of the SCR–seabed interaction in the TDZ is given in Figure 4.

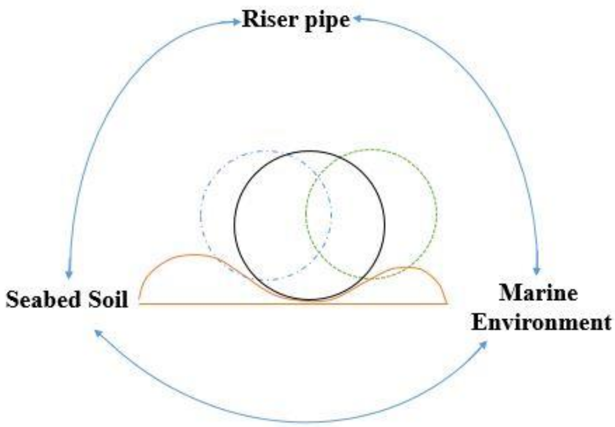


Figure 4. Schematic illustration of the pipe interaction issue

3. Case study

3.1. Environmental conditions

Wave condition can be described by either 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. For Caspian Sea, a 100-year return period is given as [1]:

- $Hs = 8m$
- $Tp = 12.47s$

According to the dominant spectra wave in Caspian Sea, finally, the

JONSWAP was used in the analyses of this paper. The resulting spectrum was:

$$s(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} e^{-1.25(\frac{f_p}{f})^4} \gamma^a \quad (1)$$

Where

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

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

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

In Eq. (1), γ, typically the value of 3.3 is recommended for general usage, f_p is the peak frequency and the values of α as the coefficient are ٠.08 and 0.008 respectively. The corresponding 10-year current profile has been shown in Table 1 [1, 14].

Table 1. Current speed vs. water depth

Water depth (m)	Current speed (m/s)
0 at water surface	0.66
700	0

3.2. Steel catenary riser model description

The SCR descends from a semisubmersible in a simple hanging catenary configuration, transitioning to a flow-line after 700m, and the SCR is connected to the floating at a mean top angle of 20^{O} to the vertical, as shown in Figure 1. The outside diameter is 461mm (18in) with a wall thickness of 21mm (0.825in) and a total riser pipe length is 2500m. The inertia coefficient C_M used in this analysis is 2.0, and the added mass coefficient is one [1].

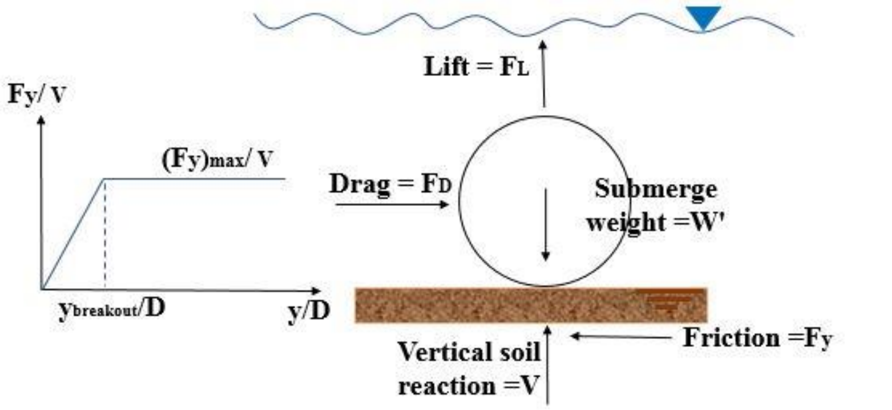
3.3. Seabed soil condition

The riser-soil interaction model consists of seabed stiffness and equivalent friction definition to represent the soil resistance to movement of the pipe. The equivalent friction resistance is mainly based on the coulomb friction for non-cohesive soil (sand), cohesive soil (clay) or a combination of the two (i.e. silt and sand), related to the soil density and the contact pressure between the soil and the pipe. Therefore, it is important to predict the soil contact pressure, equivalent friction and the soil stiffness accurately [8].

In the linear seabed models, the seabed is normally modelled as a spring and damped surface with a spring reaction force that is proportional to the depth of the penetration and the contact area, plus a damping force that is proportional to the rate of penetration. The seabed stiffness is constant of proportionality of the spring force and equals the spring reaction force per unit area of contact per unit depth of penetration. The seabed damping is the constant of proportionality of the damping force, and is the percentage of critical damping. The seabed characteristics are illustrated in Ta, which is extracted from tests conducted by Wagner [11]. Soil spring stiffness (k_0) is constant and its unit is force per square length. Up-load displacement is equal to down-load displacement. Due to the influence of linear spring, the foundation support force increases without limit by increasing the relative displacement in proportion to the spring constant [15].

3.3.1. Lateral displacement model

Existing industry procedure to estimate the soil resistance is coulomb friction model which expresses the lateral resistance as the product of the effective submerged pipeline vertical force (submerged pipe weight minus hydrodynamic lift force) and a soil friction coefficient which depends on the soil type. The conventional riser-soil design procedure is modeling the interaction with spring links at intervals along the SCR flow-line. These links provide a bilinear soil resistance in the lateral direction as shown in Figure 5. Regarding the Coulomb friction model, the seabed friction force has a magnitude of up to μV , where μ is the friction coefficient and V is the seabed reaction force, and acts tangential to the seabed plane. The SCR, which is in contact with the seabed, maintains a friction target position, and a friction force is applied that acts on this target position. The breakout force is the maximum force needed to move the pipe from its stable position on the seabed. A linear model of the friction force is employed and is given by $F = -K_s A y$ to a magnitude of not more than μV , where y is the displacement from the un-sheared position, K_s is the seabed shear stiffness, and A is the contact diameter multiplied by the length of the line represented by the node. The Coulomb friction models the friction force of $-\mu V$ to $+\mu V$ which occurs as a linear variation over the deflection range $-y_{breakout}$ to $+y_{breakout}$. Here $y_{breakout}$ is given by $y_{breakout} = \mu V / K_s A$ [10].



$$(F_y)_{\max} = \mu(W' - F_L) \qquad if\,(F_y)_{\max} \geq F_y = F_D;\, SlidingWillNotoccur$$

$$V = W' - F_L \qquad if\,(F_y)_{\max} < F_D;\, SlidingWilloccur$$

Figure 5. Coulomb friction model

4. Results and discussion

4.1. Global SCR response

Due to the unavailability of the exact specifications of soil types in

Caspian Sea for this study, the simulations were implemented for each soil type, which are listed in Table 2. It can be seen that the soft clay puts a greater effect on the riser stresses (such as Radial, Circumferential and Wall tension) at touchdown area, which can eventually lead to more damage to the riser (Figures 6, 7 and 8). Therefore, in this study the soft clay was selected as the soil type. The model analyses exhibited the maximum variation in the bending stress near the TDZ, which depended on the excursion and cyclic motions of the production units. As shown in Figures 6 and 7, for the soft clay both the seabed normal resistance was minimized and the pipe displacement in the seabed was maximized. Moreover, Figure 8 shows that the Von Mises combination stresses for the soft clay is bigger than the other soils.

Table 2. Approximate soil properties of the model [11]

Soil types	Sliding Friction Coefficient (μ)	Stiffness (kN/m/m^2)
Soft clay	0.2	140
Stiff clay	0.2	2417
Loose sand	0.6	273
Dense sand	0.6	336

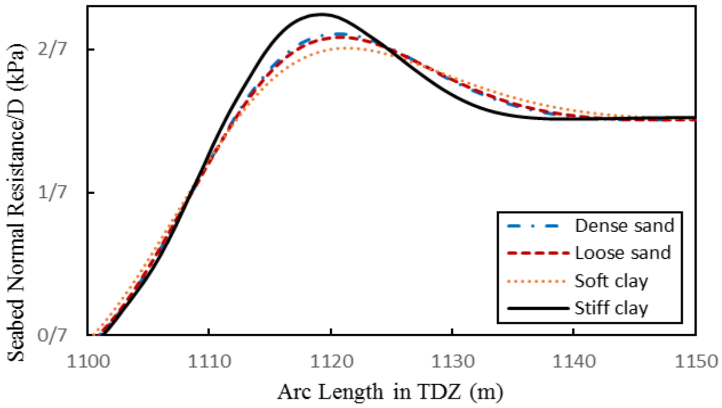


Figure 6. Seabed resistance in each soil type

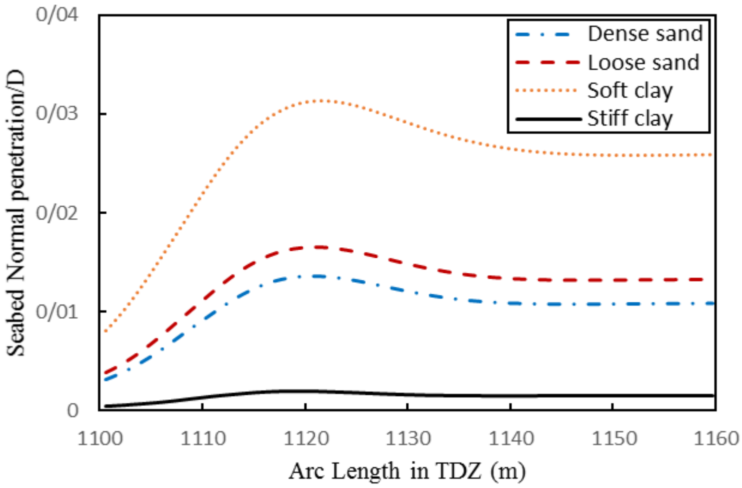


Figure 7. Seabed penetration in each soil type

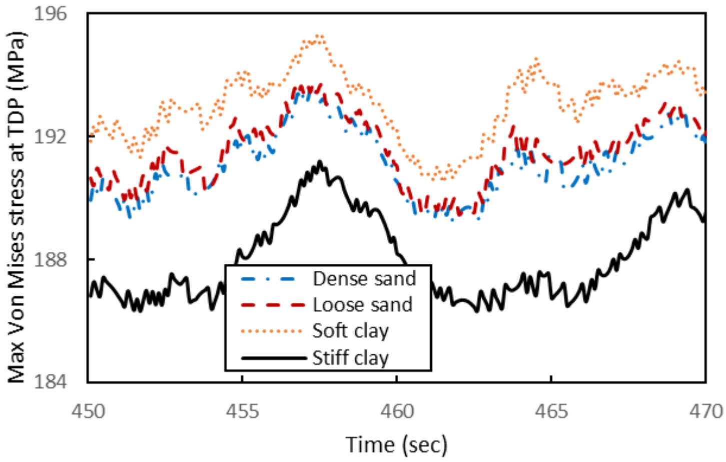


Figure 8. Effect of different soil types on stresses at TDP

The allowable Von Mises stresses of the riser are shown in Table 3. For the 0˚, 180˚ (in-plane load cases) and 90˚ (out-of-plane load case) wave and current directions, where the floater is in the mean, near and far position. The floating production unit offsets and dynamic motions in a severe environment influence the stresses in the TDZ, where the riser starts to contact the seabed.

The riser was analyzed for the extreme operating intact mooring conditions. The extreme analyses were conducted for the load cases defined by API RP 2RD , and the strength analysis was performed for near (when the vessel offset was closest to the TDP, see Figure 9), far (when the vessel drifted away from the TDP) and transverse vessel position offsets and a 100-year wave combined with a 10-year current. The most critical section for the Von Mises stress occurred at the TDZ [2, 4]. The seabed interaction model has an influence on the calculated Von Mises stresses. For example, in the case study of 0˚ wave and current direction, Von Mises utilisation factor is 0.78 for the linear soil model as compared with 0.8 for the rigid seabed model. Therefore, the evaluation of the dynamic response depends on the employed soil model. The soil parameters have an invisible influence on the global risers dynamic response. Although the results show that the riser has a sufficient margin for the strength performance, it is important to note that the strength analyses are carried out with the same floating production unit offsets, wave and current data for both the near and far positions and intact extreme operating conditions.

Table 3. Strength analyses results (3-hour simulation time length)

Wave and current direction	**Mooring condition**	**Riser offset position**	**Max Von Mises stress/σ_y at TDP**	**Allowable stress/σ_y**
0	Intact	Near	0.78	0.8
		Mean	0.71	
		Far	0.7	
90	Intact	Transverse +Y	0.71	0.8
		Mean	0.71	
		Transverse -Y	0.71	
180	Intact	Near	0.8	0.8
		Mean	0.72	
		Far	0.7	

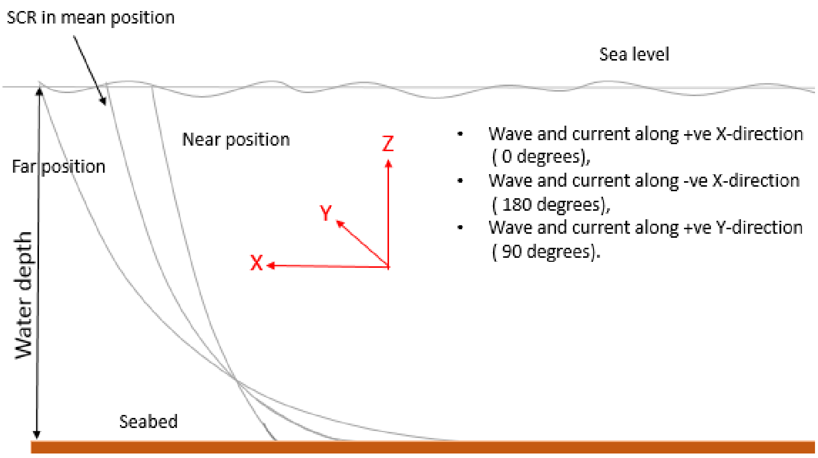


Figure 9. Static configuration of SCR under vessel offset

After modeling the riser at each position of the floating platform separately, the dynamic cyclic motions of the riser within the TDZ increased the riser's embedment beyond that produced by the static load. The bending moment and shear force were obtained and demonstrated together as a function of the riser arc length measured from the floating production unit. The floating offset governed the maximum bending moment and shear force at the TDP as shown in Figure 10.

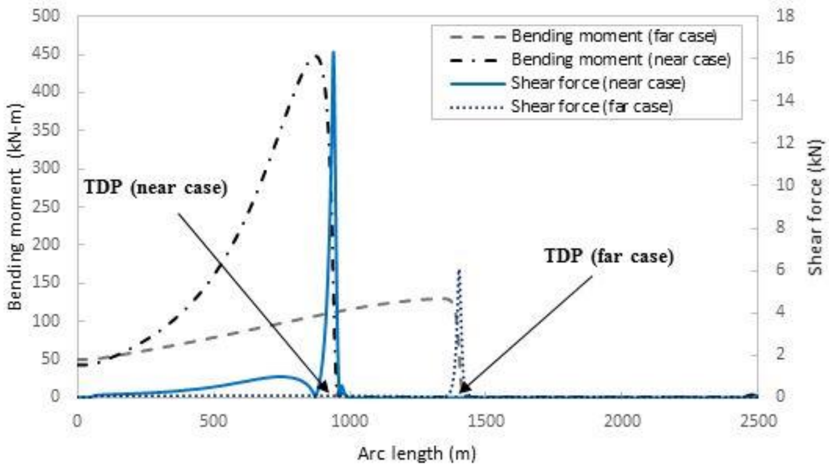


Figure 10. Riser static response for the 180˚ wave and current direction

4.2. Riser–seabed vertical interaction response

The dynamic riser-seabed penetration is explained as seabed penetration/D, and dynamic seabed contact resistance, explained as seabed resistance/D, which can be seen in Figures 11 and 12, for the 180˚ wave and current direction, respectively. The riser's vertical cyclic fluctuation had a significant effect on the riser at the TDZ. The linear soil model in the vertical direction was implemented to model. As can be seen in Figure 11, the soil resistance in linear seabed model reduced ,correspondingly, the riser's penetration into the seabed increased when the soil was modeled as linear (Figure 12). Finally, as can be seen from Figure 13, the linear seabed model exerted the greatest influence on the riser at the TDP compared with the rigid seabed. As an important consequence, the linear soil model can provide consevative results compared with the rigid soil model. It also enable us to obtain the global riser dynamic performance at the TDZ more accurately.

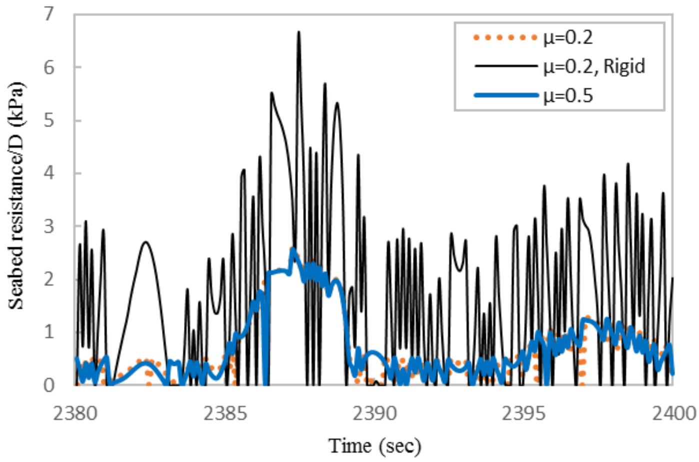


Figure 11. Dynamic SCR-seabed contact resistance in the near case (3-hour simulation)

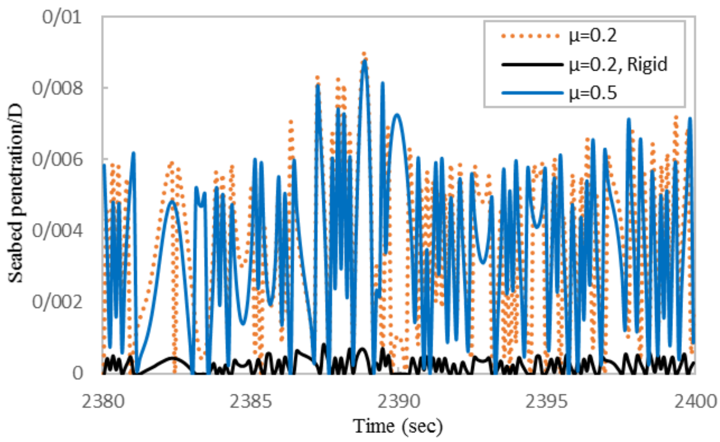


Figure 12. Displacement of SCR at the TDP

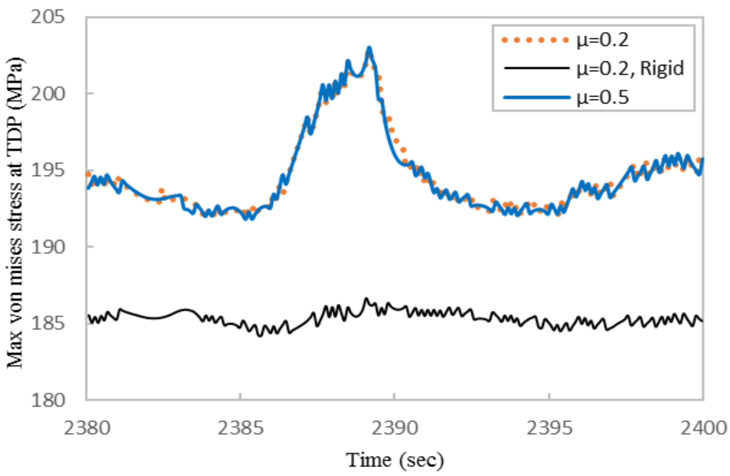


Figure 13. Maximum Von Mises stress at the TDP

4.3. Riser–seabed lateral interaction response

A linear seabed model was used to investigate the riser-soil interaction on soft clay seabed and then it was compared with the riser-soil interaction on rigid seabed models. In addition, it was integrated with the lateral riser-soil interaction models, the Coulomb friction soil model. In this model, the riser-soil response for the 100-year wave and 10-year current is investigated in the lateral direction (90˚).

The model was used to simulate the risers response by obtaining its lateral displacement. This lateral displacement on the seabed, using the severe environmental condition, has been presented in Figure 14. The analysis was done using the Coulomb friction model. Figure 14 displays the influence of the linear and rigid soil models on the specified arc length (1120 m) of the riser in the TDZ during a 3-hour simulation time. The lateral riser's movement in the TDZ obtained with the linear soil model was smaller than the rigid soil model for the same sliding friction factor ($\mu = 0.2$) due to the effect of the passive soil resistance.

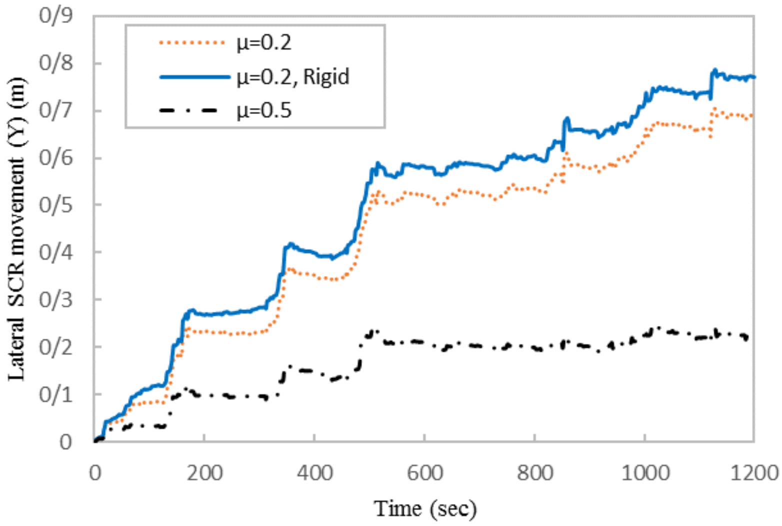


Figure 14. SCR–seabed lateral interaction at arc length 1120m (3-hour simulation)

5. Conclusion

The main objective of this study was to simulate the dynamic behavior of the riser in the vicinity of the touchdown zone by implementing linear SCR-seabed interaction model. In this paper, the effect of irregular wave angle of the incidence on riser and the contribution of floater transfer functions were considered. It was found that the maximum variation in the bending moment near the TDZ, depended on the offset and cyclic motion of the floater. This paper described a detailed analysis of the SCR connected to a semi-submersible in Caspian Sea environment. The dynamic analysis was performed for wave and current directions of 0˚, 180˚ and 90˚ (out-of-plane load case). The conclusion was that the maximum Von Mises stress of the SCR in TDP is at 180˚ wave and current direction when the FPU was in the near position.

The significance of the soil types in the response of riser pipeline at TDP was analyzed based on the vertical and lateral interaction. The fully non-linear time domain finite element model was used to simulate the riser behavior. This paper discussed the significance of SCR-seabed interaction in the design of SCR for deep-water applications and reported the results of analysis of an SCR on soft clay in 700m depth of water for Sardar-e Jangal gas field.

Past studies mostly focused on riser-soil interaction in the vertical direction. Therefore, present paper aimed to investigate the riser-soil interaction during the lateral cyclic pipe movements and the influence of seabed evolution around the TDZ based on the vertical cyclic pipe movements. Moreover, the significance of the soil types in the response of riser pipeline at the TDP was analyzed based on the vertical and lateral interaction. It was shown that the lateral displacement obtained with a linear soil model was smaller than the rigid soil model. Also, it was found that the differences between the sliding friction coefficients in the linear soil model with $\mu = 0.2$, $\mu = 0.5$ were negligible in the vertical interaction. However, it was so significant in the lateral SCR-seabed interaction due to the passive soil resistance. Finally, it is concluded that the proper riser-soil vertical and lateral interaction model enables designers to obtain the global riser dynamic performance in the TDZ more accurately.

Nomenclature

D	Pipe outer diameter (mm)
F	Sliding resistance of the pipeline along soil surface (kN/m)
FPSO	Floating production storage and offloading
FPU	Floating production unit
RAO	Response amplitude operation
H_s	Significant wave height (m)
K	Soil stiffness (kN/m/m^2)
SCR	Steel catenary riser
t	Pipe wall thickness (mm)
TDZ	Touchdown zone
TLP	Tension leg platform
T_p	Wave peak period (s)
TDP	Touchdown point
V	Vertical seabed reaction force (kN/m)
y	Displacement from the unsheared position in lateral direction (m)
z	Embedment depth of pipe below the seabed (m)
γ'	Submerged unit weight of soil (kN/m^3)
μ	Sliding friction factor

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تأثیر اندرکنش رایزر و خاک بستر دریا بر روی رفتار دینامیکی

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ناحیه تماس با بستر
نوع خاک بستر دریا
اندرکنش رایزر و خاک بستر دریا
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چکیده

در سال های اخیر، تولید نفت و گاز به سمت آب های عمیق با عمق بیش از۵۰۰ متر توسعه یافته است. در حال حاضر این توسعه در نقاط مختلف آب های عمیق دنیا محقق شده است (بطور مثال، دریای خزر، خلیج مکزیک و غیره). حرکت نوسانی شناور سبب ایجاد تنش های شدید در نقطه تماس رایز با بستر دریا میشود. هدف اصلی از این مطالعه، شبیه سازی رفتار دقیق رایزر در محل تماس با بستر دریا با در نظر گرفتن مدل خطی اندرکنش خاک و بستر دریا میباشد. این مقاله به بررسی اندرکنش رایزر و خاک بستر در حین نوسان جانبی خط لوله رایزر و در نتیجه اثر تغییر شکل های خاک بستر در ناحیه تماس، براساس حرکت نوسانی در جهت قائم میپردازد. بعلاوه، تاثیر انواع خاک بر پاسخ خط لوله رایزر در نقطه تماس با بستر دریا، بر اساس اندرکنش قائم و اندرکنش جانبی آنالیز شده است. جهت شبیه سازی دقیق رفتار رایزر، از یک مدل اجزای محدودی غیر خطی در حوزه زمان استفاده شده است.