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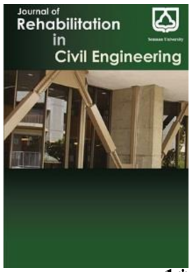

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Steel Catenary Riser-Seabed Interaction Due To Caspian Sea Environmental Conditions

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ABSTRACT

This paper investigates the integrated riser/vessel system which is subjected to random waves. Riser pipelines are the main components of the oil and gas offshore platforms. Whereas Iran country has been located on the fringes of Caspian Sea deep water, therefore study and research in this area is increasingly essential. The fluctuation of floating production causes the intense response and greatest fatigue damage near the Touchdown Point (TDP) where the Steel Catenary Riser (SCR) first touches the seabed. Therefore, analysis the response of SCRs in the TDP is very important to approximate the behavior of the riser. In this study, initially, the structural parameters (wall thickness and diameter) according to design codes due to the intense climatic conditions are obtained. In the next step, Pipe-soil interaction is modelled using a linear model in the vertical direction and Coulomb friction models in the lateral direction. Also, the significance of SCR-seabed interaction in the global response of riser pipeline at TDP when subjected to random waves on soft clay is analyzed based on the Caspian Sea environmental conditions. A fully three-dimensional non-linear time domain finite element program with a robust meshing technique has been applied to simulate the haphazard large deflections of the flexible from the initial configuration by using the commercial software OrcaFlex.

1. Introduction

Offshore riser technology is the first priority in deep water technologies. Due to the development of oil and gas resources toward in deep waters with especial environmental and loading conditions such as the Caspian Sea, the precise study of different effect parameters on dynamic behavior of marine risers is mandatory to achieve the proper design, which is the main requirement of the deep water technology [1].

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Deep sea or ultra-deep water has required a transition to Steel Catenary Riser (SCR) systems instead of the conventional methods. SCRs offer a low-cost alternative to the rigid and flexible risers on the floating platforms and also provides an economic solution for fixed platforms by relative cost savings made as a result of the simplified arrangement [2]. Fluctuation of a floating vessel unit which is attached to a SCR in upper end and near its Touchdown Area cause to contacting with the seabed. The vessel oscillations can cause an intense riser response, which having a sudden consequence in criteria of riser strength. ROV surveys has been shown deeply trench under the SCR that shown cutting area into the seabed [3].

SCRs have been associated with floating platforms since the mid-1990s and were first used as export risers for the Auger TLP [4]. In order to progress for more applications export risers have been used for semisubmersibles and FPSOs [5]. SCRs are under of much continuing research, specially with regard to interaction with the seabed and fatigue [6]. Seyed investigated the sensitivity of flexible riser performance to a series of structural and environmental parameters [7-8].

The total proven reserves of the Iranian Sardar-e Jangal gas field, as specified by the Iranian Ministry of Petroleum, are around 1.4 trillion cubic meters. Therefore, study in this area is increasingly essential. The appeal of research in this topic is inevitable for the Iranian petroleum industry [9].

In this paper the minimum wall thickness and diameter of the riser are obtained based on design codes, also discussed the importance of the SCR's geometry, wave and current directions and SCR-seabed soil interaction using the nonlinear finite element model for a time domain simulation. The numerical results of the riser's response regards to critical point in the TDZ are demonstrated. The seabed was modelled using a linear spring-riser model [10] in the vertical seabed direction, and Coulomb friction approach [11-13] lateral soil model direction. In this paper the seabed was modeled and compared at rigid and linear models, therefore dissembles the nature of the trenching development process into the seabed.

2. Calculation of minimum wall thickness

As shown in Fig. 1, 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, study and research in this area, such as obtaining the structural characteristics of marine risers according to the environmental conditions of the Caspian Sea is increasingly essential.

Oil and gas fields fluctuate in geology and environments, and these differences can cause to different riser's design methods. SCRs are subjected to different types of loads and deformations. The scopes of SCRs design is to perform the systems that can tolerate load effects in conjunction with its predicted lifetime. The design is secure if the opposition is more than response and the ratio of response over opposition should be less than acceptance criteria or allowable factor. Safety factor must be assimilated to design check regarding to account for various uncertainties due to natural variability, inexactitude in analysis procedures and control of load effects and uncertainties in structural resistance.

Fig. 1. Location of Sardar-e Jangal gas field

There are two methods to found acceptance criteria in structural design. One method is often referred to as Working Stress Design (WSD) where unique safety factor is used for each limit state in order to consideration of uncertainties. Another method is regarding to as Load and Resistance Factor Design (LRFD) where partial safety factor is applied for each load effect and resistance. In riser systems design, WSD is provided in API-RP-2RD; meanwhile, LRFD is provided in DnV-OS-F201.

WSD method has been widely used in industry. This approach can lead to more conservative designs. As the complexity of riser design systems increases because of ongoing to deeper water field developments and intense environment, a more economical riser design is being pursued. LRFD method provides more consistency design because it allows the loading uncertainty to be accounted for in the load factor and the uncertainty in yield stress to be accounted for in the material partial safety factor. The wall thickness of the SCR is calculated in the first step of design. It shall be designed to tolerate pressure containment (burst criteria) and collapse criteria. In addition, corrosion allowance shall be considered. For deep water field development, resistance to collapse is the major driver for deciding minimum wall thickness [14-16].

Table 1. shows the minimum wall thickness requirement for 419mm (16.5”) ID, X65 material steel grade and internal design pressure of 20,000kpa [17] for Sardar-e Jangal gas field in the Caspian Sea.

Table 1. Minimum wall thickness requirement (mm)

API-RP-2RD		DnV-OS-F201			
Hydrostatic collapse	Collapse propagation	Burst operation	Burst system test	Collapse	Propagating buckling
17.9	29.2	20.3	18	15	30

The highest requirement for wall thickness is given by propagating buckling (30mm). In order to keep local buckle remains local and does not lead to the successive collapse of neighboring pipe section, the relatively thick section is required. It is the reason why propagating buckling appears to be a driven criterion. In practice, it will not be economical to design the riser that can have the ability to prevent propagating buckling by its section, because it can easily be prevented by providing buckle arrestor at some critical regions. Hence, minimum wall thickness of 21mm is used for this study.

3. Numerical modeling of marine riser

Floating operation can be under the large static lateral displacements due to environmental conditions such as wind, current, and other loads in different directions. The static deviation of vessel concerns to operating extreme reaction for intact mooring condition analysis is 10% of water depth and 12% for failure condition. When these displacements are in the plane and out of the plane of a steel catenary riser, This can lead to major changes in the TDP area as illustrated in Fig. 2. There is an origin in the location of floating platform on the surface of the water and shows the mean of position. Y axis is in an upward direction. The SCR is shown based on the position of floating platform at three locations: near, mean and far, respectively at coordinates (+70,0,0), (0,0,0) and (-70,0,0).

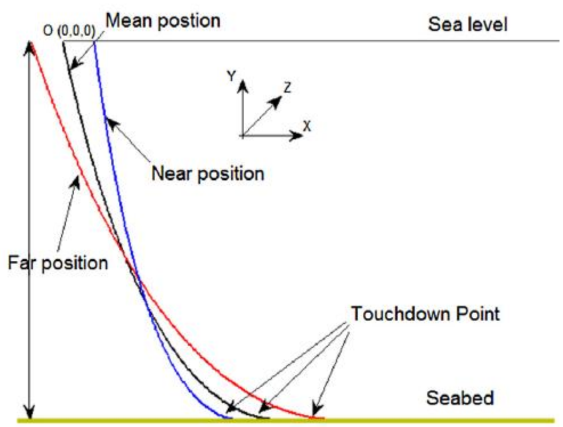


Fig. 2. Static configuration of SCR under vessel offset [18]

OrcaFlex is a fully three dimensional non-linear time domain finite element model, which it has been used for 3D numerical simulations of the marine riser. The conventional shape of riser attached to the vessel has been factor in based on Fig. 3. The linear seabed model embedded in this study is conceptually based on the position of the nodes and their direction of movement on the riser body at all the increasing time associated with cyclic loading.

In the linear model, upward displacement is equal to downward displacement. Due to the influence of linear spring, the support forces increase without any limitations by increasing the relative displacement [10].

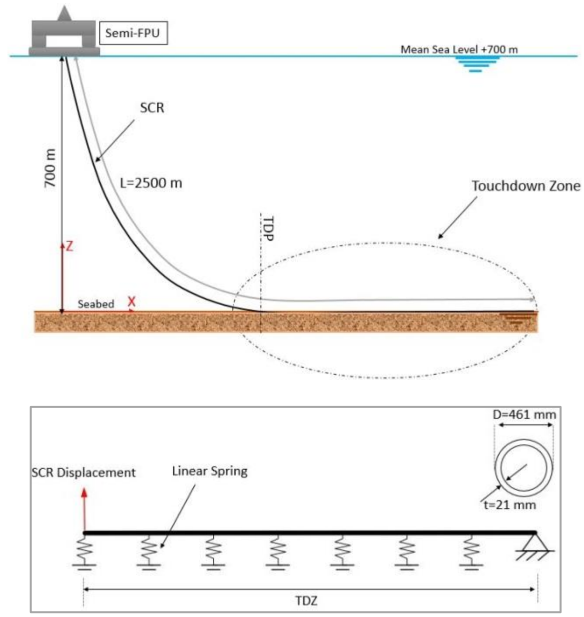


Fig. 3. Pipe-linear soil spring support model

It is found that the dynamic behavior of the riser has a prominent point to fatigue life. Therefore, the effects of the dynamic behavior of the riser include drag, inertia, and also added mass to make the evaluation more realistic. The system has been studied based on displacement control, quasi-static and dynamic analyses with the floating excitation based on generic approximated RAOs from the Caspian Sea. Also, since all consideration are based on displacement control, the vessel is excited by two dimensional deviations from RAO's general estimation. Therefore, no hydrodynamic software is required to obtain floating RAO under environmental loads, which is a major exercise in load-control analysis [19].

The dynamic analysis is exerted for 0˚, 180˚ (i.e., in-plane force cases) and 90˚ (i.e., lateral force case) wave directions. The response analysis is specified by

- According to applied the finite element modeling, SCR line has been discretizing into a series of line parts that modelled by considering the nod at each end accordance with straight massless model segments.
- The SCR's static shape is established.
- Non-linear time domain is used to analysis the response of the riser, calculation of the SCR physical shape and stresses are at each constant time step is done with a duplicate procedure, and the riser's dynamic response has been estimated by the integration layout (i.e., forward Euler). Dynamic analysis is the temporal simulation of motion in a particular time period which has been started from the position of static analysis.

4. Parametric studies of marine riser dynamics

SCR failures reduce or suspend production and revenue. It can also lead to shedding or contamination and may endanger life. The main factors to control the bending stress in the risers are riser characteristics, environmental criteria and touchdown zone characteristics (seabed stiffness, friction coefficient). Parametric studies relevant to these factors were conducted with the pipe-linear soil spring support model as shown in Fig. 3. The intricate interaction between the SCR and the seafloor is examined when the SCR is exposed to oscillatory motions. The most important fatigue focus occurs in TDZ. Riser-seafloor interaction is an essential factor to consider in assessing strength and fatigue. The exact pattern of this response has been a upstanding topic for academic research [20].

5. Case Study

5.1. Environmental Conditions

Wave conditions can be pinpointed by a deterministic design or by using wave spectra. Most spectra are described in terms of significant wave height (Hs), spectral peak period(Tp), spectral shape and direction. For design purposes, design of SCR has been done for a 100-year wave condition combined with a 10-year current profile, based on DnV acute environmental condition [21]. For the Caspian Sea, a 100-year return period is given as:

- $H_s = 8m$
- $T_p = 12.47s$

After consideration of Joint North Sea Wave Observation Project (JONSWAP) data's, Hasselmann et al. (1973), found that the wave spectrum was never fully developed. An additional factor was added to improve the Pearson-Moskowitz. Hence, the JONSWAP is the Pierson-Moskowitz spectrum multiplied by an additional peak amplification factor. The location of the study area determines which spectral model should be used. Regarding to dominant wave spectrum in the Caspian Sea, JONSWAP will eventually be used in the analysis of this paper. The spectrum results is

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

Where

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

$$\sigma = 0.07 \text{ When } f < f_p$$

$$\sigma = 0.09 \text{ When } f \geq f_p$$

In Eq. (1), γ usually has values of 1.6 to 6, but 3.3 is recommended for general usage, f_p is the peak frequency and α coefficient is ٠.08 and 0.008 respectively [22-23]. The corresponding 10-year current profile is shown in Table 2.

- $\rho_{sw} = 1025\,kg/m^3$
- $Depth = 700\,m$

Table 2. Current velocity and water depth

Water depth (m)	Current velocity (m/s)
0 at mean sea level	0.66
700	0

5.2. Delination of SCR model

The SCR come down from a semisubmersible-FPU in a simple hanging catenary shape, transitioning to an export flow line after 700m, and the riser is connected to the vessel at a top angle of 20° to the vertical, as shown in Fig. 3. The outside diameter is 461mm (18 in.) with a wall thickness of 21mm (0.825 in.), and a total riser pipe length is 2500m. The riser created of line pipe with 448MPa of yield stress. The drag coefficient (C_d) can be specified to vary with the Reynolds number (R_e). The drag coefficient as a function of the Reynolds number, C_d (R_e). The inertia coefficient C_M used in this analysis is 2.0, and the added mass coefficient is 1.0, as shown in Table 3. The model parameters and SCR properties are shown in Tables 4.

Table 3. Transverse hydrodynamic coefficients for Morison's equation

Riser transverse hydrodynamic coefficient		
Drag (C_D)	Inertia (C_I)	Added mass (C_A)
1.2	2	1

Table 4. Riser pipe parameters

Parameters	Symbol	Value
Outer diameter	D_o	461mm
Wall thickness	t	21mm
Coating thickness	$t_{coating}$	75mm
Pipe wall modulus	E	207GPa
Yield stress	σ_y	448MPa
Coating density	$\rho_{coating}$	800kg/m³
Steel density	ρ	7850kg/m³

5.3. Seabed soil condition

The riser-seabed interaction model includes of seafloor hardness and equivalent friction equilibrium to show the soil resistance to pipe movement. Many of the new discoveries in deep water fields are in areas where soft clay is identified. Therefore, in this study, soft clay is considered as soil type.

5.3.1. Vertical displacement model

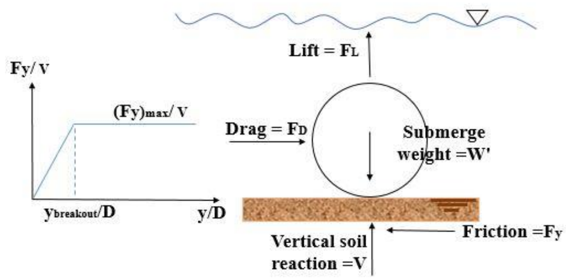
The seafloor is usually modeled as a spring-moist surface with a spring reaction force that is proportional to the depth of penetration and contact area, plus a damping force that is proportional to the penetration rate. The hardness of the seabed is proportional to the spring force and is equal to the spring reaction force per unit area of contact with the penetration depth unit. The damping of the seabed is proportional to the damping force and is a percentage of the critical damping [12].

5.3.2. Lateral displacement model

As shown in Fig. 4, soil resistance model has been estimated by coulomb friction model which shown the lateral resistance as depended on soil friction coefficient and inundated vertical soil reaction force of pipeline (inundated weight of pipeline minus hydrodynamic lift force). The traditional soil-SCR interaction design process has been done with considering a spring links at intervals along the riser.

In accordance with the coulomb friction model, the seabed friction force has a value with greatness μV . μ is the friction coefficient and V is the seabed reaction force, and actions tangentially on seabed surface. The SCR, in contact position of touch down area, holds the position of objective friction, and a friction force is exerted that actions on this objective position.

The fracture force is the maximum force required to displace the pipe from its stable position in the seafloor. Friction force has been embedded as a linear model by $F = -K_s Ay$, which μV is maximum value. A and y is the contact diameter multiplied by the length of the line and displacement from the un-sheared position respectively. Seabed shear stiffness shown by K_s. The friction force models $-\mu V$ to $+\mu V$ which occurs as a linear variation over the deflection range $-y_{breakout}$ to $+y_{breakout}$. $y_{breakout}$ was given by $y_{breakout} = \mu V / K_s A$. Recommended values of the Coulomb friction coefficient is in the range 0.2–0.8 and in this study is used 0.2 for soft clay, while the displacement to mobilize this resistance is typically 0.1 pipe diameters [20].



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

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

Fig. 4. Coulomb friction model

6. Results and discussion

6.1. Global riser response

As shown the allowable Von Mises stresses of the riser in Table 5, the 0˚, 180˚ (in-plane load cases) and 90˚ (out-of-plane load case) wave and current directions with the situation of vessel in near, mean and far. The vessel offsets and dynamic motions in an intense environmental condition effects the stresses in touch down zone, where the riser starts to contact the seabed. At TDZ the maximum critical part for the stress has been accured with domination of excursion and cyclic fluctuations of the vessel.

The riser is analyzed for the exessive operating intact mooring conditions. The excessive analyses carried out for the load cases which have been shown by API RP 2RD, and the strength analysis is done for the far postion (when the vessel departured away from the TDP) and near position (when the vessel departured near to the TDP, see Fig. 5), and vessel departure to the transverse position. A 100-year wave is synthesized with a 10-year current. The summary of these strength analyses is presented in Table 6. As shown most critical section for the Von Mises stress occurs at the TDZ.

The Von Mises stresses/σ_y magnitudes, along the riser are shown in Fig. 6, for the 0˚, 90˚ and 180˚ wave and current directions vessel is in near situation. The vessel devition and dynamic flactuation in a intense environment effects the stresses in the TDZ. At the TDZ the maximum critical part for the Von Mises stress has been occured, and the model analyses show the maximum change in the bending moment near the TDZ, with domination of excursion and cyclic fluctuations of the vessel.. Deviation of the vessel influances the maximum Von Mises stress at the TDP and top-end maximum tension of riser.

The calculation of Von mises stresses has been affected by seabed interaction model. For instance, when the linear soil model is used, the state of 0˚ wave and current direction, intact mooring and near deviation, gives Von Mises utilization of 0.78 while a value of 0.8 are reported in state of exerting the rigid plane for the seabed soil model. So, appraisal of dynamic response of riser is affected by embedded soil model. The soil parameters have an imperceptible effect on the total risers dynamic response. however the results of analysis have been shown that the SCR has a acceptable status for strength performance, it is vital to note that the strength analyses are done with the same vessel devitions, wave and current data for near and far situations and intact excessive operating status.

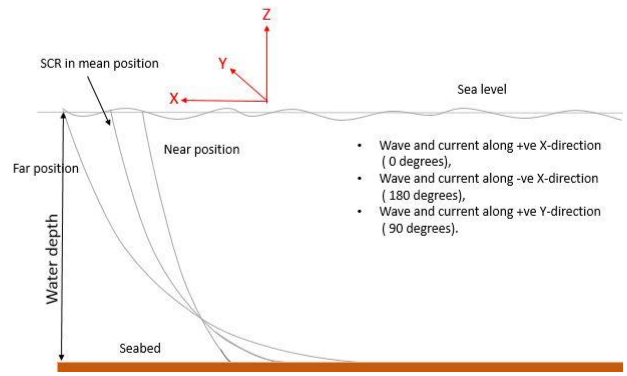


Fig. 5. Static configuration of SCR under vessel offset

Table 5. Results of Strength analyses (3-hour simulation time period)

Wave and current direction	Mooring condition	Riser offset position	Max Von. Mises stress/$\sigma_y$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	

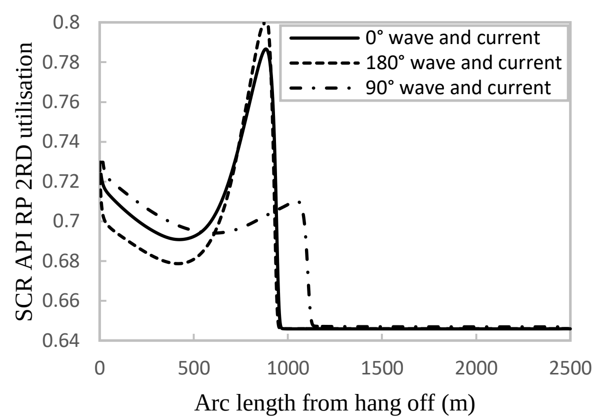


Fig. 6. API RP 2RD manipulation along the riser arc length in the near situation

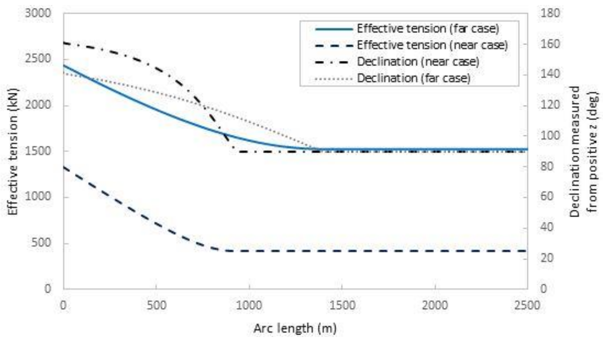


Fig. 7. Static response of riser for 180˚ wave and current direction

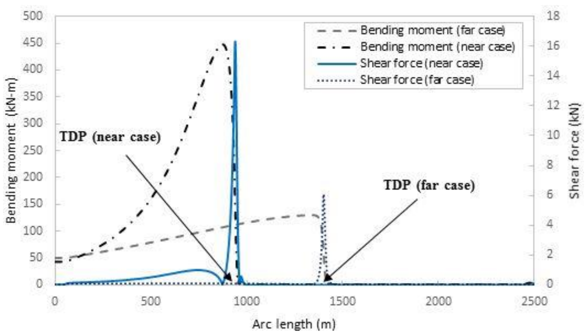


Fig. 8. Static response of riser for 180˚ wave and current direction

After modeling the riser at each position of the floating platform separately, the dynamic cyclic fluctuations of riser has been caused to increasing of embedment of the riser beyond that produced by the static load. The effective tension, declination, bending moment and shear force are obtained and demonstrated together base on the riser length measured from the vessel. The vessel deviation rules the maximum bending moment and shear force at the TDP and the maximum tope-end effective tension of riser as shown in Figs. 7-8.

In the riser-seabed static response, as shown in Figs. 9-10, the seabed resistance and seabed penetration are obtained to emphasize the area of seabed clash. TDP position is placed at length of 937m in the near load state and 1397m in the far load state, as indicated from the floating vessel, with a maximum static seabed penetration of 0.045D happening 10m back to the TDP and corresponding to the maximum seabed resistance of 3.87D, compared with 9.3D kPa when rigid seabed plane is applied for the near load case.

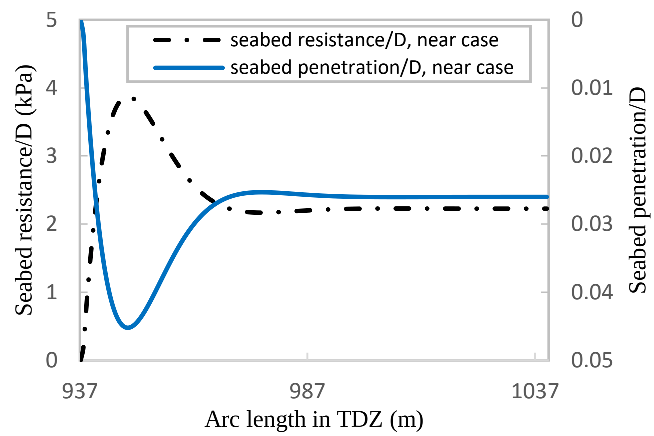


Fig. 9. Static response of riser for 180˚ wave and current direction in near case

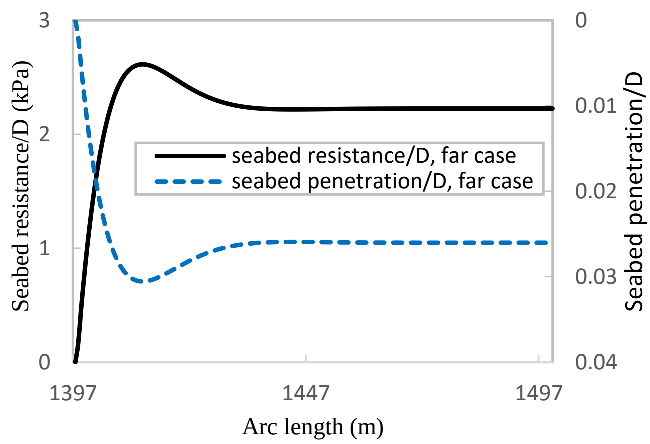


Fig. 10. Static response of riser for 180˚ wave and current direction in far case

6.2. Riser–seabed vertical interaction response

The dynamic penetration of riser-seafloor has been shown as seabed penetration/D, and dynamic contact resistance at the seafloor, is expressed as seabed resistance/D, as shown in Figs. 11-12, for the 180˚ wave and current direction. In the TDZ the vertical cyclic fluctuation of riser has a noticably effect on riser. The linear soil model in the vertical direction is embedded to model. The influence of the linear vertical soil models on the riser embedment is shown in Fig. 11. It is shown that the soil resistance in linear seabed model is reduced ,correspondingly, the riser's pipe penetration into the seabed is increased when the soil is modeled as linear (Fig. 12). Finally as shown in Fig. 13, the linear seabed model has the greatest influences on the riser at the TDP compared to the rigid seabed.

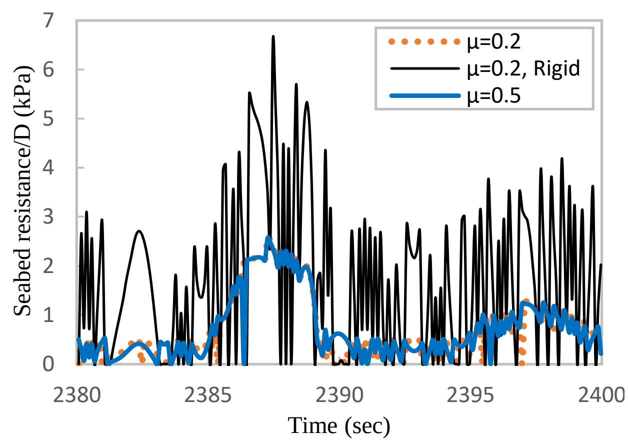


Fig. 11. Dynamic riser-seabed clash resistance in near state (3-hour simulation)

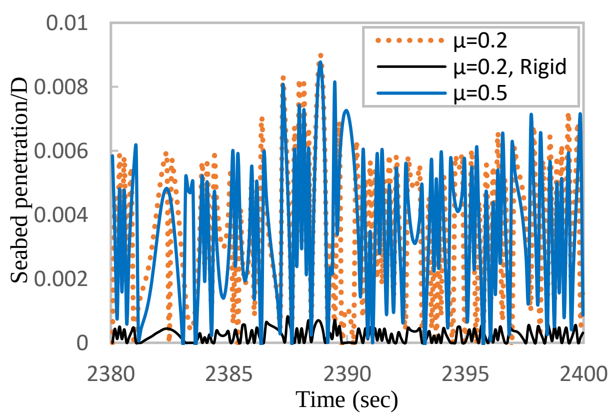


Fig. 12. Riser Displacement at TDP

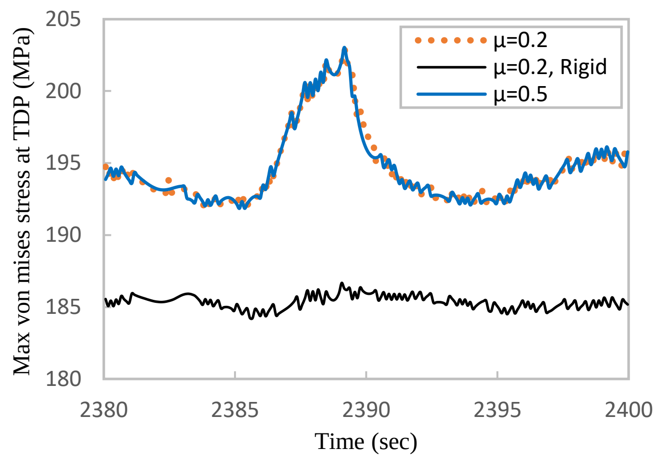


Fig. 13. Maximum Von Mises stress at TDP

6.3. Riser–seabed lateral interaction response

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

The linear riser-seabed resistance model also affects the maximum effective tension along the total length of riser. Fig. 14 shows the impressible tension along the riser by exerting a soft clay with the seabed sliding friction coefficient 0.2 and 0.5 in the linear seabed model and rigid soil model for the vertical direction. The effective stress has been representing with $T_{eff} = T_W - P_i A_i + P_o A_o$, which T_w is the riser body stress, P_i is the internal pressure, P_0 is the external pressure and A_i and A_0 are the internal and external regions, respectively.

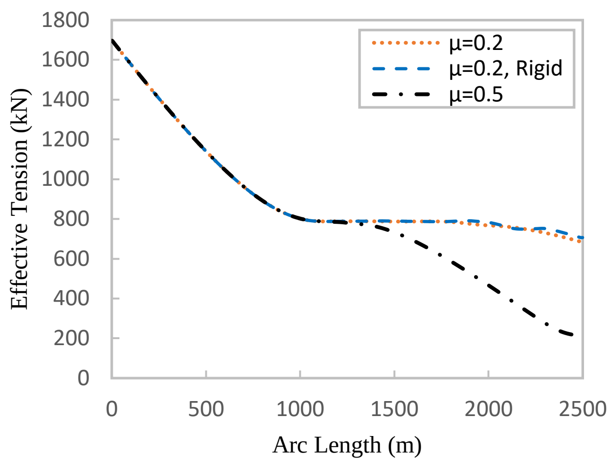


Fig. 14. Maximum impressible tension along the riser

The model has been done in order to simulate the risers response by its lateral displacement calculation by using the intense environmental condition of a 100-year wave combined with a 10-year current, which is shown in Figs. 15-16. The analysis is carried out by implementing the Coulomb friction model. Fig. 16 shows the effect of linear and rigid soil models on the specified length (1120 m) of the riser in the TDZ within 3-hour simulation time. The lateral riser's movement in the TDZ gained with the linear soil model is less than the rigid soil model for the same sliding friction factor ($\mu = 0.2$) because of the effect of the passive soil resistance.

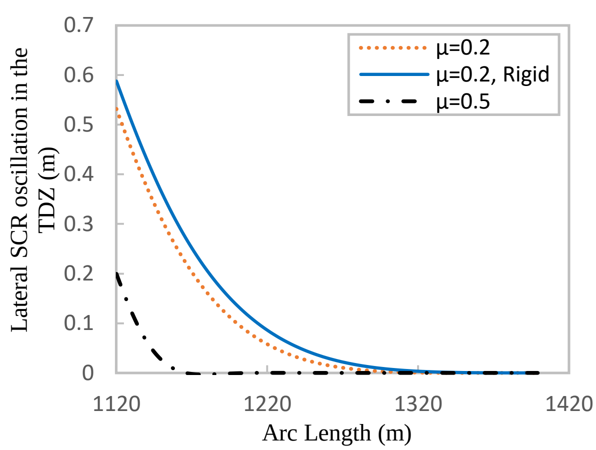


Fig. 15. Dynamic lateral fluctuation of riser in TDZ

(3-hour simulation)

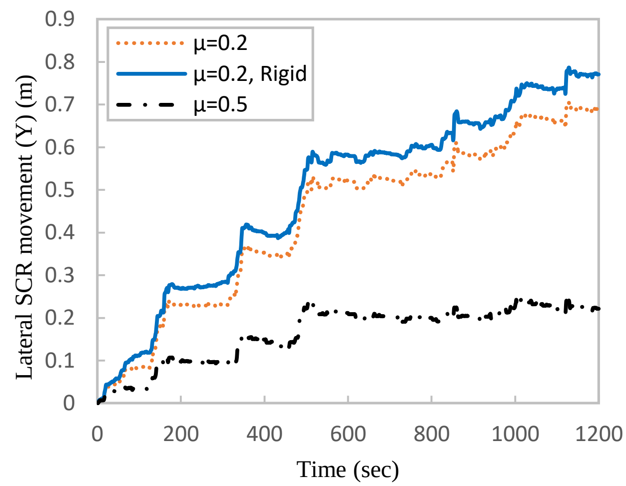


Fig. 16. Lateral interaction of SCR–seabed at length 1120m

7. Conclusions

The initial sizing of the wall thickness of the marine risers is controlled by collapse pressure. It is the case in deepwater application because external hydrostatic pressure increases with water depth. Bases on the API-RP-2RD and DnV-OS-F201 codes, the minimum wall thickness and diameter are suggested (21mm for wall thickness and 461mm (18") for outer diameter) for the proper steel catenary risers in the Caspian Sea.

In this paper, a steel catenary riser is modeled according to the environmental condition of the Caspian Sea using a finite element program. The effect of random wave angle of incidence on riser and contribution of vessel transfer functions are considered. It is shown that the maximum difference of bending moment near the TDZ affects the deviation and cyclic fluctuations of the vessel.

This paper describes a detailed analysis of the riser connected to a Semi-FPU in the Caspian Sea environment for intact mooring statuses in a intense environment. The dynamic analysis is carried out for wave and current status of 0˚, 180˚ and 90˚. in-plane load cases for the 180˚ and out-of-plane load case 90˚. The effect of wave and current direction of total dynamic response of riser is considerable.

Due to climatic conditions in the Caspian Sea and the physical characteristics of riser pipe including diameters and length, the maximum displacement of the floating vessel should not be exceeded more than 70 meters. Otherwise, if it exceeded the acceptable values, it can lead to damage of the riser pipeline in the critical area such as TDP.

In this paper, the effect of linear and rigid soil models on the behavior of riser pipeline in accordance with the real environmental conditions in the CaspianSea is investigated. The noticeable of the riser-seabed interaction on design of riser are investigated and the analysis of a riser on soft clay in the 700m water depth based on the Sardar-e Jangal gas field are discussed.

This study also highlights potential lateral soil resistance models that shown the lateral displacement of SCR-seabed interaction obtained with a linear soil model is smaller than the rigid soil.

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