Chapter

Geotechnical Response Models for Steel Compliant Riser in Deepwater Clays

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Abstract

The touchdown zone (TDZ) often proves to be a spot where cyclic bending stresses are the largest and is therefore a critical location for fatigue. Catenary steel compliant pipelines or risers (SCRs) are subject of much ongoing research, particularly with respect to their fatigue life, which is strongly influenced by seabed soil conditions in the TDZ. This chapter reviews the recent publications that might have an impact on the SCR-seabed interaction. The review starts by looking at the SCR general arrangement. Thereafter, the focus moves to the review of the recent research that studied the interactions between deepwater SCRs and the seabed. In addition, the review went over the analysis techniques of the SCR, including the modelling philosophy and models for geotechnical response. The research gap and the need for future research are identified.

Keywords: steel catenary pipeline, touchdown zone, rigid seabed, non-linear seabed model, lateral soil resistance, geotechnical response

1. Introduction

Catenary steel compliant risers (SCRs) have joined the riser family, building on the catenary equation that has assisted in creating bridges across the world. SCRs are commonly used with TLPs, FPSOs, semisubmersibles and spars, as well as fixed structures, compliant towers and gravity structures. SCRs have been accompanied by floating platforms since 1994 and were first used as export risers for Auger TLP in an 872 m water depth [1, 2]. Since then, SCRs have been employed with many applications. The number of SCRs is increasing quickly because of its simplicity, economic effectiveness, and well-known material properties. A free-hanging simple catenary riser is connected to a floating production vessel and the riser hangs at a prescribed top angle. The riser is free-hanging and gently curves down to the seabed at the touchdown point (TDP). At the TDP, the SCR pipe embeds itself in a trench and then evenly rises to the surface where it rests, and is effectively a static pipeline. SCRs may be described as consisting of three portions [3], as shown in **Figure 1**:

- Catenary zone, where the riser suspends in a catenary section
- Buried zone, where the riser pipe penetrates into a trench
- Surface zone, where the riser pipeline rests on the seabed.

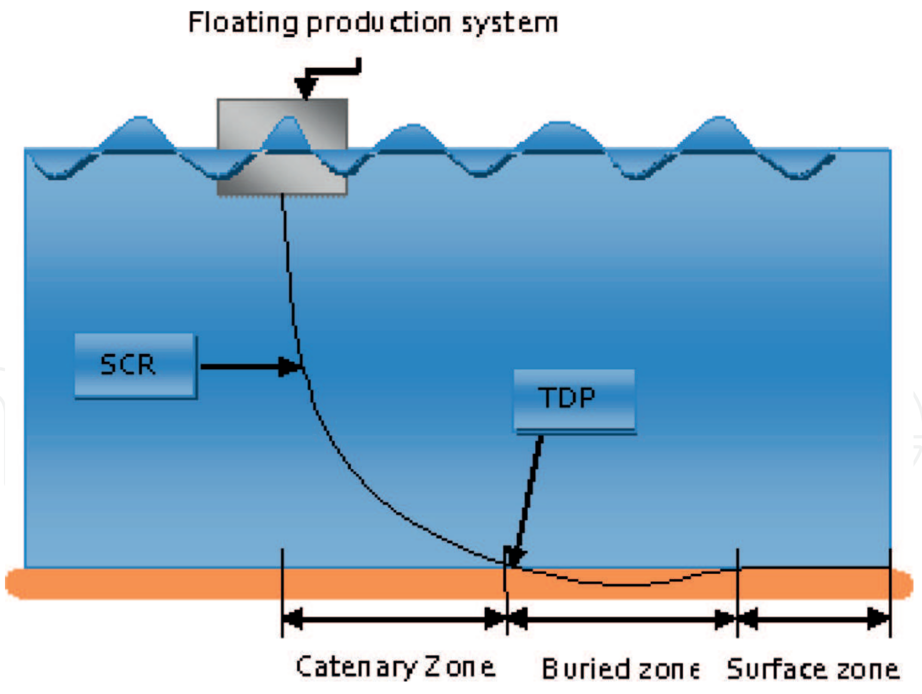

Figure 1.
General SCR arrangement.

A complex interaction between the SCR and seabed is experienced when the SCR is subjected to oscillatory motions. For SCRs, the most critical fatigue hotspot occurs in the TDZ. The SCR-seabed interaction is an essential key factor that should be considered in strength and fatigue assessment. How to precisely model this interaction response is still an issue and has been a hot field for academic research. A number of researches have been focused on understanding the soil-riser interaction. Better predictions of the SCR's fatigue life require an accurate characterisation model of seabed stiffness as well as a realistic description of the load/deflection curve. Therefore, this chapter gives a state-of-the-art review of the recent research on soil-riser interaction models. Briefly, a series of previous work associated with seabed-riser interaction mechanism and simulation models, as well as load/deflection models, will be described and discussed.

2. SCR configuration design

The catenary riser length is estimated using simple geometric considerations, as following [4]:

$$L = \left(\frac{D - (MBR)A}{\cos\theta}\right) + (0.5\pi(MBR)A) \tag{1}$$

where L is the total length of the riser, D is the water depth, A is a factor depending on severity of environment (1.0 for mild environments and 1.2 for severe environments), θ is the riser top angle to vertical, typically between 10 and 25 degrees depending on severity of environment and water depth, and MBR is minimum bend radius based on 80% material yield strength. An additional riser pipeline length of approximately 750 m should be included to allow for TDP movement between near and far offset conditions as shown in **Figure 2**.

The SCR's static configuration must be determined before carrying out the dynamic analysis. The initial stage of any analysis of an SCR is the computation of

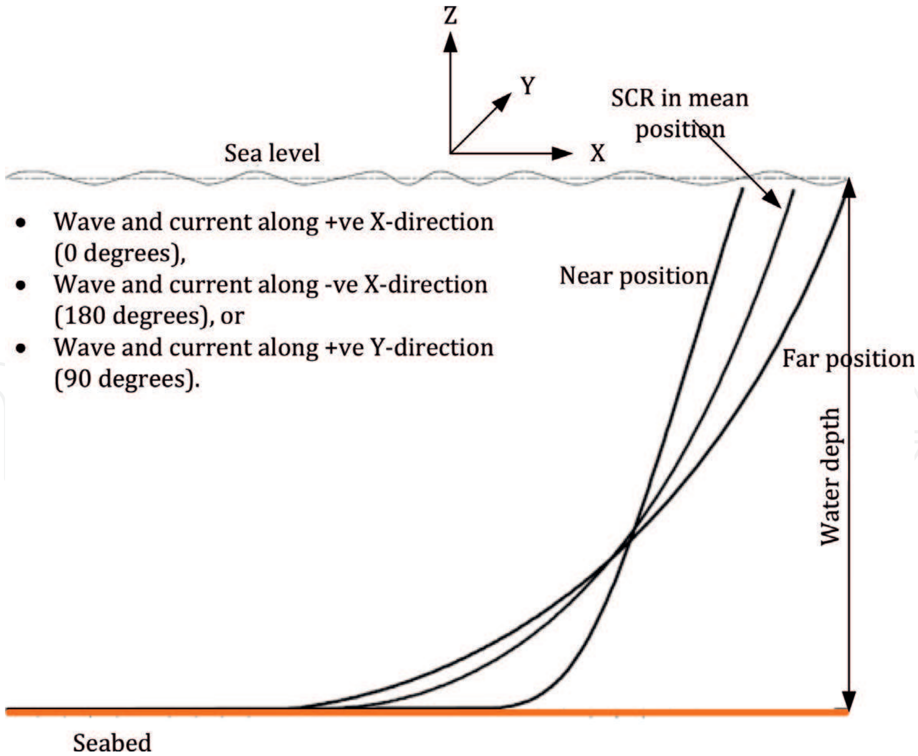

Figure 2.
Schematic of SCR configuration and vessel offsets.

its configuration under a set of static forces. The catenary equation gives a good first approximation for this, but in their basic formulation it only involves loads due to riser weight and assumes a riser pipe of zero bending stiffness, as presented before. However, the SCR static analysis is a large deflection non-linear behaviour problem with the influences of bending and tensional stiffness included. Therefore, many approaches have been developed to handle this problem using a combination of catenary equations and numerical techniques through iterative analysis. A review of existing approaches can be found in [5]. **Figure 3** shows an example of static configuration of an SCR in a 910 m water depth with a hang-off angle of 20° and a 273 mm outer diameter connected to the floating platform (FP) in the zero mean offset position (i.e., the FP is in its initial position without drifting in any direction), which is calculated using OrcaFlex/finite element analysis (FEA) software.

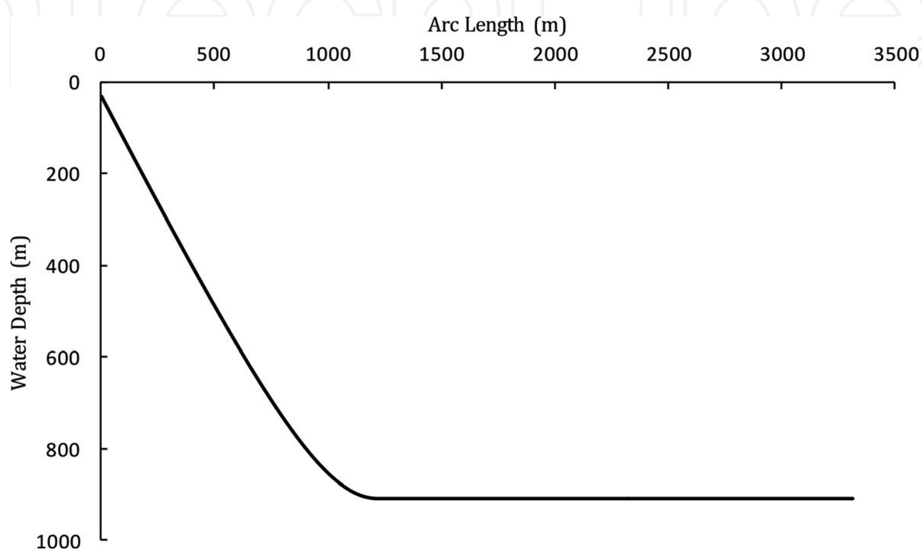

Figure 3.
Static configuration of SCR model.

Generally, SCRs have a limited amount of additional pipeline length available to accommodate the FP motions. Alterations in the catenary suspended length are obtained by the riser either being picked up or laid down on the seabed. Limitations are approached when either the SCR tension at the FP becomes too great as the FP drifts away from the TDP (far load case, as shown before in **Figure 2**) or when the bending stresses near the seabed become too great as the FP drifts towards the touchdown point (near load case). SCRs are less appropriate for FPSO applications where vessel offsets are considerably higher. **Figure 4** shows the effect of the horizontal vessel offset on the horizontal projection of the TDP. While the top of the SCR has the highest tension and lowest bending moment, the TDP has the lowest tension and the highest bending moment. The maximum bending stress and effective tension along the SCRs' arc length and the horizontal projection of the TDP due to the vessel offsets are presented in **Figures 5** and **6**, respectively.

The vessel offset governs the maximum bending stress at the TDP and also the maximum tension at the riser's top end. In the left region of **Figure 6**, where the

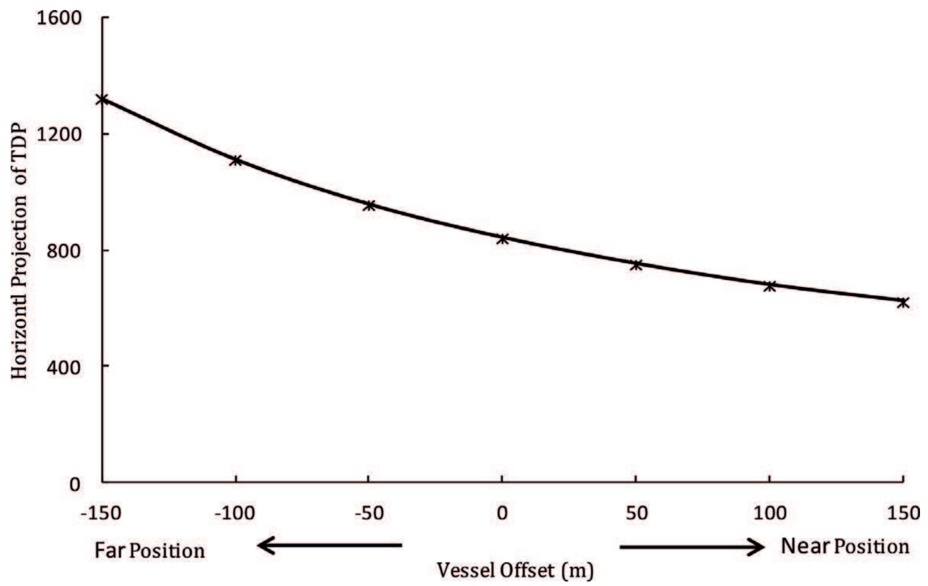

Figure 4.
Effect of the vessel offsets on the horizontal projection of the TDP.

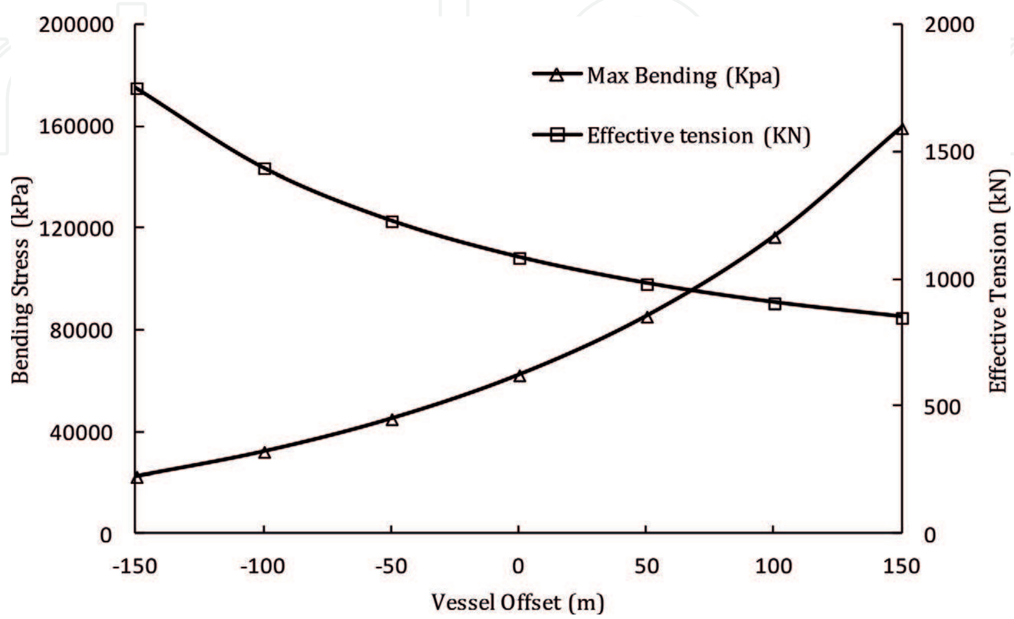

Figure 5.
Alterations of maximum bending stress and maximum effective tension with the horizontal vessel offset.

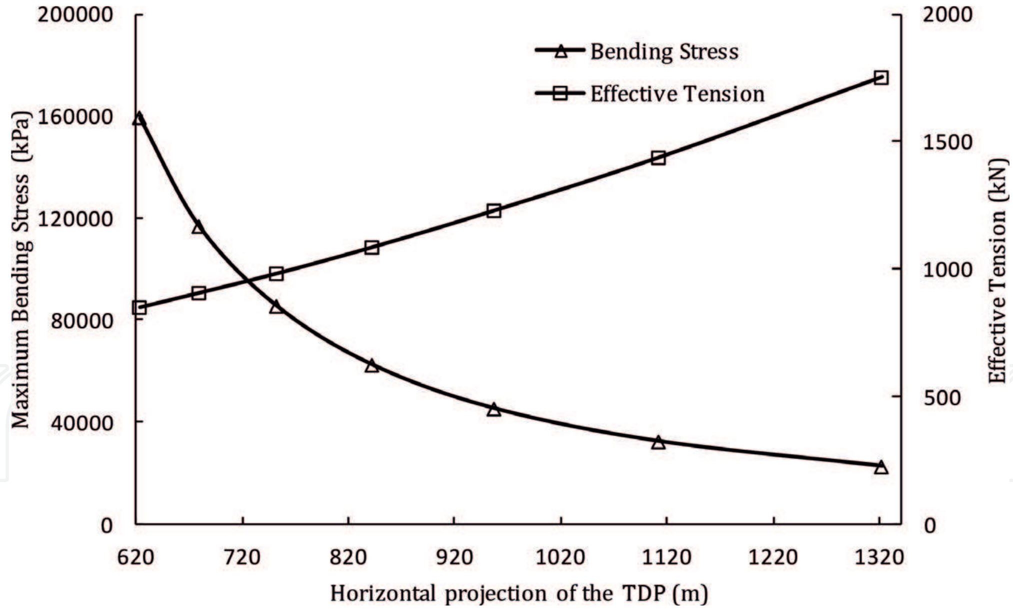

Figure 6.
Alterations of maximum bending stress and effective tension with the horizontal projection of the TDP.

vessel drifts towards the TDP (near load case), the bending stress at the TDP is increased rapidly within small change in the vessel offset. In the intermediate region, the bending stress and tension are slightly increased with the vessel offset. In the right region, where the vessel drifts away from the TDP (far load case), the bending stress slightly decreased, while the tension increased. Therefore, the conclusion from these results is that the vessel mean position should be offsetting the TDP with a roughly distance of 0.75–1.5 of the water depth. Furthermore, the catenary equation is a simple implementation tool to figure out the load distribution, geometric properties and static loads on an SCR. The specialist non-linear/FEA is implemented for the SCR design to tackle the complex nature of non-linear, large deflection behaviour of SCRs and to be post-processed quickly. The evaluation of the forces and behaviour of SCRs in the TDZ need more sophisticated methods.

3. Models for seabed response

3.1 Problem description of an SCR pipe embedment

SCR pipe penetration is defined as the depth of penetration of the pipe invert (bottom of pipe), relative to the undisturbed seabed as shown in **Figure 7**. Pipe penetration affects the riser pipe-seabed contact area, which subsequently affects the axial and passive soil resistance against the riser. Consequently, the passive soil resistance influences the lateral breakout force. Heave of seabed soil during embedment increases the local penetration of the SCR pipe by raising the soil surface level against the shoulders of the pipe. The typical geometry of heave produced during vertical embedment of an SCR pipe is such that the nominal penetration is approximately 50% less than the local embedment relative to undisturbed seabed surface [6].

The SCR-seabed interaction response characteristic is a highly non-linear phenomenon. It is important not to restrict the modelling of this interaction to a linear seabed model approximation and the riser analysis techniques must be improved by refining the riser-seabed interaction [7]. SCR-seabed interaction modelling should involve vertical and lateral soil responses to the cyclic loading oscillations of the SCR in the TDZ, which can cause trenching and dynamic embedment of the SCR into the

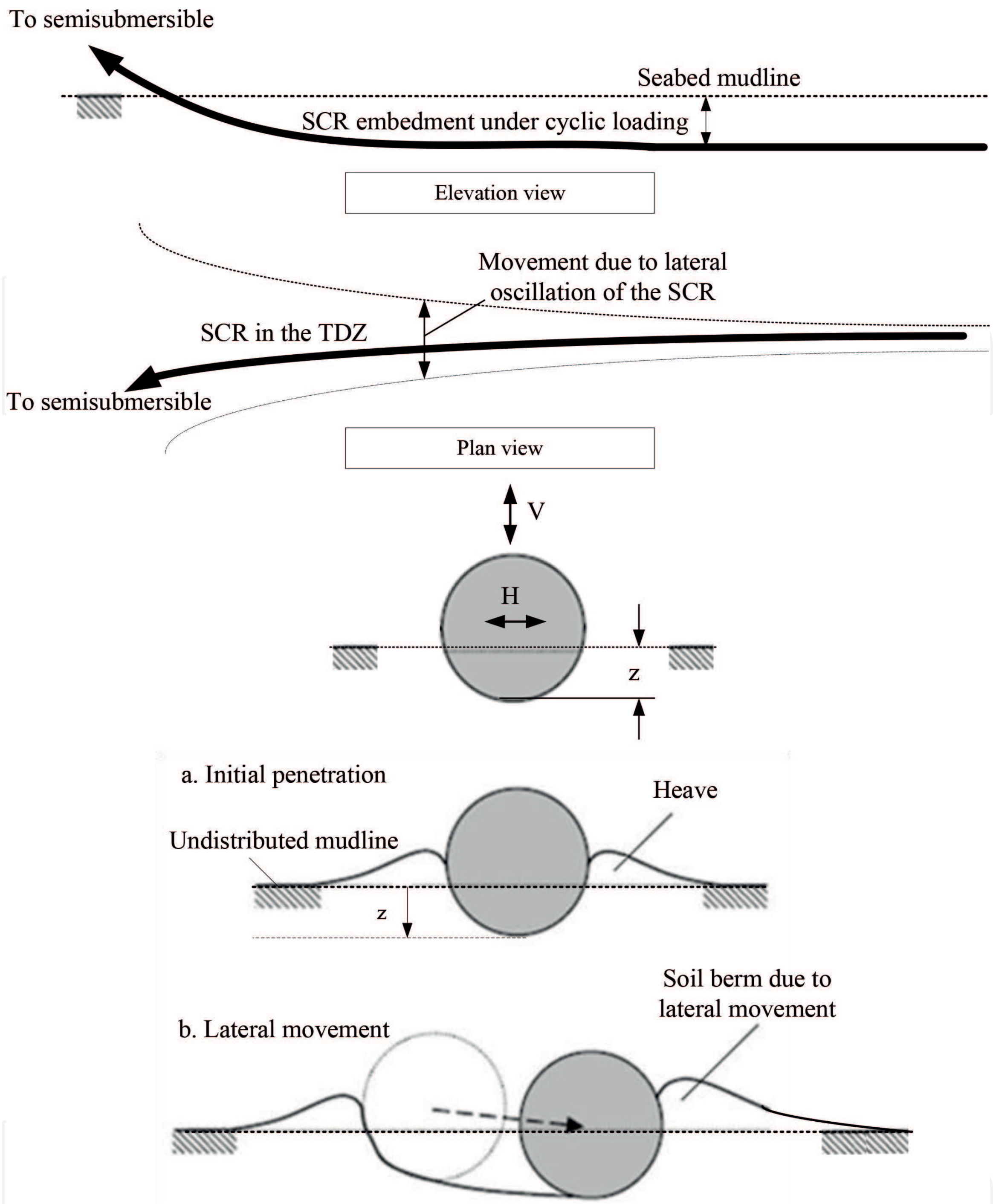

Figure 7.
Schematic illustration of the SCR-seabed interaction in the TDZ.

seabed. A typical schematic illustration of the SCR-seabed interaction and trench formation in the TDZ are shown in **Figure 7**.

3.2 SCR/seabed vertical interaction

The application of SCR systems has increased with the progressive development of hydrocarbon production further offshore and into deeper waters. The SCR-soil interaction at touchdown with the seabed is a major key factor for SCRs. An SCR is subjected to oscillatory motions from the host vessel and wave action. Therefore, the SCR experiences a complex interaction between the riser and seabed in the touchdown area, and deep trenches thus cut into the seabed in the buried zone beyond the TDP [8–10].

An appropriate SCR-seabed interaction model must be used. The TDZ is one of the key locations where the fatigue damage happens. The sophistication of the interaction model depends on the type of analysis and accuracy required. These interaction models vary from a simple rigid seabed with soil friction coefficients to more sophisticated ones, including vertical and lateral stiffness, friction and suction.

3.2.1 Rigid and elastic seabed

A potential fatigue damage of the SCR in the TDZ is related to maximum bending stress in the SCR, which relies on the soil stiffness of the seabed and the motions of the SCR. For example, the SCR on a soft seabed will have reduced bending stresses when a load is applied, while the one on a rigid seabed will have more critical bending stresses. A rigid surface generally contributes a conservative result, since it is unyielding, while the non-linear soil model is a better approximation of a seabed. Extreme offsets of the floating production unit with soft seabed model may then give higher stresses than those calculated on rigid seabed stiffness, since the catenary pipeline must be broken out of the seabed soil and high suction forces must be overcome. **Figure 8** shows a schematic of an SCR close to the TDP with the forces acting on a rigid seabed. The shear force F in the near horizontal segment close to the TDP is given by:

$$F = \frac{dM}{dx} = \frac{d}{dx}\left[EI\left(\frac{d^2y}{dx^2}\right)\right] = EI\left(\frac{d^3y}{dx^3}\right) \quad (2)$$

then $d^3y/dx^3 = (w/H)ke^{-kx}$ and the shear force close to the TDP is thus given by:

$$F = EI\left(\frac{w}{H}\right)ke^{-kx} \quad (3)$$

The bending moment at the TDP diminishes from the catenary bending moment to zero, and there is a concentrated reaction force. Since $k = \sqrt{H/EI}$, the TDP shear force that is transmitted to the soil [2, 11] is given by:

$$F_{TDP} = w\sqrt{EI/H} \quad (4)$$

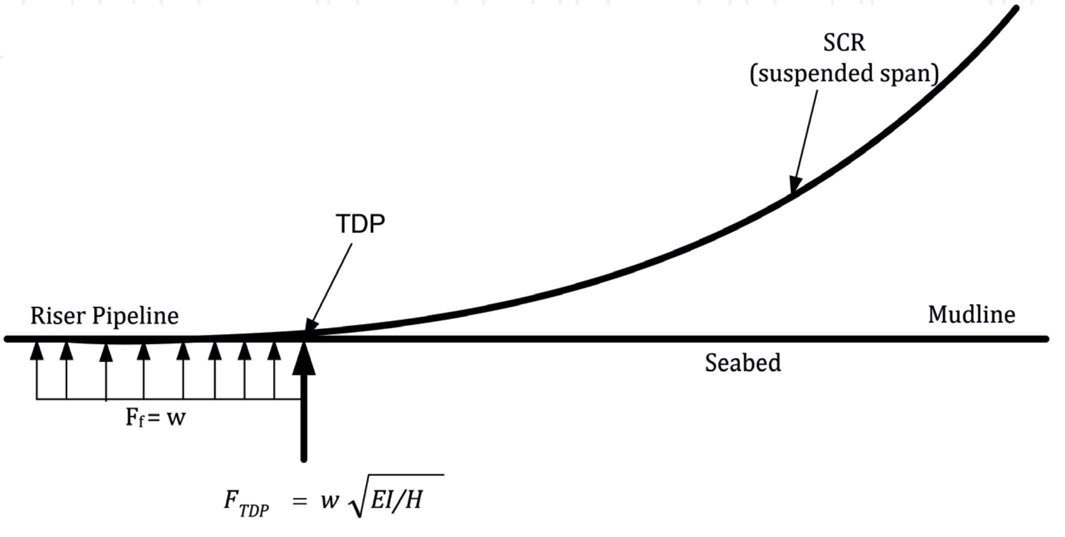

Figure 8.
Configuration of SCR close to TDP with a rigid seabed.

where F_{TDP} is the concentrated reaction at the TDP, assuming a rigid surface seabed, F_f is the reaction to the pipe resting on the seabed, as shown in **Figure 8**.

For the elastic soil response, configuration of an SCR close to the TDP is shown in **Figure 9** by representing a seabed with a linear elastic model. The curvature in the surface zone (i.e., the pipeline is resting on the seabed) is zero. In the TDZ, the riser's pipe is resting on linear elastic foundations. The solution for a beam element resting on an elastic foundation can be found in [12, 13], who introduced solutions that can be implemented for SCR-seabed interaction.

3.2.2 Non-linear load/deflection model

The current practice for the FEA of SCR-seabed interaction response is to model this interaction as structural soil springs [10] by using the developed models for buried pipelines and strip foundation theory. The conventional modelling of riser-seabed interaction use the non-linear elastic load/deflection curves, as described in [14]. Since the resistance force does not exceed the friction resistance limit (μV), the soil spring has a constant stiffness coefficient, K. The load/deflection model has zero resistance force at zero displacement, as the pipe displacement is increasing the resistance force also increases linearly until the peak seabed resistance is approached. When the seabed friction exceeds the limit friction force, the resistance force becomes constant with changing pipe displacement (large displacements occur without a further increase in the friction resistance force) and the spring stiffness becomes zero (i.e., slip occurs). The maximum seabed resistance load is given by the backbone curve [15], which corresponds to virgin penetration of the riser pipe into the seabed.

Linear soil stiffness can be used by FEA codes to model the non-linear riser-seabed interaction curves. Linear soil stiffness is defined as the ultimate bearing load divided by the riser pipe displacement, as given below:

$$K = \frac{V}{\Delta} \tag{5}$$

where K is the soil stiffness per unit length; V is the force per unit length; Δ is the riser pipe displacement. Different approaches are used to characterise the linear seabed stiffness, such as secant, tangent and Young's modulus stiffness, for more details see Barltrop et al. [16]. Herein, the secant stiffness type is considered because it is more stable than the tangent stiffness approach and is being used to model the load/deflection curve. The secant stiffness is the average stiffness between two points, typically the origin and the point in question, see **Figure 10**. Static seabed

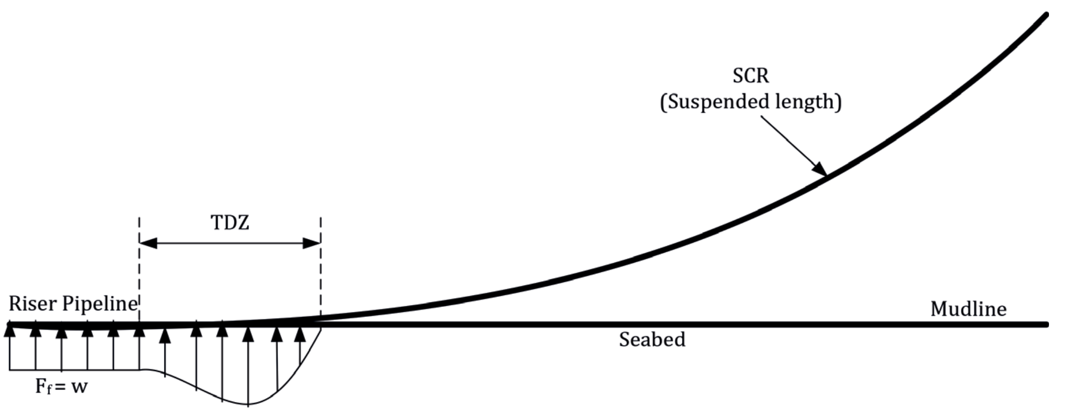

Figure 9.
SCR's configuration close to TDZ with linear elastic seabed.

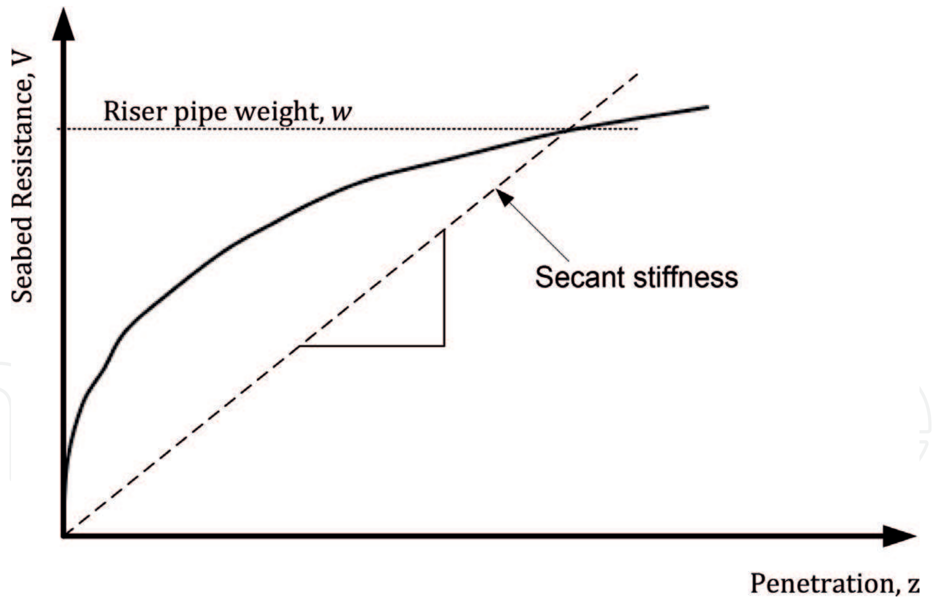

Figure 10.
Static and secant stiffness for non-linear seabed V-z *model.*

stiffness is using a linear stiffness to represent the backbone curve in riser-seabed interaction analysis. It is assumed that the riser will penetrate into the seabed until the bearing load equals the submerged riser pipe weight; $w = V_u$ where w is the submerged riser pipe weight, and V_u is the ultimate bearing load.

The non-linear soil model is recently developed and based on a hyperbolic secant stiffness formulation proposed by Bridge et al. [17], Aubeny et al. [18], and Randolph and Quiggin [19]. The non-linear seabed model is more sophisticated than the linear model, as it models the non-linear hysteretic behaviour of the seabed in the vertical direction, including modelling of suction effects when the SCR rises up sufficiently. The model uses data such as the pipe diameter, the seabed soil shear strength profile with depth and the soil density as its primary sources. Different functions are used for the initial penetration, for uplift and for re-penetration, whilst the function parameters are updated each time a penetration reversal occurs. This enables the model to capture the hysteretic behaviour of the seabed soil response and the increasing penetration of the pipe under cyclic loading in the vertical plane.

The typical *V-z* curve patterns [17, 19], as shown in **Figure 11**, of pipe-soil interaction are produced by laboratory model experiments [15] of vertically loaded horizontal pipes in weak sediment. These curves can be divided into four different paths. The pipe-soil interaction process is described and the depiction of the development of the interaction curve is given in **Figure 11**, associated with the uplift/re-penetration cycle. If the riser pipe continues to experience oscillatory loading movement, the *V-z* interaction curve will repeat the loop enclosed by path 1-2-3-1 under the assumption of a non-degradation model.

3.3 SCR/seabed lateral interaction

One of the main issues encountered with the use of the SCR is the large lateral movements on the seabed due to the FP motions and marine environment. Thus, better understanding of the lateral soil resistance to SCR pipe movements must be considered for SCR design. Many researchers had focused on studying and investigating the pipe-seabed lateral interaction response [6, 20–24]. Three different approaches [25, 26] can be considered for determining the lateral soil resistance of partially embedded pipelines:

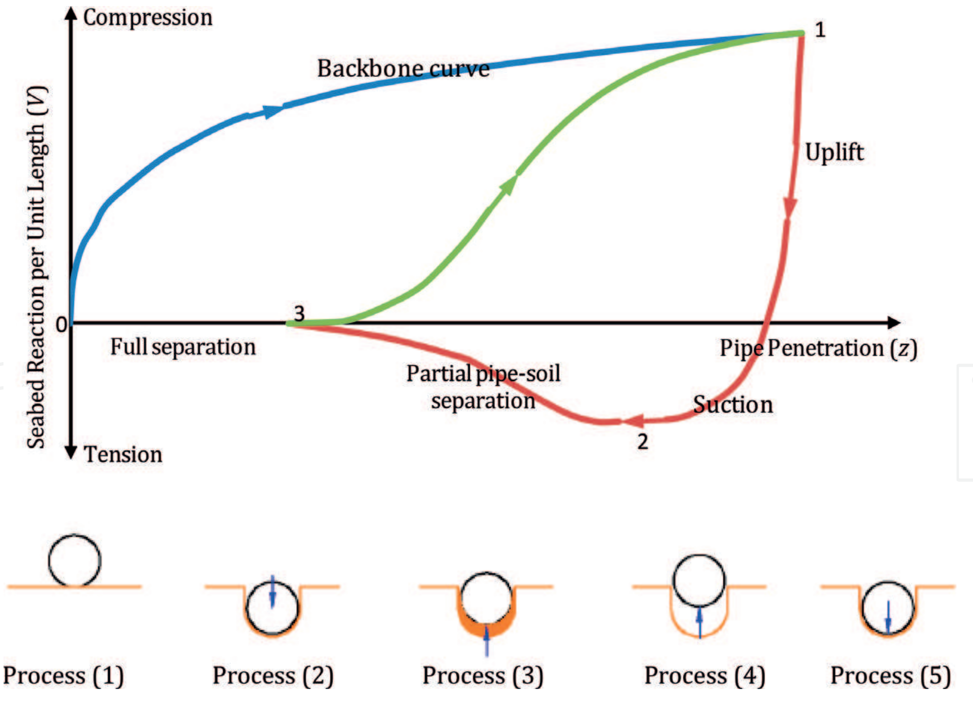

Figure 11.
Depiction of typical V-z *behavior [7].*

- A single friction factor "Coulomb friction model" approach, where the lateral soil resistance is related to the submerged weight of the pipeline and the soil type. This approach is fairly simplified, as it does not pertain to pipe embedment;

- A two-component model, where the lateral soil resistance consists of a sliding resistance component and a lateral passive pressure component [20, 23, 27]; and

- A plasticity model approach: Zhang et al. initially developed the plasticity model for calcareous sand and clays [28]. However, the clay's model is established on the behaviour of shallow flat footings in which a large lateral movement does not occur.

Therefore, the Coulomb friction approach and the two-component soil resistance models for the assessment of SCR global response are presented in this chapter.

3.3.1 Coulomb friction "Bilinear" model

Present industry procedure is to evaluate the soil resistance with a Coulomb friction model, as shown in **Figure 12**, 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 that depends solely on soil type. Recommended values of the Coulomb friction coefficient, μ, lie in the range 0.2–0.8, while the displacement to mobilise this resistance is typically 0.1 pipe diameters [20, 23, 24, 29].

3.3.2 Tri-linear pipe-seabed interaction model

The experiment results show that the pipe-soil lateral motion is far more complicated than simple coulomb friction. An improved model is essential in order to mimic

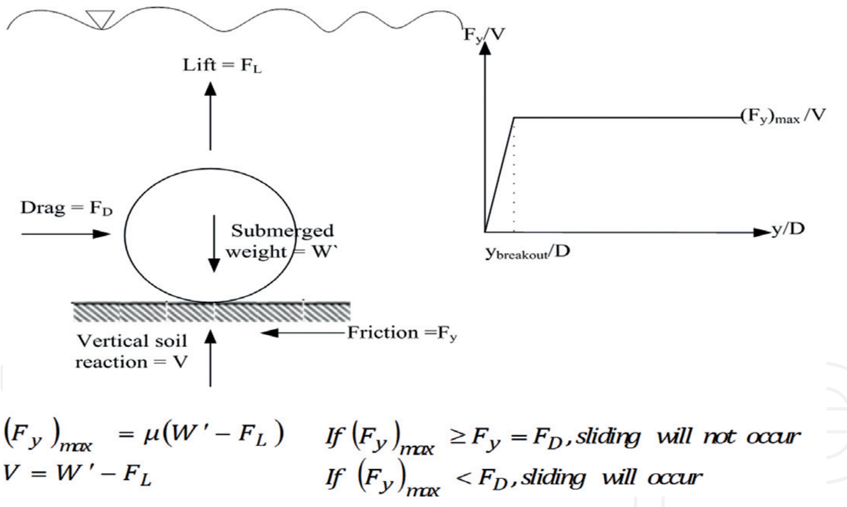

Figure 12.
Coulomb friction model analysis.

the effects of soil strength and the load history of the catenary pipeline as well as the associated pipe embedment on the lateral seabed soil resistance. The improved empirical model utilises two components to predict the seabed resistance to lateral pipeline movements, resulting in the improved so-called "two-component model."

The two-component model uses an empirical formula to assess the soil resistance to lateral pipeline motions. The first component depends on the vertical pipe weight (pipe weight minus hydrodynamic lift force) and imitates the sliding resistance of the pipeline along the soil surface, while the second component depends on the pipe penetration and soil strength.

Generally, the two-component models are based on empirically fitting laboratory test data. A summary of some of the proposed formulas is given in **Table 1**. The peak lateral soil resistance is a key parameter for the on-bottom pipeline movement. Several reported methods [20, 23, 27, 30] have been published for the assessment of the lateral soil resistance. These determined resistances were then compared with the results of the available pipe model tests.

Figure 13 shows the lateral load response from step 0 to 3, characterised as follows [31]:

(0–1)	First load breakout, with elastic response characterised by the mobilisation displacement and a peak that is dependent on the initial pipe embedment;
(1–2)	Suction release phase and elevation correction, depending on initial pipe embedment;
(2–3)	Steady state of residual friction.

3.4 SCR/seabed axial interaction

The axial soil resistance for SCR movement is typically modelled using the Coulomb friction model, which is adopted to evaluate the axial resistance of a partially embedded riser pipe, and is expressed as [25, 32]:

$$F_x = \mu_A W_s \tag{6}$$

where F_x is the axial soil resistance and μ_A is the coefficient of axial coil friction. The typical values for axial friction have been reported to vary between 0.2 and 0.5 for clay soil [33].

Author	Lateral soil resistance formulas	Comments
Wagner et al. [23]	$F_y = \mu(W' - F_L) + \beta S_u A/D$ F_y = lateral soil resistance μ = sliding resistance coefficient W' = submerged pipe weight F_L = hydrodynamic lift β = empirical soil passive resistance coefficient S_u = undrained shear strength of the clay A = 0.5 × embedded area	Monotonic $\mu = 0.2$ $\beta = 39.3$
		Cyclic (oscillations below the monotonic breakout load [<static failure]) Penetration × 2 $\beta = 31.4$
		Cyclic (large displacement oscillations) Penetration × 2.5 $\beta = 15.7$
Brennodden et al. [20]	$F_y = \mu(W' - F_L) + F_R$	$\mu = 0.2$ F_R calculated considering accumulated energy
Verley and Lund [27]	$F_y = F_C + F_R$ $F_y = \mu(W' - F_L) + F_R$ $F_R = 4.13 D S_u \left(\frac{S_u}{\gamma D}\right)^{-0.392} \left(\frac{z}{D}\right)^{1.31}$	Clays (S_u < 70 kPa) $\mu = 0.2$
Bruton et al. [30]	$(F_y)_{dimensionless} = \mu v + \frac{3}{\sqrt{\frac{S_u}{\gamma' D}}} \frac{z_{init}}{D}$ $(F_y)_{dimensionless} = \frac{F_y}{S_u D}$ $\frac{z_{init}}{D}$= normalised initial pipe penetration $v = \frac{V}{D S_u}$ normalised vertical load due to the effective pipe weight $\frac{(f_y)_{res}}{v} = 1 - 0.65\left[1 - \exp\left(-\frac{1}{2}\frac{s_u}{\gamma' D}\right)\right]$	Soft clays (0.15 < S_u < 8 kPa) $\mu = 0.2$

Table 1.
Lateral resistance models of partially embedded pipelines in soft clay.

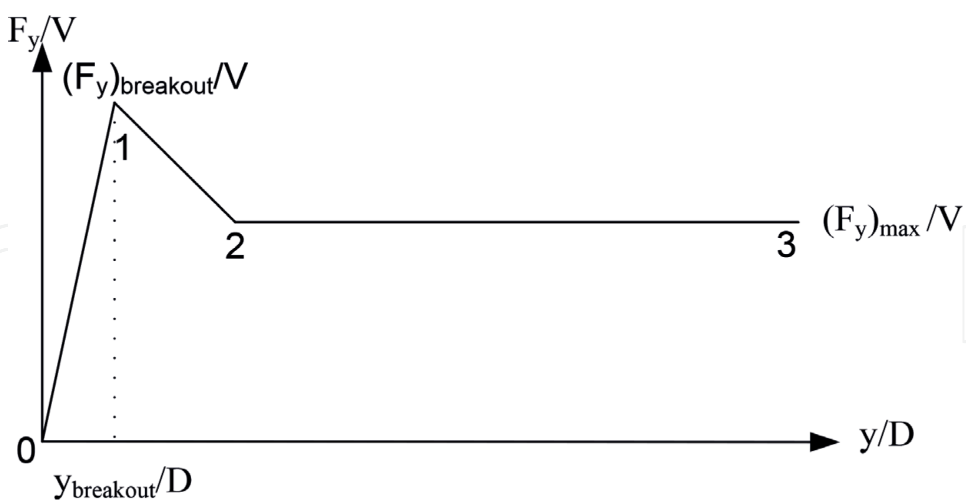

Figure 13.
Schematic of the tri-linear soil resistance model.

4. Summary of SCR-seabed interaction models technique

A number of scientific papers have been published on the study of soil-riser interaction. **Table 2** details the considerable diversity in the level of sophistication used in the analysis of SCR-seabed interaction response in a representative set of studies published in the last 25 years, with five areas previously highlighted as commonly conservative and broken into components of increasing degree of sophistication and accuracy. **Table 2** have been addressed for appropriate modelling of the physical SCR-seabed interaction process and graded with a three levels ranging from α which represents state-of-the-art practice, β a compromise method and γ a conservative method. General and brief discussion on the components presented in **Table 2** are as follows:

SCR-seabed interaction models: The majority of experimental studies carried out in recent years have presented the non-linear behaviour of SCR-seabed interaction and trenching effects in the TDZ. An SCR in the TDZ was recently identified as a fatigue hotspot that substantially increased fatigue damage under the SCR-seabed interaction phenomenon. Better understanding of the significance of SCR-seabed interaction behaviour and soil properties improves the fatigue life prediction in the TDZ. Most of the existing riser models unrealistically simplified SCR-seabed interaction behaviour by assuming a rigid or linearly elastic seabed. Trench formation and trench deepening have also significant influence on SCR-seabed response.

Pipe-seabed interaction models: Experimental model tests and analytical models of vertically loaded horizontal pipes in clay sediment provided valuable information for better awareness of SCR-seabed interaction in the TDZ. These experimental and analytical data produce the general load/deflection curve for pipe-seabed interaction and necessary information for validation of *V-z* model and determination of geotechnical parameters used in the model.

Cyclic loading: SCR-seabed interaction processes should cover vertical and lateral responses to cyclic loading. Movement and oscillation of the SCR in the TDZ will cause trenching and dynamic embedment of the SCR into the seabed. Seabed stiffness degradation due to cyclic oscillations has a significant influence on the behaviour of an SCR in the TDZ, and especially on the SCR's strength and fatigue performance. After the seabed soil approaches the maximum strength throughout the applied cyclic loading, the seabed soil tends to lose strength and stiffness with the increase in plastic embedment during cyclic oscillations. The seabed soil stiffness degradation mechanism comprises stiffness reduction presented in uplift, suction, and separation as well as the re-penetration process. The degradation of soil stiffness with cyclic loading is best captured by the non-linear seabed model.

Wave loading: The use of regular wave theories does not adequately represent wave loading on SCRs. However, when used, the level of sophistication in random wave loading is highly variable. For example, the length of simulation used to estimate response levels differs widely. Most studies use simplifying assumptions due to the extensive computational time needed to perform random time domain simulation properly.

Analysis (coupled vs. uncoupled): SCRs have a relative effect on the motions of a floating unit, which in turn affects the SCR fatigue life. In a coupled analysis, the floating unit and SCR are modelled together including their mass, stiffness and damping. Coupled analysis is computationally demanding, especially for robust finite element mesh size. In uncoupled analysis, platform wave frequency is computed in separate models by different programs. Once the floating unit motions are obtained, either from coupled or uncoupled analysis, they are imported as input into the riser analysis software for the uncoupled riser analysis. In uncoupled analysis, the riser is considered to have no effect on the platform at its top. These effects are usually negligible, and an uncoupled analysis is adequate.

5. Further research

The literature review introduced in this chapter reveals that the SCR motion at the TDP is predominantly lateral, vertical and cyclic in nature. SCRs are the subject

Author	Year	SCR-seabed interaction models					Pipe-seabed interaction models					Cyclic loading		Wave loading		Analysis	
		Model tests	Analytical models				Model tests	Analytical models									
			γ	β	α	α		γ	β	α	α	α	α	β	α	β	α
			Rigid seabed	Linear seabed	Non-linear seabed	Trenching effects		Rigid seabed	Linear seabed	Non-linear seabed	Trenching effects	Vertical	Lateral	Regular	Irregular	Uncoupled	Coupled
Sharma and Aubeny [34]	2011				√	√						√			√	√	
Cao [35]	2010			√													√
Cardoso and Silveira [36]	2010						√						√			√	
Hodder et al. [37]	2010						√					√				√	
Jin et al. [38]	2010						√						√			√	
Kimiaei et al. [39]	2010				√									√		√	
Nakhaee [40, 41]	2008 and 2010									√	√	√		√		√	
Aubeny et al. [18, 42]	2006 and 2009									√	√	√				√	
Randolph and Quiggin [19]	2009									√	√	√			√	√	
Oliphant et al. [43]	2009						√						√			√	
Bruton et al. [6, 30]	2006 and 2008						√						√			√	
Clukey et al. [44]	2008						√					√				√	
Palmer [11]	2008		√													√	
Sen [45, 46]	2008			√													√
Xia et al. [47]	2008			√											√		√

Author	Year	SCR-seabed interaction models					Pipe-seabed interaction models					Cyclic loading		Wave loading		Analysis	
		Model tests	Analytical models				Model tests	Analytical models									
			γ	β	α	α		γ	β	α	α	α	α	β	α	β	α
			Rigid seabed	Linear seabed	Non-linear seabed	Trenching effects		Rigid seabed	Linear seabed	Non-linear seabed	Trenching effects	Vertical	Lateral	Regular	Irregular	Uncoupled	Coupled
Akpan et al. [48]	2007		√														√
Karunakaran et al. [9]	2005			√											√		√
Bridge et al. [17]	2004											√					
Giertsen et al. [49]	2004						√		√	√	√	√					
Bridge et al. [3]	2003	√					√					√					√
Langner [50]	2003		√												√		√
Bridge and Willis [51]	2002	√										√					√
Thethi and Moros [10]	2001	√										√					√
Willis and West [52]	2001	√										√					√
Pesce et al. [53]	1998			√													
Verley and Lund [27]	1995						√						√				
Hale et al. [54]	1992						√					√	√				
Dunlap et al. [15]	1990						√					√					
Brennodden et al. [20]	1989						√						√				
Morris et al. [22]	1988						√						√				
Wagner et al. [23]	1987						√						√				

Table 2.
Level of complexity used in SCR-seabed interaction technique.

of much ongoing research, particularly with respect to fatigue and interaction with the seabed at the TDP. The current SCR's analysis is performed using simplified pipe-seabed interaction models and disregards the SCR's embedment into the seabed as well as soil suction effects in the TDZ; this will affect the predicted SCR response. Previous experiments showed that the soil suction effect can increase the bending stress of SCRs in the TDZ. The predominant offshore soil condition in a deepwater environment is soft clay soil with small undrained shear strength. Field observations have introduced that the trench is a common feature due to the SCR pipe penetration into the seabed. However, there are few published literatures that investigate the trenching effects of the riser pipe in the TDZ on the SCR's dynamic structural behaviour and fatigue performance.

Seabed stiffness degradation due to cyclic motion is an important parameter in order to estimate the SCR fatigue in the TDZ. This aspect is not well investigated, and the seabed is traditionally not properly modelled in the current SCR fatigue analysis. Existing literature has introduced that fatigue damage is highly sensitive to the soil model utilised in the fatigue estimation calculation. The seabed non-linear model, to simulate the SCR-seabed interaction, has been shown to be more sophisticated compared to those SCR-seabed interactions with linear soil springs.

It can be concluded from the summary of models presented in the existing literature survey that:

- Although a linear seabed model is the common modelling for seabed response [9, 47, 55], which is too simplified to capture the nature of SCR-seabed interaction, SCR-seabed interaction is a considerably non-linear phenomenon. For better understanding of SCR behaviour and reliable prediction of the fatigue life in the TDZ, a numerical study and analysis of SCRs with vessel motions should be performed;

- Fatigue performance assessment of the SCR in the TDZ remains a serious design challenge for SCR behaviour. Despite some research papers presenting a reduction in fatigue damage [34, 40, 50] due to riser embedment in the TDZ, other studies have proposed an increase in fatigue damage [7, 49]. These confounding results due to different geotechnical parameters have been imposed with trenches. The trench deepening, gradual embedment of the riser and soil stiffness have an important influence on the SCR's fatigue life in the TDZ. Furthermore, the soil parameters used in riser-seabed analysis can have a significant effect on fatigue life of SCRs. Therefore, SCR's fatigue damage in the TDZ is a critical design aspect where geotechnical consideration becomes important; and

- Although lateral movements of the SCR can influence the riser performance, as suggested by [42, 49], the adduced SCR-seabed interaction analytical models regard only the vertical SCR motions and neglect lateral soil friction, as presented by [40, 41].

The aforementioned research gap points are subjected to ongoing research and investigations and being tackled by the authors.

6. Conclusion

The interested engineer or researcher will find here the necessary background on the geotechnical interaction model for SCR issue, and then will be able to proceed with the research literature. In this chapter, the main objective was to explore the various modelling approaches used in recent studies towards better clarification of the response behaviour of pipe-soil interaction under cyclic motions.

The seabed response due to riser loading and the trench formation phenomenon are of great significance for safe and economic riser design. Current studies of SCR technology focused on better understanding of the TDZ and its interaction with the seabed soil. The soil-riser interaction involves a number of complexities, including non-linear soil behaviour, trench width and depth variability and softening of the seabed soil under cyclic loading. The seabed-riser interaction modelling allows the effect of physical phenomena, such as lateral resistance, soil suction forces and vertical seabed stiffness on the SCR performance to be identified and investigated. Non-linear seabed-riser model interaction will determine the influence of the seabed response model on SCR fatigue. A small change in seabed stiffness can result in a small change in bending stress, but this causes a significant change in fatigue life. Therefore, the need for seabed-riser interaction modelling to be as realistic as possible is evident. A comprehensive review of the recent studies on the SCR-seabed interaction was introduced.

After reviewing the different parts of literature relevant to this study, some of the required knowledge to be used in the current and future research is acquired and some other existing gaps in the field are identified. This chapter has presented a review of the state-of-the-art SCRs with seabed interaction and analysis techniques. It has also discussed the existing theories for modelling SCR-seabed interaction with detailed explanation of currently used methods for evaluating the SCR structural performance in the TDZ. The research gap addressed in this chapter is under the investigation and ongoing research by the author.

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