**Structural Engineering and Mechanics**, *Vol. 57, No. 3 (2016) 403-423*
DOI: http://dx.doi.org/10.12989/sem.2016.57.3.403 

# Significance of seabed interaction on fatigue assessment of steel catenary risers in the touchdown zone

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*(Received July 7, 2014, Revised December 28, 2015, Accepted January 7, 2016)*

**Abstract.** The challenges involved with fatigue damage assessment of steel catenary riser (SCR) in the touchdown zone (TDZ) are primarily due to the non-linear behaviour of the SCR-seabed interaction, considerable uncertainty in SCR-seabed interaction modelling and geotechnical parameters. The issue of fatigue damage induced by the cyclic movements of the SCR with the seabed has acquired prominence with the touch down point (TDP) interaction in the TDZ. Therefore, the SCR-seabed response is critical for reliable estimation of fatigue life in the TDZ. Various design approaches pertaining to the lateral pipe-soil resistance model are discussed. These techniques have been applied in the finite element model that can be used to analyse the lateral SCR-seabed interaction under hydrodynamic loading. This study investigates the sensitivity of fatigue performance to geotechnical parameters through a parametric study. In this study, global analyses are performed to assess the influence of vertical linear seabed springs, the lateral seabed model and the non-linear seabed model, including trench evolution into seabed, seabed normalised stiffness, re-penetration offset parameter and soil suction resistance ratio, on the fatigue life of SCRs in the TDZ.

**Keywords:** steel catenary riser; touchdown zone; soil model; lateral seabed; soil stiffness; geotechnical parameters; deepwater; soft clay, non-linear seabed

## 1. Introduction

Recently, steel catenary riser (SCR) systems have been developed to exploit hydrocarbon resources in deepwater around the world. An SCR, attached to a floating platform at its upper end, encounters oscillations in and near its TDZ that interact with the seabed. The motions at the semisubmersible and environmental loads can produce severe riser response, causing difficulties in meeting strength and fatigue criteria at the touchdown zone (TDZ). Many of these fresh discoveries are in regions where soft clay is detected (Sen and Hesar 2007). The challenges involved in SCR fatigue damage assessment in the TDZ are primarily due to the non-linear behaviour of SCR-seabed interaction, considerable uncertainty in SCR-seabed interaction modelling and geotechnical parameters. As the SCR-seabed response is critical to reliable estimation of fatigue life in the TDZ, a better understanding of the SCR-soil interaction mechanism must be developed to provide a realistic technique for determining structural strength

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http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

behaviour and fatigue performance in the TDZ.|

The non-linear vertical and lateral seabed model as well as the influence of the trench shape is typically ignored in the traditional SCR design analyses. This is due to restrictions of seabed modelling to linear spring model approximation as well as uncertainty as to how the non-linear soil model will affect the fatigue performance of SCRs in the TDZ, which can lead to conservative fatigue damage. Therefore, the seabed parameters used in the SCR analysis can have a significant influence on the global riser response and the fatigue life in the TDZ. The seabed response model behaviour is an area where the understanding of the SCR behaviour must be improved in an attempt to reduce the number of accidents. In addition, the interaction model should have sufficient accuracy to give reliable estimates of fatigue life of SCRs in the TDZ. The TDZ has recently been identified as a fatigue hotspot that substantially increases fatigue damage under the SCR-seabed interaction phenomenon. Although research studies on SCR fatigue assessment in the TDZ have presented a reduction in fatigue damage (Langner 2003, Sharma and Aubeny 2011, Nakhaee and Zhang 2008) due to riser embedment in the TDZ, other studies have introduced an increase in fatigue damage (Giertsen *et al*. 2004, Leira *et al*. 2004). These confounding results are due to different geotechnical parameters imposed with synthesis trenches. The non-linear seabed model is typically ignored in traditional SCR design analyses. Therefore, the seabed parameters used in SCR analysis can significantly influence global riser response and fatigue life in the TDZ. In addition, the interaction model should have sufficient accuracy to give reliable estimates of SCR fatigue life in the TDZ.

The following conclusions are taken from previous studies of riser-soil interaction:

a. Although the linear seabed model is commonly used for seabed response modelling of SCRs, it is too simplified to capture the nature of the highly non-linear physical behaviour involved. To better understand SCR behaviour and a reliable prediction of fatigue life in the TDZ, a numerical study of SCRs with vessel motions should be performed.

b. Although lateral movements of the SCR can influence the riser dynamic structural response, as suggested by (Aubeny and Biscontin 2009, Verley and Lund 1995), the adduced SCR-seabed interaction analytical models consider only vertical SCR motions and ignore lateral soil resistance, as presented by Clukey *et al*. (2008), Sharma and Aubeny (2011).

c. Although a number of research studies on SCR fatigue assessment in the TDZ have presented a reduction in fatigue damage (Langner 2003, Nakhaee and Zhang 2010, Sharma and Aubeny 2011) due to riser embedment in the TDZ, other studies have introduced an increase in fatigue damage Giertsen *et al*. 2004, Leira *et al*. 2004). The non-linear seabed model is typically ignored in traditional SCR design analyses, as is the uncertainty in geotechnical parameters as to how the non-linear soil model will affect SCR fatigue performance in the TDZ, which can lead to contradictory fatigue damage results. Therefore, the seabed parameters used in SCR analysis can significantly influence global riser response and fatigue life in the TDZ. In addition, the interaction model should have sufficient accuracy to give reliable estimates of SCR fatigue life in the TDZ.

This study discusses the significance of SCR-seabed soil interaction on SCR fatigue life in the TDZ as it relates to the design of SCRs for deepwater developments; it also details analyses of an SCR on soft clay at a 910 m depth of water. The SCR-seabed interaction is investigated using an OrcaFlex/non-linear time domain finite element model, along with a robust meshing technique. This study investigates the sensitivity of fatigue performance to geotechnical parameters, using the non-linear soil model suggested by Randolph and Quiggin (2009). Numerical results of a parametric study of SCR fatigue performance in the TDZ are presented here. Successions of numerical analyses of SCR/semisubmersible in irregular sea are performed. These analyses are accompanied by a hysteretic non-linear model in the vertical seabed direction and bilinear (as in references (Wagner *et al*. 1987, Brennodden *et al*. 1989, White and Cheuk 2008, Lyons 1973)) as well as tri-linear (as in references (Wagner *et al*. 1987, Brennodden *et al*. 1989, Verley and Lund 1995, Bruton *et al*. 2006)) soil model alternatives in the lateral seabed direction. These analyses are performed to examine the influences of main seabed soil parameters on SCR fatigue performance in the TDZ. Parametric studies for fatigue performance in the TDZ are conducted by examining the effects of lateral, vertical linear and non-linear seabed models. The main non-linear soil model parameters considered are normalised maximum stiffness, soil suction resistance ratio, normalised re-penetration offset parameter and trenching effects. This study summarises how these parameters affect SCR fatigue performance in TDZ. The type of seabed model and geotechnical parameters are found to have a substantial influence on fatigue performance in the TDZ.

## 2. Background

Several studies have been published on the soil-riser interaction (e.g., references (Aubeny *et al*. 2006, Aubeny and Biscontin 2009, Bridge *et al*. 2004, Thethi and Moros 2001)). The interaction of SCRs with the seabed is not fully understood. However, the seabed response can be depicted from SCR field observations or large-scale tests (Thethi and Moros 2001, Xia *et al*. 2008, Pesce *et al*. 1998, Karunakaran *et al*. 2005). ROV surveys of installed SCRs have shown deep trenches that cut into the seabed in the TDZ. Realistic predictions of the fatigue life of SCRs require an accurate characterisation model of seabed stiffness as well as a realistic description of the load-deflection curve. Present SCR models that represent the seabed as rigid (Langner 2003, Akpan *et al*. 2007, Palmer 2008) or linear (Cao 2010, Sen 2008, Xia *et al*. 2008, Pesce *et al*. 1998, Karunakaran *et al*. 2005, Grealish *et al*. 2007) disregard the nature of the process of trench development into the seabed and non-linear interaction in the TDZ. Recently, a number of vertical non-linear soil models have recently been suggested by Aubeny and Biscontin (2009), Randolph and Quiggin (2009) that are based on experimental results and analytical models.

The majority of SCR full-scale experimental studies (Bridge *et al*. 2004, Thethi and Moros 2001, Willis and West 2001, Bridge and Willis 2002, Hodder and Byrne 2010) carried out in recent years have presented the non-linear behaviour of the SCR-seabed interaction and trenching effects in the TDZ. Furthermore, pipe-seabed interaction experimental model tests (Bridge *et al*. 2004, Hodder and Cassidy 2010, Cardoso and Silveira 2010, Jin *et al*. 2010, Wagner *et al*. 1987, Morris *et al*. 1988, Brennodden *et al*. 1989, Dunlap *et al*. 1990, Hale *et al*. 1992, Verley and Lund 1995, Giertsen *et al*. 2004, Oliphant *et al*. 2009, Burton *et al*. 2006, Clukey, *et al*. 2008) and analytical models (Aubeny. and Biscontin 2009, Bridge *et al*. 2004, Randolph and Quiggin 2009, Nakhaee and Zhang 2010, Sharma and Aubeny 2011) of vertically loaded horizontal pipes in clay sediment provide valuable information for better representation of SCR-seabed interaction in the TDZ. These experimental and analytical data produce the general load-deflection curve for the pipe-seabed interaction as well as the information necessary for validation of the load-deflection model. The data also determine the geotechnical parameters used in the non-linear model.

Xia *et al*. (2008) introduced a mathematical model of the seabed vertical reaction force experienced by a pipeline or catenary riser in contact with the seabed. The model uses data such as pipe diameter, seabed soil shear strength profile with depth and soil density. As shown in Fig. 1, there are four different penetration modes in this seabed model: not in contact, initial penetration,

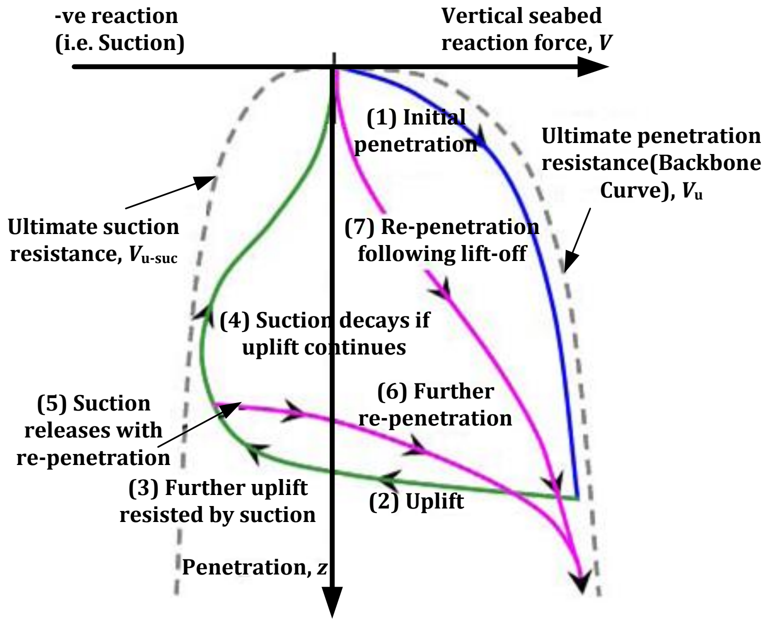



Fig. 1 Soil model characteristics for different modes (Randolph and Quiggin 2009)

uplift and re-penetration. This set of modes 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 model was validated against laboratory and field-scale experiments with reasonable accuracy. This model has been implemented in OrcaFlex software, which is widely used for riser response analysis. Indeed, non-linear model is particularly suitable, as it models the vertical pipe-soil interaction on soft clay according to dynamic aspects more accurately than a linear seabed model.

However, the lateral soil resistance of the partially embedded pipeline must be determined at the design stage. For lateral movement considerations, one principal factor is the ability to model lateral movements with cyclic motions. Three different approaches (Morris *et al*. 1988, Brennodden *et al*. 1989) can be considered for determining the lateral soil resistance of partially embedded pipelines:

a. a single friction factor “Coulomb friction model” approach, in which 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);

b. a two-component model, in which the lateral soil resistance consists of sliding resistance and lateral passive pressure components (Hodder and Byrne 2010, Hodder and Cassidy 2010, Jin *et al*. 2010); and

c. a plasticity model. Zhang *et al*. initially developed this model for calcareous sand and clays (Dunlap *et al*. 1990). However, the model of clays is established on the behaviour of shallow flat footings in which large lateral movement does not occur.

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

## 3. Modelling approach and analysis technique

### *3.1 Pipe-seabed vertical interaction model*

The SCR is oscillating vertically due to motions of the floating platform and random waves. As the SCR touches down on the seabed, plastic deformation of the soil occurs until the penetration is sufficient; it continually occurs until the bearing area is sufficiently large to provide the necessary resistance. If the soil loading at TDZ is greater than the SCR effective weight, then the soil experiences unloading as the SCR oscillations continue.

The entrenched SCR pipe endures loads as the riser is uplifted from the trench due to the weight of soil backfill on the top of the entrenched riser as well as suction and adhesion. Bridge *et al.* (2004) presented the non-linear force-deflection curve for an entrenched pipe experiencing suction. The suction force is a function of SCR diameter, bearing width of the riser, riser penetration and undrained shear strength of the soil.

The non-linear soil model is based on a hyperbolic secant stiffness formulation that is proposed by Bridge *et al.* (2004), Aubeny *et al.* (2006), Randolph and Quiggin (2009). The non-linear seabed model is more sophisticated than the linear model in that it models the non-linear hysteretic behaviour of the seabed in the vertical direction, including suction effects when the SCR rises sufficiently. The model uses data such as pipe diameter, seabed soil shear strength profile with depth and soil density as its primary sources.

The non-linear seabed model is an appropriate means by which to model soft clays and is particularly suitable for deepwater cases in which the mudline un-drained shear strength is low and the seabed/riser contact behaviour is governed by plastic penetration rather than elastic response (Orcina 2010).

### *3.2 Pipe-seabed lateral interaction models*

#### *3.2.1 Coulomb friction 'bilinear' model*

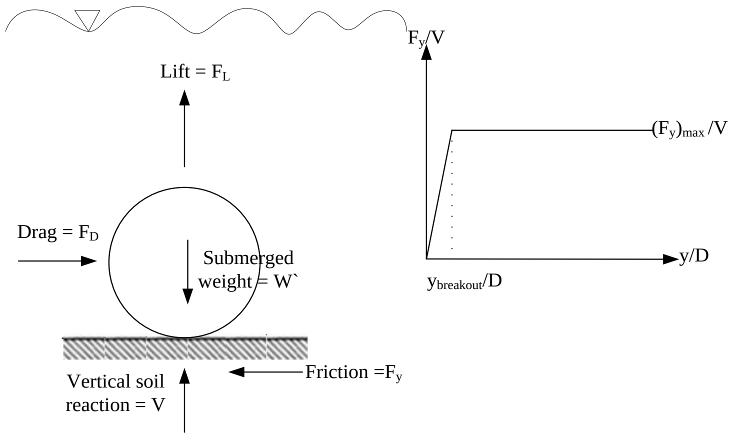
The present industry practice is to estimate soil resistance with a Coulomb friction model, as shown in Fig. 3, which expresses lateral resistance as the product of the effective submerged pipeline vertical force (submerged pipe weight minus hydrodynamic lift force) and a soil friction coefficient that depends solely on soil type. The conventional riser-soil design practice is to model the interaction by spring links at intervals along the riser flow-line. These links provide a bilinear relationship in the lateral direction as shown in Fig. 2.

Consequently, in the friction model, the seabed friction force has a maximum magnitude of $\mu V$ and acts tangential to the seabed plane, where $\mu$ is the friction coefficient and $V$ is the seabed reaction force. The SCR, which is in contact with the seabed, maintains a friction target position, and a friction force is applied that acts towards this target position.

A linear model of the friction force is used that is given by $F=-k_sAy$ up to a limit no more than $\mu V$ in magnitude, 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. Coulomb friction models the friction force from $-\mu V$ to $+\mu V$ as a linear variation over the deflection range $-y_{breakout}$ to $+y_{breakout}$. Here, $y_{breakout}$ is given by $y_{breakout}= \mu V/k_sA$.

#### *3.2.2 Improved 'tri-linear' pipe-seabed interaction model*

The experimental results show that the pipe-soil lateral motion is far more complicated than




$$(F_y)_{max} = \mu (W' - F_L) \qquad If\ (F_y)_{max} \geq F_y = F_D\text{, sliding will not occur}$$

$$V = W' - F_L \qquad If\ (F_y)_{max} < F_D\text{, sliding will occur}$$

Fig. 2 Coulomb friction ‘bi-linear’ model

simple Coulomb friction. An improved model is essential to mimic the effects of soil strength, 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 peak lateral soil resistance is a key parameter for on-bottom pipeline movement. Several reported methods (Wagner *et al*. 1987, Brennodden *et al*. 1987, Verley and Lund 1995, Bruton *et al.* 2006) 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.

Assessment of the lateral soil resistance $F_y$ required the pipe to move laterally; the current practice is to use empirical expressions evaluated from model tests (as in Wagner *et al.* 1987, Brennodden *et al.* 1989, Verley *et al.* 1995, Bruton *et al.* 2006). Generally, these empirical expressions divide the ultimate lateral soil resistance into two contributions, a frictional component that is linked to the pipe weight and a passive component linked to the soil strength $S_u$ and embedment depth of the pipe $z$. Total lateral soil resistance, $F_y$, is divided into two components that are given below

$$F_y = F_F + F_R \tag{1}$$

where $F_y$ is the total lateral soil resistance, $F_F$ is the sliding resistance force equal to a sliding resistance coefficient multiplied by the vertical pipe weight and $F_R$ is the passive resistance (penetration dependent soil resistance force).

The next degree of sophistication of pipe-soil response beyond the simple bilinear frictional model is modelling the lateral response using independent values of soil-pipe breakout friction, $(f_y)_{breakout}/V$, and residual soil resistance $(f_y)_{res}/V$ using a tri-linear response, as shown in Fig. 3. The improved soil resistance model can be applied by using a combination of seabed friction and a pure damper-type link to provide additional resistance. The small range of velocity over which it

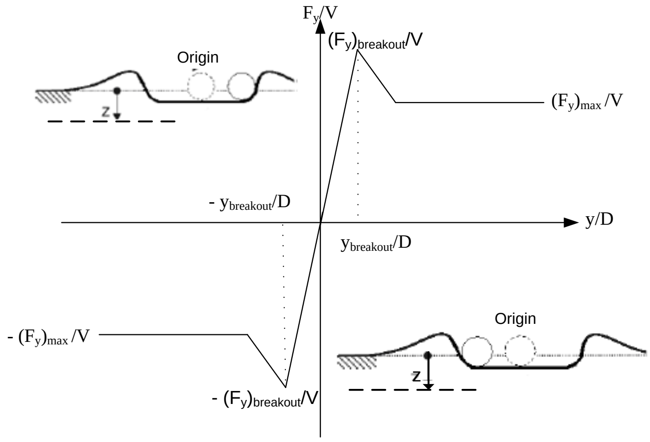



Fig. 3 Lateral pipe-soil interaction using a tri-linear model

operates is intended to include the fact that this additional force only applies at the very start of motion. The damper is set to apply force over a small range of velocity but to apply nothing once a limiting velocity is exceeded. The sliding resistance part will represent the constant resistance that the SCR encounters in the TDZ once it has overcome the initial peak in resistance and the load has settled. The force applied by the damper represents the additional force above the constant value. This force will cope with the cyclic nature of the motion because it is applied each time the pipe moves. The disadvantage of this type of scheme is that it will likely require a large number of links to appropriately restrain the seabed section of the line.

### *3.3 Analysis scheme*

In this study, non-linear time domain fatigue analyses are conducted. The SCR dynamic response is established by performing non-linear dynamic response analysis using irregular waves. Fatigue damage is calculated using a specified S-N curve and rain flow cycle counting. The basic fatigue capacity is given in terms of *S-N* curves that show the number of stress cycles to failure, $N$, for a given constant stress range, $S$

$$N = AS^{-m} \tag{2}$$

where $A$ and $m$ are empirical constants based on experiments.

The stress range to be used in fatigue damage calculations is found by the application of a stress concentration factor as well as a thickness correction factor to the nominal stress range

$$S = S_0 \; SCF\left(t_{fat} / t_{ref}\right)^k \tag{3}$$

where $S_0$ is the nominal stress range, $SCF$ is the stress concentration factor, $(t_{fat}/t_{ref})^k$ is the thickness correction factor, $t_{fat}$ is the average representative pipe wall thickness $t$ (set equal to $t_{\mathrm{ref}}$ for thickness less than $t_{ref}$) and $t_{ref}$ is the reference wall thickness, equal to 25 mm for welded connections; $k$ is the thickness exponent and is related to the *S-N* curve (DNV 2010, DNV 2005).

Miner's rule is adopted for accumulation of fatigue damage from stress cycles with variable range

$$D = \sum_i \frac{n(S_i)}{N(S_i)} \tag{4}$$

where $n(S_i)$ is the number of stress cycles with range $S_i$ and $N(S_i)$ is the number of stress cycles to failure.

## 4. Case study and numerical implementation

The SCR descends from a semi-submersible pontoon in a simple catenary configuration, transitioning to a flow-line below 1260 m. In addition, the SCR is connected to the semisubmersible at a mean top angle of 20° to the vertical. The outside diameter is 273 mm (10.75 in), with a wall thickness of 20.6 mm (0.812 in) and a riser total length of 3310 m. In the global analysis, the top-end is modelled as pinned whilst being free to rotate. The drag coefficient $C_d$ can be specified to vary with Reynold’s number ($R$e). The inertia coefficient $C_m$ used in this analysis is 2.0, meaning the added mass coefficient $C_a$=1.0.

Many fresh discoveries of deepwater fields are in regions where soft clay is detected. The typical range of shear strength, $S_{u0}$, of seabed soft clay is from 1.2 to 3.8 kPa at seabed level, and the shear strength gradient, $S_{ug}$, ranges from 0.8 to 2.0 kPa/m (Sen and Hesar 2007, DNV 2005).

The OrcaFlex/non-linear time domain finite element is a commercial software package for numerical analysis of offshore marine systems and is used to model semisubmersible and SCR motions. The environmental data input into the analysis is based on a typical northern North Sea (NNS) scatter diagram.

A non-linear seabed model has been implemented in OrcaFlex, as it models the dynamic behaviour of the vertical SCR-seabed interaction on soft clay more precisely than does a linear seabed model. The non-linear penetration resistance is established in a power law expression for the nominal bearing factor, $N_c=V/DS_U$, where $V$ is the vertical force per unit length, $D$ is the SCR diameter and $S_U$ is the undrained shear strength at the catenary pipe invert (bottom of the outer surface of the pipe), expressed by Aubeny *et al*. (2005) in the following way

$$N_c \approx a\left(\frac{z}{D}\right)^b \tag{5}$$

where $z$ is the riser penetration into the seabed. Fitted values of the power law expression, $a$ and $b$, rely on the relative roughness of the pipe-soil boundary and the strength profile with depth $\eta$, $\eta=S_{UG}D/S_{U0}$. Values of the power law coefficients, a and b, in Eq. (5) provide a reasonable fit to the numerical results in the range of $0\leq\eta\leq\infty$ and are shown in Table 1.

The normalised secant stiffness, $K_{\max}$, is the pipe-soil stiffness normalised by the ultimate net bearing pressure at that depth and is a measure of the effective stiffness since the last reversal in penetration or since penetration started; the factor is defined in the following way

Table 1 Power law coefficients

| Boundary | $z/D\leq0.5$ | $z/D\succ0.5$ |
|---|---|---|
| Smooth | $a$=4.97, $b$=0.23 | $a$=4.88, $b$=0.21 |
| Rough | $a$=6.73, $b$=0.29 | $a$=6.15, $b$=0.15 |

$$K_{\max} = \frac{Pipe\text{ - }soil\,stiffness}{Ultimate\ net\ bearing\ pressure} = \frac{\Delta V/\Delta z}{(V_u/D)} = \frac{\Delta V/\Delta z}{N_c(z).S_u} \tag{6}$$

with typical values for soft clay in the range of 150 to 250 (Bridge *et al*. 2004). The non-linear soil model parameters are discussed by Randolph and Quiggin (2009).

Seabed stiffness degradation due to cyclic oscillations has a significant influence on the behaviour of SCRs in the TDZ and especially on the strength performance of SCRs. After the seabed soil approaches its 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 a re-penetration process. Seabed soil degradation must be involved in the soil modelling efforts to capture dynamic cyclic loading in the response of the SCR. The degradation of soil stiffness with cyclic loading is best captured by the non-linear seabed model.

The SCR-seabed response in the TDZ follows the general characteristics of nonlinear soil behaviour illustrated by Randolph (2009) and asymptotic merging of the limiting resistance curves $V_u(z)$ and $V_{u\text{-}suc}(z)$. The penetration parameter $z$ for the ultimate resistance limits increases for penetration motion and decreases for uplift motion. The ultimate penetration and suction resistance asymptotic limits are given by $V_u(z)=N_cS_U(z)D$ and $V_{u-suc}(z)=-f_{suc}\cdot V_u(z)$, respectively, where $S_U(z)=S_{U0}+S_{UG}z$ is the undrained shear strength at penetration $z$ (Randolph and Quiggin 2009).

The basic configuration is obtained by performing non-linear time domain finite element analysis. The dynamic analysis is performed for 0, 90 and 180° wave directions (in-plane and lateral load cases). The response analysis is specified by:

- The SCR is modelled by a finite element model. The riser is divided into a series of line segments that are then modelled by straight massless model segments with a node at each end. The SCR line is divided into 1022 elements. The element length of 0.5 m is chosen for the TDZ and 5 m for other zones.
- The static configuration of the SCR is established.
- Non-linear dynamic time domain response analysis is used. The SCR configuration and tension are calculated at each time step by an iterative procedure, and the dynamic response of the SCR system is estimated using the integration scheme (forward Euler with a constant time step). 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 static analysis. In this study, a nonlinear time domain simulation time-step of 0.05 s is utilised in the dynamic analysis.

## 5. SCR fatigue performance

In the fatigue calculations for practical SCRs, the total fatigue damage is the combined damage from first order wave effects, vessel drift motions and vortex-induced vibration (VIV), which are analysed dynamically in the time or frequency domain. As noted above, the present study considers the effects of seabed interaction on fatigue performance rather than an accurate estimation of total fatigue damage. As such, fatigue analyses have been simplified by considering only the first order wave effects of the semi-submersible to observe clear trends for different soil response parameters.

The fatigue criterion that shall be satisfied can be written as $D_{fat}\cdot DFF\leq 1$, where $D_{fat}$ is the accumulated fatigue damage (Miner's rule) and *DFF* is the design fatigue factor recommended by DNV (DNV 2005). The SCRs are considered to be non-inspectable; therefore, a fatigue life of 20 *y* (service life) with a safety factor of 6.0 (120 *y*) is required. The SCR base case is as follows:

| | |
|---|---|
| Configuration | Lateral load case |
| Vessel offset | Mean position |
| SCF | 1.0 |
| S-N curve | DNV-Seawater with cathodic protection (Fig. 4) |
| Sea-state scatter diagram | Northern North Sea |

In this study, a series of numerical analyses over a total time simulation length of 3 h (10,800 s) is used for every sea state block. The simplified sea state fatigue blocks are shown in Table 2, and the JONSWAP Spectrum is used. The non-linear soil model parameters used are given in Table 3.

## 6. Results and discussion

### 6.1 Parametric study for SCR fatigue performance in the TDZ

#### 6.1.1 Effects of lateral seabed model

SCR-seabed interaction is modelled by a non-linear spring in the vertical direction, whilst the Coulomb friction model is used in the lateral direction together with an improved model that

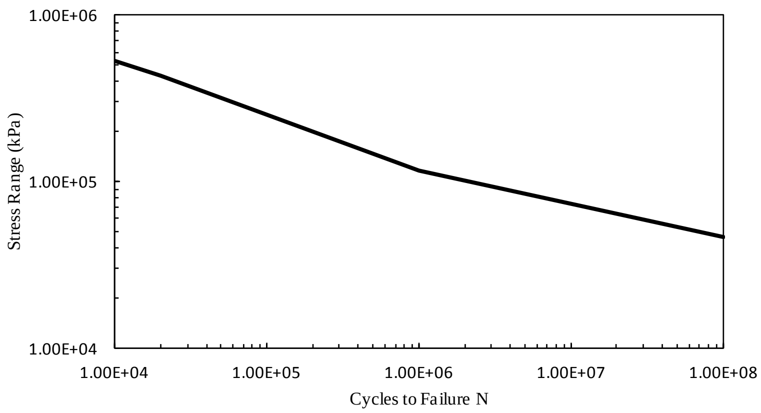



Fig. 4 An example of a DNV S-N curve (from DNV-RP-C203)

Table 2 Sea-state fatigue bins

| No. | *Hs* (m) | TP (s) | Probability (%) |
|---|---|---|---|
| 1 | 1.32 | 4.5 | 3.14 |
| 2 | 2.23 | 7.5 | 29.09 |
| 3 | 3.43 | 10.5 | 41.82 |
| 4 | 4.54 | 13.5 | 22.05 |
| 5 | 5.17 | 16.5 | 4.43 |
| 6 | 4.25 | 19.5 | 0.43 |
| 7 | 2.91 | 22 | 0.04 |

Table 3 Non-linear soil model parameters

| Parameters | Symbol | Value |
|---|---|---|
| Pipe diameter | $D$ | 0.273 m |
| Mudline shear strength (median range) | $S_{u0}$ | 2.6 kPa |
| Shear strength gradient (median range) | $S_{ug}$ | 1.25 kPa/m |
| Friction coefficient | $\mu$ | 0.2 |
| Saturated soil density | $\rho_{soil}$ | 1.5 t/m$^3$ |
| Power law parameter | $a$ | 6.15 |
| Power law parameter | $b$ | 0.15 |
| Normalised maximum stiffness | $K_{\max}$ | 200 |
| Suction ratio | $f_{suc}$ | 0.7 |
| Suction decay parameter | $\lambda_{suc}$ | 0.6 |
| Re-penetration parameter | $\lambda_{rep}$ | 0.3 |

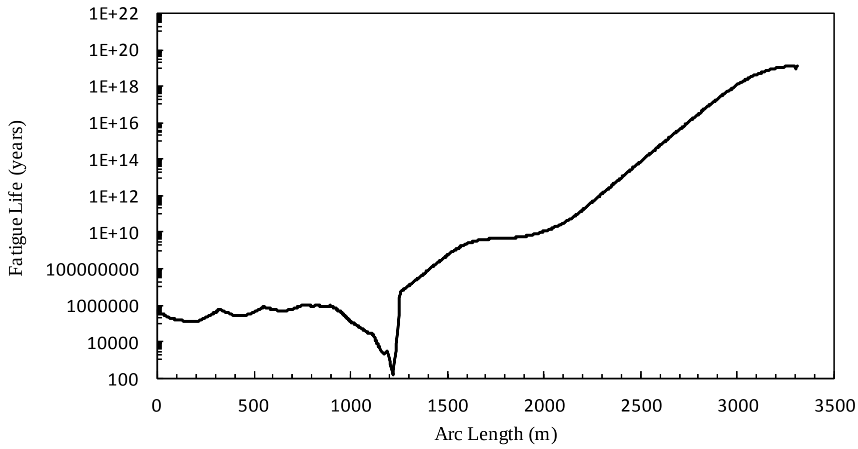



Fig. 7 Fatigue life along the SCR arc length measured from vessel with Coulomb model

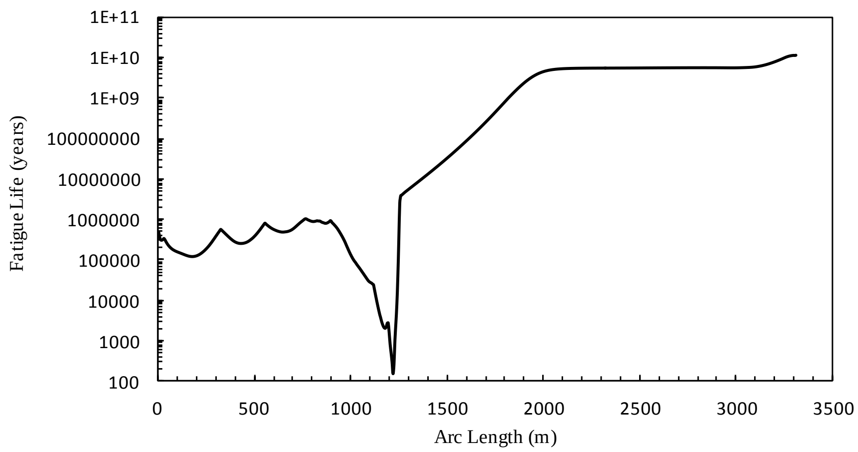



Fig. 8 Fatigue life along the SCR arc length measured from vessel with improved model

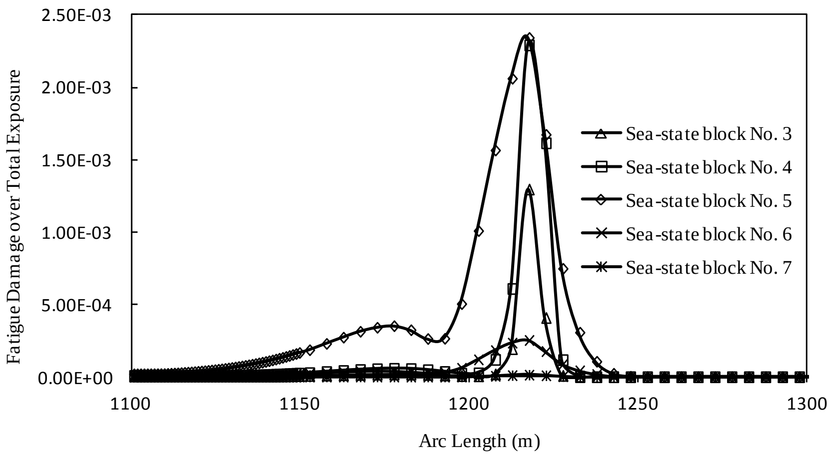



Fig. 9 Fatigue damage over total exposure for worst sea-state block (linear scale)

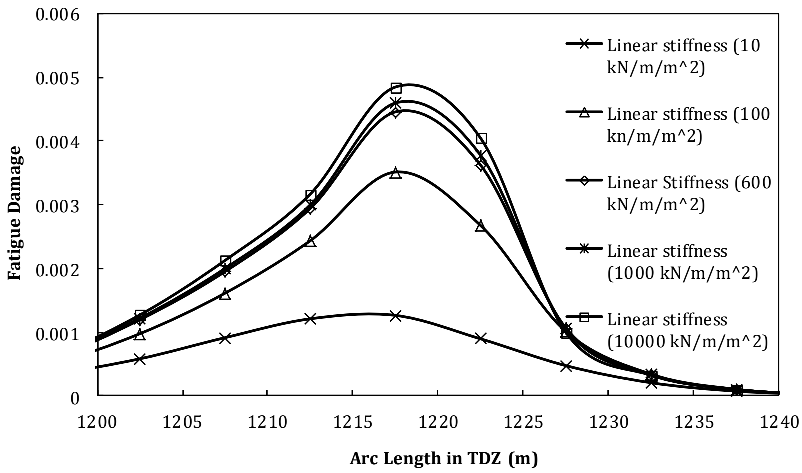



Fig. 10 Effect of linear soil stiffness on SCR cumulative fatigue damage in the TDZ

includes the breakout resistance, as explained in section 2. The fatigue life along the SCR length for both seabed Coulomb and improved soil models is shown in Figs. 7 and 8, respectively, using the non-linear soil parameters in Table 3. The critical locations for fatigue are at the touchdown area and close to the top-end. The shortest fatigue life when the seabed is modelled as Coulomb friction in the lateral direction is 161.2 *y*, while 159.9 *y* is found when the improved soil model is applied in the lateral direction at the touchdown zone. However, the lateral soil resistance can dramatically affect the fatigue life of the riser's flowline due to the passive resistance component. Although, the riser's flowline is less significant than the TDZ but further research for the flowline with different trench shapes and depths is recommended for future research. The resulting cumulative fatigue damage distribution along the SCR in the TDZ for the worst sea-state blocks is shown in a linear scale in Fig. 9. The improved lateral seabed interaction model has little influence on the resulting fatigue life.

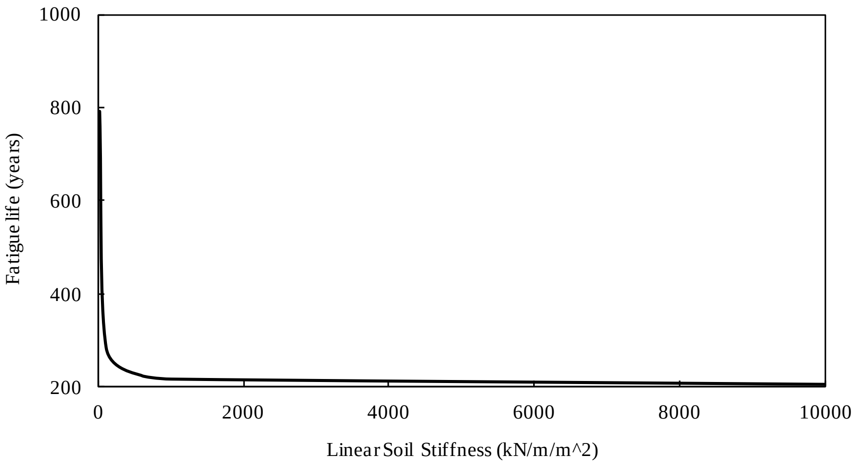



Fig. 11 Linear seabed model: soil stiffness effect on predicted fatigue life

### *6.1.2 Effects of vertical linear seabed model*

The SCR-seabed modelling analyses can influence the predicted riser fatigue life. Fatigue life studies for SCRs are conducted using a linear seabed stiffness in the TDZ, although there is a general awareness that stiffness will vary along the TDZ, depending on the amplitude of cyclic motions (Clukey *et al*. 2008).

Fatigue analyses are undertaken using a linear soil model with a range of values for linear stiffness; the stiffness equals the spring reaction force, per unit area of contact, per unit depth of penetration. The effect of seabed linear stiffness on the predicted fatigue damage and fatigue life is shown in Figs. 10 and 11, respectively. High values of soil stiffness (around 10,000 kN/m/m$^2$) produce fatigue damage similar to those calculated using a rigid seabed, which is clearly concluded from Fig. 11. The effect is significant; higher soil stiffness gives lower predicted fatigue life, whilst lower soil stiffness in contrast may not be representative.

### *6.1.3 Effects of normalised maximum stiffness, $K_{max}$ (non-linear soil model)*

The normalised maximum stiffness, $K_{\max}=(\Delta V/\Delta z)/(V_u/D)$, is the pipe-soil stiffness, $dV/dz$, normalised by the ultimate net bearing pressure at that depth, $V_u/D$, which is a measure of the effective stiffness since the last reversal in penetration or since penetration started. It has been found (Bridge 2004, Clukey 2008, Aubeny 2008) that $K_{\max}$ depends on the cyclic displacement of the SCR pipe, and it is suggested that the maximum value of $K_{\max}$ is 400, which corresponds to a small cyclic displacement, while the lower limit of $K_{\max}$ is 20, corresponding to a large cyclic displacement.

Fatigue analyses are then performed using the non-linear seabed model parameters in Table 3 but applying a range of values for the normalised maximum stiffness: $K_{\max}$=20, 40, 100, 150, 200, 300 and 400. The predicted fatigue damage and fatigue life are shown in Figs. 12 and 13, respectively, as a function of the normalised maximum stiffness. As with the non-linear soil model, a higher normalised maximum stiffness gives a lower fatigue life of ~151 *y* than does a lower normalised maximum stiffness, which gives a higher fatigue life of ~ 204 *y*. In addition, the resulting trench profiles for sea-state block No. 3 ($H_s$=3.43 m, $T_p$=10.5 s) based on the coupled analysis are shown in Fig. 14 as a function of normalised maximum stiffness.

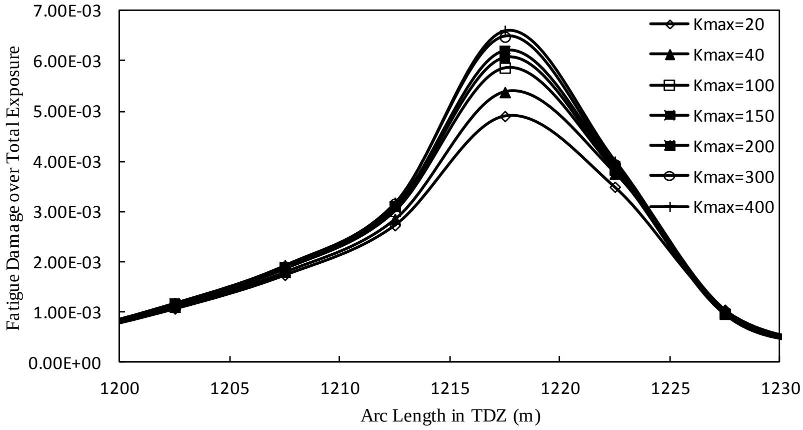



Fig. 12 Normalised maximum stiffness effect on fatigue damage in the TDZ

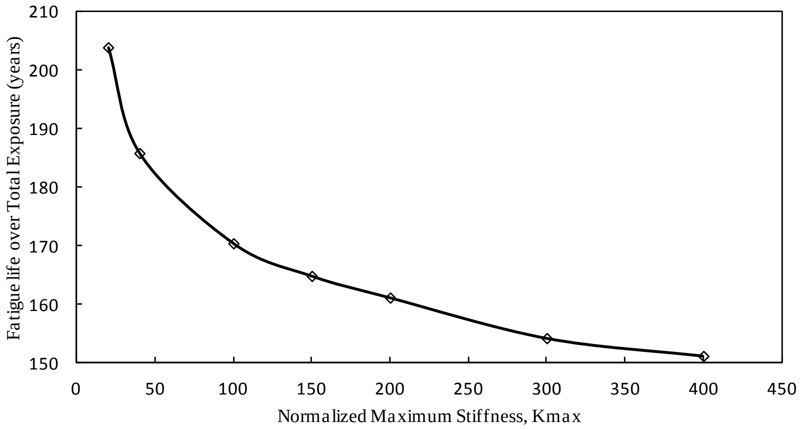



Fig. 13 Normalised maximum stiffness effect on fatigue life in the TDZ at arc length 1217.5 m

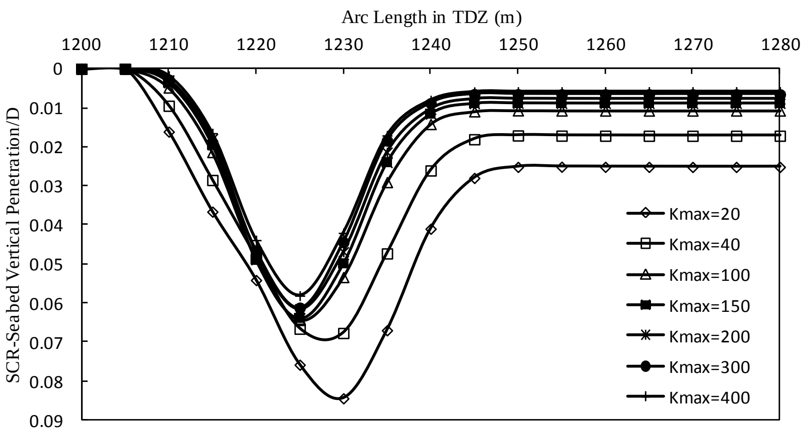



Fig. 14 Normalised maximum stiffness effect on trench deepening in the TDZ

### *6.1.4 Effect of suction resistance ratio, $f_{suc}$ (non-linear soil model)*

The magnitude of the suction resistance force mobilised by the non-linear seabed model is mainly controlled by the suction resistance ratio $f_{suc}$. As noted by Randolph and Quiggin (2009), $f_{suc}$ has been found to depend partially on the soil shear strength and partially on the riser velocity. The ratio also depends on the period of sustained suction as well as the recent history of cyclic motion; therefore, use of a constant factor $f_{suc}$ is a simplification. Because of the very limited experimental data currently available, the non-linear soil model has utilised a range of zero to unity for $f_{suc}$.

Fatigue analyses are then performed using the non-linear seabed model parameters presented in Table 3 but applying four different levels of the suction resistance ratio, $f_{suc}$=0, 0.3, 0.7, 1.0. The influence of suction on the cumulative fatigue damage is evaluated, while sea-state fatigue bins are applied for 10800 s (3 h) simulation time. Fig. 15 compares the cumulative fatigue damage for different suction ratios between zero and unity. The cumulative fatigue damage is approximately doubled between zero and full suction resistance force. The predicted fatigue life near TDP is presented as a function of the suction ratio, $f_{suc}$. The reduction in fatigue life due to soil suction between the upper level, $f_{suc}$ (full soil suction), and lower level, $f_{suc}$ (no suction), is approximately 42% as shown in Fig. 16. The effects of soil suction ratio and normalised maximum stiffness should be combined to demonstrate their influence on predicted fatigue life, as presented in Fig. 16. If the upper level of normalised maximum soil stiffness is 400, then fatigue life is reduced by around 32% when $f_{suc}$ is increased from 0.0 to 0.7. If the normalised maximum stiffness is further reduced to 20, then the fatigue life is reduced by around 20% when $f_{suc}$ is increased from 0.0 to 0.7. High values of seabed stiffness, around 10,000 kN/m/m$^2$, introduce fatigue life similar to those calculated using a rigid seabed as shown in Fig. 11. If the lower level of normalised soil stiffness, 20, is used with no suction effect, then fatigue life in the TDZ increases by around 22% compared to those calculated using a rigid seabed, while fatigue life in TDZ is reduced by around 1.2% with $f_{suc}$=0.7. Likewise, if the upper level of normalised soil stiffness, 400, is used with no suction effect, fatigue life in TDZ increases by around 8% compared to those calculated using a rigid seabed, while fatigue life in TDZ is reduced by around 27% with $f_{suc}$=0.7.

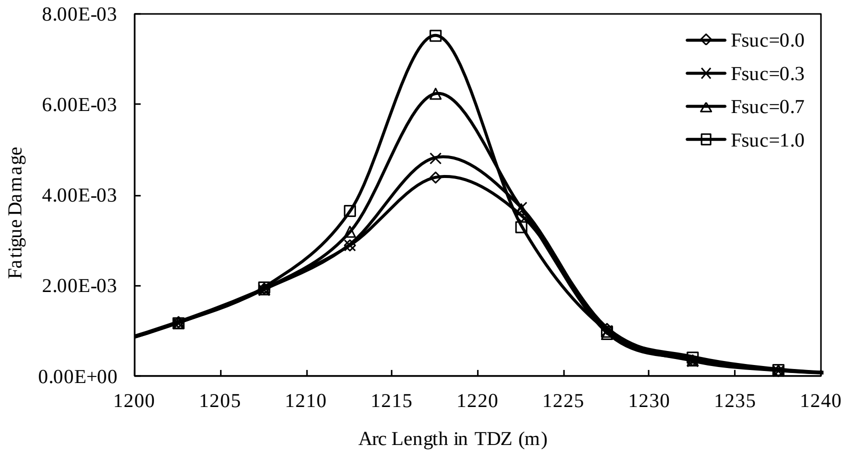



Fig. 15 Cumulative fatigue damage for different suction ratios in the TDZ ($K_{\max}$=200)

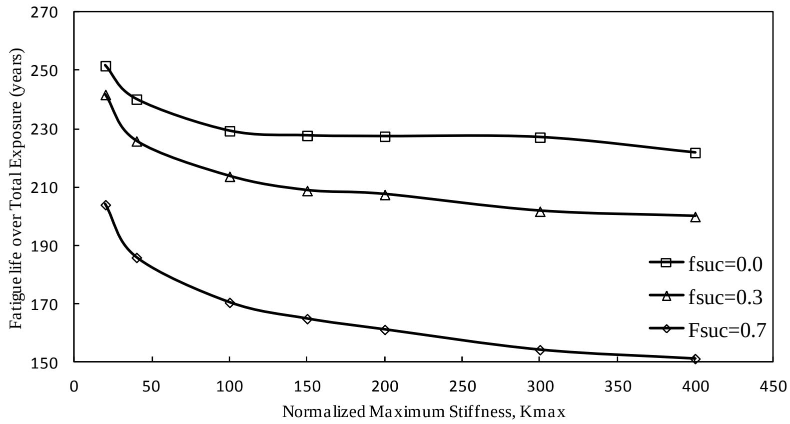



Fig. 16 Influence of maximum normalised stiffness and soil suction ratio on the predicted fatigue life

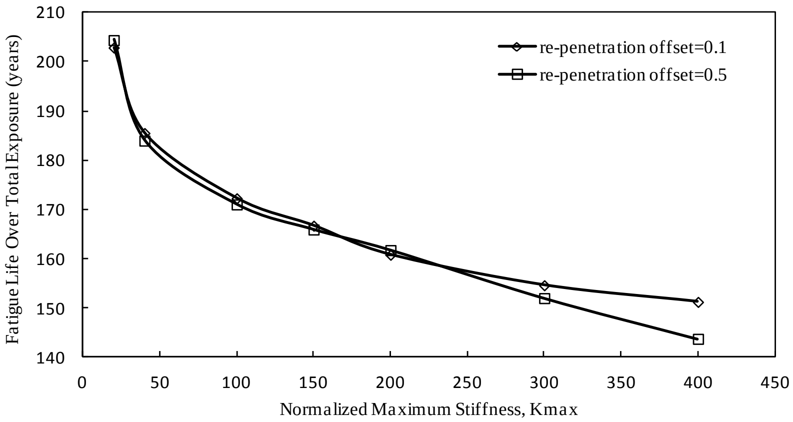



Fig. 17 Influence of normalised re-penetration offset on the predicted fatigue life

### *6.1.5 Effects of normalised re-penetration offset, $\lambda rep$ (non-linear soil model)*

The normalised re-penetration offset, $\lambda_{rep}$, controls the delay in mobilising the ultimate soil resistance curve during re-penetration and is presented to capture progressive penetration under cyclic movements. As noted by Randolph and Quiggin (2009), $\lambda_{rep}$ has a value in the range of 0.1 to 0.5 and fits the experimental data.

Further fatigue analyses are then performed using the non-linear seabed model parameters presented in Table 3 but applying two different levels of normalised re-penetration offsets: $\lambda_{rep}$=0.1 and 0.5. The effects of normalised re-penetration offset on the cumulative fatigue damage are observed, and the sea-state fatigue bins are applied for 10800 s (3 h) simulation time. The predicted fatigue life in the TDZ is shown in Fig. 17 as a function of normalised re-penetration offset, $\lambda_{rep}$. The influences of the normalised re-penetration offset parameter and normalised maximum stiffness should be combined to show their effects on the predicted fatigue life. The reduction in fatigue life due to the re-penetration offset parameter between the upper level, $\lambda_{rep}$=0.5, and lower level, $\lambda_{rep}$=0.1, is around 5% at which $K_{\max}$=400 as shown in Fig. 17.

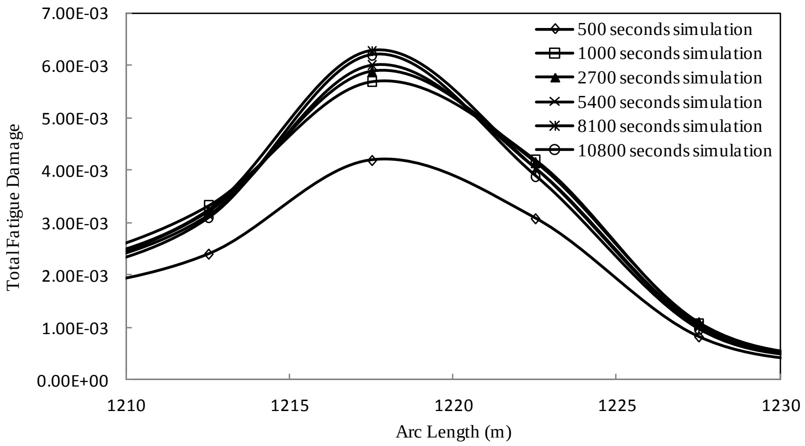



Fig. 18 Cumulative fatigue damage under different simulation time lengths (linear scale)

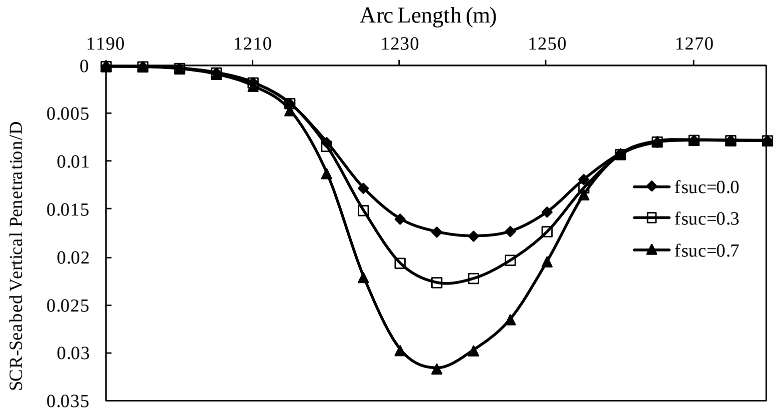



Fig. 19 Final trench profile for various values of the suction ratio

### *6.1.6 Trenching effects*

The gradual deepening of trenches also significantly influences fatigue life prediction. Cyclic dynamic motions applied to the floating production unit affect the gradual variation of trench embedment in the TDZ.

The resulting cumulative fatigue damage distribution along the SCR in the TDZ under different simulation time lengths is shown in Fig. 18. After 8100 s of simulation time, steady values of cumulative fatigue damage are clearly achieved.

The soil suction ratio also affects the final trench profile under cyclic loading. A comparison of the final seabed trench profiles under the influence of the soil suction ratio is presented in Fig. 19, which shows that the increase in the soil suction ratio causes deeper penetration under the same load condition and application of a single sea-state block No. 5.

Seabed soil resistance would increase with trench gradual variation and deepening. In addition, the value of the suction ratio will influence the distribution of SCR-seabed resistance in the TDZ. The final seabed resistance envelope under application of a single sea-state block No. 5 is shown

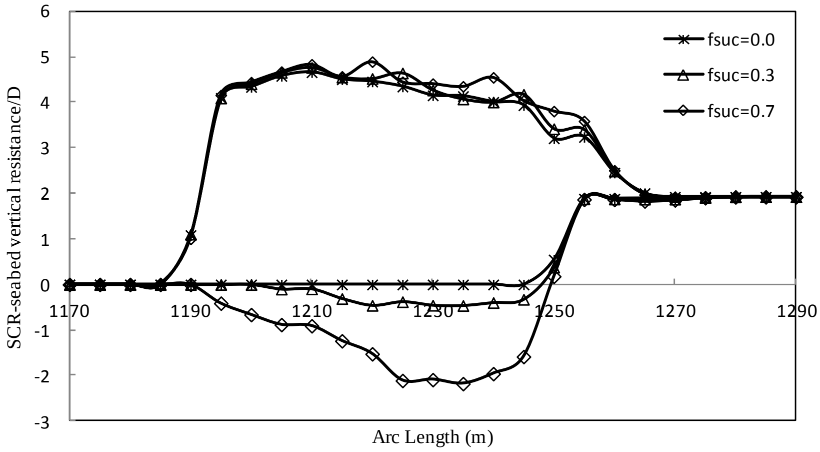



Fig. 20 Seabed resistance envelope for a range of suction values

in Fig. 20. This figure demonstrates that the suction force is generated in the zone around the TDP. As such, this region is subjected to large cyclic motions.

In this study, detailed fatigue analyses of an SCR connected to a semisubmersible in NNS have been performed. An investigation has also been conducted into the SCR-seabed interaction response and the effects of geotechnical parameters on the fatigue performance of an SCR near the touchdown point on soft clays. The results of a parametric study of SCR fatigue performance in the TDZ have been presented using lateral, vertical linear and non-linear SCR-seabed interaction models to investigate how the main geotechnical parameters affect the SCR fatigue life.

The SCR-seabed interaction analyses allow the effects of physical phenomena such as soil suction forces as well as lateral and vertical seabed stiffness on SCR performance to be identified and quantified. These analyses also provide a better understanding of the complex physical process of SCR-soil interaction. An outline of the fatigue analysis methodology utilised and the numerical results are presented.

## 7. Conclusions

Detailed fatigue analyses are conducted using linear and non-linear seabed models with cyclic strength degradation and trench deepening for a range of fatigue bins. Global analysis is performed to assess the influences of vertical linear seabed springs, the lateral seabed model, the non-linear seabed model, gradual trench deepening into the seabed, seabed normalised stiffness, re-penetration offset parameter and soil suction resistance ratio on SCR fatigue in the TDZ. A sensitivity study of the linear and non-linear seabed models, including linear soil stiffness, normalised maximum seabed stiffness, soil suction resistance ratio and re-penetration offset parameter, is investigated and presented for a wide range of values. The following key observations and conclusions are also drawn from this study:

- The lowest SCR fatigue life was found in the TDZ due to the non-linear seabed interaction response.
- Compared to the Coulomb friction model, SCR fatigue life in the TDZ is slightly affected by

an improved soil ‘tri-linear’ model in the lateral direction near TDP, while the flow-line of the SCR is highly affected by improved lateral soil resistance. The improved model can significantly affect the dynamic performance of the SCR in the touchdown region which is proved by authors before; Elosta *et al.* (2013).

• The seabed linear stiffness has a considerable influence on the assessed fatigue life in the TDZ; higher soil stiffness gives lower predicted fatigue life. Conversely, lower soil stiffness may not be representative.

• If the non-linear seabed model is used, then the fatigue life is reduced by around 44% compared to the linear seabed model, with soil stiffness of 100 $kN/m/m^2$, whilst the fatigue life is also reduced by around 22% compared to the rigid seabed model of high seabed stiffness (10,000 $kN/m/m^2$). This difference indicates that the SCR-seabed interaction cannot be represented by linear or rigid seabed models, and the significance of geotechnical parameters should be investigated.

• Sensitivity studies of normalised maximum stiffness, $K_{max}$, are performed using a wide range of stiffness values. The difference in fatigue life between the upper and lower bounds of $K_{max}$ is more than 50 *y*, which represents a significant difference for an SCR fatigue life prediction. In addition, $K_{max}$ has a significant effect on the gradual deepening of the trench in the TDZ, as also reflected in the fatigue life prediction.

• The soil suction resistance ratio has a significant influence on the final trench profile, seabed resistance and, consequently, the SCR fatigue life in the TDZ. Higher values of the soil suction resistance ratio give lower fatigue life, and the difference in fatigue life between zero suction and the full suction ratio is around 100 *y*. Furthermore, fatigue life prediction is affected by the variation of soil suction with normalised maximum stiffness; as the soil suction ratio increases, the difference in fatigue life increases with the variation of normalised maximum stiffness from low ($k_{max}$=20) to high stiffness ($k_{max}$=40), with values of up to 50 *y* for the same soil suction ratio. These results help in interpreting the confounding fatigue life results reported by other published studies.

• The normalised re-penetration offset parameter, $\lambda_{rep}$, has a negligible effect on the SCR fatigue life for a wide range of $K_{max}$ up to a value of 250, while $\lambda_{rep}$ would slightly affect the SCR fatigue life with high values of $K_{max}$ ($K_{max}$=400).

• The influences of the gradual embedment of the riser into the seabed and development of deep trenches on SCR fatigue performance in TDZ have been studied through the use of a hysteretic non-linear seabed model. Gradual deepening of the trench under random loads and cyclic motions significantly increases SCR fatigue damage in the TDZ.

The results from fatigue analyses presented in this study prove that the confounding results introduced by previous research studies on SCRs in the TDZ are due to different geotechnical parameters imposed by the soil model and trench formation. Trench deepening, as well as the gradual embedment of riser and soil stiffness, strongly influences SCR fatigue life in the TDZ. Furthermore, the soil parameters used in riser-seabed analysis can have a significant effect on SCR fatigue life. Therefore, SCR fatigue damage in the TDZ is a critical design aspect in which geotechnical consideration becomes important.

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