Impact of seabed slope on steel catenary riser touchdown zone response

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Abstract. Several factors can affect the response of steel catenary risers (SCR) around its touchdown zone (TDZ). These include the stiffness of the soil, the soil suction force on the riser TDZ, the soil degradation with cyclic TDZ loading, etc. Riser strength and fatigue response computation are usually performed considering flat seabed and with the use of rigid or linear (spring) riser soil interaction model. However, bathymetric information obtained for the SCR lay path on the seabed reveal complex seabed profile variation, indicating that the seabed is far from being flat around the SCR TDZ. This paper presents findings from an investigation conducted on the influence of seabed slopes on the strength and fatigue response of SCRs, using a non-linear (NL) riser soil interaction model. The responses of SCRs on positively and negatively sloped seabed (rotated about the static touchdown point on flat seabed) are compared with responses of SCRs on flat seabed. From the results, it can be deduced that the SCR dynamic and fatigue responses may be overpredicted or underpredicted in magnitudes dependent on the slope deviation of actual seabed from a flat seabed.

1. Introduction

Steel catenary risers are the most attractive riser solution because of their simplicity and robustness in application [1]. A major challenge with SCR application is the high stress and fatigue damage incurred around its critical sections, which are the hang off (HO) and the TDZ, shown in Figure 1. Prediction of SCR stress and fatigue response around the TDZ was in the early history of SCR design performed using a rigid soil model. This approach was then progressively improved by the development and implementation of linear (spring) soil-riser interaction models. More recently, considerable efforts have been made to improve the SCR TDZ interaction model by the development of the non-linear models [2-4]. The NL riser soil interaction model provides a more realistic approach for evaluating riser response interactions with the seabed.

It is a common practice during the design of SCR to assume a flat seabed [5]. Realistically, seabed can hardly be flat. Bathymetric data reveal complexities in the topography of the seabed and the variation of the seabed profiles along riser azimuth. Sloped seabed, especially in the immediate region surrounding TDZ, may impact SCR configurations calculated based on the flat seabed assumption, leading to SCR TDP mismatch [6]. The mismatch is the distance between the SCR TDP on an assumed flat seabed and the SCR TDP on realistic sloped seabed. This work investigates the influence of seabed
slope on the flat seabed static SCR configurations and the impact sloped seabed can have on the strength and fatigue response around the SCR TDZ.

Figure 1. Conventional steel catenary riser schematic [7].

The impact of seabed slope on SCR response is investigated, considering the hysteretic non-linear soil interaction model developed by Randolph and Quiggin [2]. The sloped seabed in this investigation extends linearly before the TDP to the SCR seabed termination. The slopes of the linear seabed profiles considered are 0deg (flat seabed), ± 2deg, ± 4deg, ± 7deg and ± 10deg. Three groups of SCRs with hang-off angles of 8deg, 12deg and 16deg are implemented on these profiled seabed. The SCRs static, dynamic and fatigue responses are calculated considering nominal configurations of the risers, i.e. no vessel offsets. Findings from this study will provide not only relevant information about SCRs behaviour on the sloping seabed but also possible seabed modifications to improve SCR response.

2. Analysis data
There are three groups of SCRs characterised by their hang-off angles (with the vertical), which are 8deg, 12deg and 16deg, respectively. Each group consists of the SCR resting on nine linear profiled seabed with seabed slopes of 0deg (flat seabed), ± 2deg, ± 4deg, ± 7deg and ± 10deg as presented in Table 1. For each hang off group of SCR configuration, the sloped seabed is made to pass through the static touch down point of the SCR configuration on the flat seabed for that group. The SCRs are made up of 12inch pipe joints, hosted by a floating production system in a water depth of 1500m, and are conveying fluid of density 600kg/m³. The SCRs wall-thickness (27.5mm) is calculated based on DNV-OS-F201 criteria [8], considering burst and collapse requirements for a design pressure of 10ksi. The hang-off connection stiffness of each SCRs has a linear value of 12kN.m/deg. Note that the HO angles given in Table 1 are the angles the riser makes with the vertical at the riser vessel interface.

| Group | Hang off-angle (deg) | Seabed Slope (deg) |
|-------|----------------------|---------------------|
| 1     | 8                    | 0, ±2, ±4, ±7, ±10  |
| 2     | 12                   | 0, ±2, ±4, ±7, ±10  |
| 3     | 16                   | 0, ±2, ±4, ±7, ±10  |
2.1. Storm and fatigue load data

Presented in Table 2 are the selected storm and fatigue wave loads under which we investigate the responses of the groups of SCRs. Since the study is comparative rather than project design-based, we consider here a total exposure time of the SCRs to the fatigue load to be 30 years, neglecting stress concentration factors and other safety factors.

Table 2. Storm and fatigue wave load.

| Analysis   | Hs(m) | Tp (sec) | gamma |
|------------|-------|----------|--------|
| Storm      | 8.0   | 13       | 1.6    |
| Fatigue    | 1.5   | 5.5      | 1.8    |

2.2. Seabed data

The non-linear hysteretic riser-soil interaction model developed by Randolph and Quiggin (R&Q) is applied for this investigation. Table 3 presents the default model data for the R&Q model. Details of the NL model can be found in [2]. Recall that the seabed profiles investigated in this study are 0deg (flat seabed), ± 2deg, ± 4deg, ± 7deg and ± 10deg.

Table 3. Non-linear soil model data [2].

| Model Parameter               | Value       |
|-------------------------------|-------------|
| Mudline shear strength        | 5kPa        |
| Shear strength gradient       | 1.5 kPa/m   |
| Power law parameters (a, b)   | (6, 0.25)   |
| Normalised maximum stiffness  | 200         |
| Suction ratio                 | 0.6         |
| Suction decay parameter       | 0.4         |
| Penetration parameter         | 0.2         |

3. Methodology

In this study, we conducted the analysis calculations using OrcaFlex finite element (FE) software package. The initial flat seabed SCR configurations for the FE modelling is calculated using the catenary equations (1) to (5), with equations (4) and (5) derived from the basic catenary equations (1) to (3). Where s is the catenary length from HO to TDP, x is the horizontal span from HO to TDP, z is the vertical span from HO to TDP, w is the submerged unit weight of pipe section, θ is the HO angle with the horizontal, which can be expressed as (tan⁻¹(V/H)). H is the horizontal components of tension, V is the vertical components of tension, and T is the resultant tension force of H and V. These equations are developed based on the assumptions of infinite axial stiffness and negligible bending stiffness for the lines and are suitable for calculating initial line configurations.

\[
z = \frac{H}{w} \left[ \cosh \left( \frac{wx}{H} \right) - 1 \right] \tag{1}
\]

\[
s = \frac{H}{w} \sinh \left( \frac{wx}{H} \right) \tag{2}
\]

\[
T = H + wz \tag{3}
\]

\[
H = \frac{wz}{(\tan \theta)^2 \left( 1 + \sec \theta \right)} \tag{4}
\]

\[
x = \frac{H \sinh^{-1}(\tan \theta)}{w} \tag{5}
\]
3.1. Seabed Slope Modelling

The objective of this study is to investigate the impact of the sloped seabed on SCR TDZ responses and compared them with those of the SCR on the flat seabed. Therefore, we first calculate the initial SCR configuration on flat seabed using the catenary equations presented in the previous section, and then rotate the seabed about the static SCR TDP to impose the seabed slope influence on the TDZ section. We apply this technique for the modelling of the three groups of the SCRs of different HO angles resting on the nine seabed slopes (see Table 1). The following conventions were adopted for the sloped seabed modelling:

- The seabed slope is positive when the seabed increases in the positive direction (upward relative to the TDP) from the SCR TDP to the riser seabed termination.
- The seabed slope is negative when the seabed increases in the negative direction (downward relative to the TDP), from the SCR TDP to the seabed termination.

Consider a flat seabed (AD), as shown in Figure 2. We will need to determine the coordinates of point B and C to be able to define the linear sloped seabed profile BC. The coordinates of B and C will be such that the line joining them passes through the static TDP of the SCR on a flat seabed. By performing this rotation, we can impose the effect of the sloping seabed on the SCR configuration. This approach represents the scenario during riser preliminary layout design where the static TDP is known for an assumed flat seabed, which is eventually found not to be flat but sloped, or a scenario where a flat seabed is assumed. Referencing all points from the hang-off point (O) on the mean sea level (MSL) in Figure 2, z coordinates of point B and C can be expressed as:

\[ Z_B = Z_A - (X_A - X_{TPD}) \tan \alpha \]  
\[ Z_C = Z_D + (X_D - X_{TPD}) \tan \alpha \]

Where \( X_A = X_B \) is the x coordinate of point A and B, \( Z_A = Z_{TPD} = Z_D \) is the elevation of the seabed referenced from the riser hang-off point, \( X_{TPD} \) is the x coordinate of the static TDP of the SCR on a flat seabed, and \( \alpha \) is the seabed slope. OrcaFlex FE software possesses the capability to create profiled seabed as well as model the NL riser soil interaction. With the Z coordinates of point B and C calculated from equation (6) and (7), the seabed profile can be defined in OrcaFlex. Examples of SCRs configurations on the flat, positive and negative sloped seabed are shown in Figure 3 (a), (b) and (c). The seabed incidence angle, \( \beta \) is the angle the riser makes with the vertical at the static TDP. Under
dynamic conditions, the dynamic incidence angle ($\beta_{\text{dynamic}}$) varies about the static incidence angle ($\beta_{\text{static}}$). Increasing the HO angle with the vertical and the angle of the positively sloped seabed will result in increasing $\beta_{\text{static}}$, vice versa as observed in Figure 3 (a), (b) and (c), where $\beta_1 > \beta_2 > \beta_3$. $\beta$ is an essential SCR geometric parameter, influenced by the HO angle, seabed slope and riser motion. It will be shown later how $\beta$ correlates with the SCR TDZ response under dynamic loading conditions.

![Figure 3](image)

**Figure 3.** Example: OrcaFlex SCR model with HO angle with vertical = 16deg on (a) flat seabed (0deg), (b) positive sloped seabed (+10deg) and (c) negative sloped seabed (-10deg).

### 3.2. Numerical solution approach and response calculation

The FE simulations are conducted in the time domain, which is fully non-linear and couples the riser dynamics with the vessel motions. The implicit integration scheme is applied. The modelling, simulation and post-processing are automated using MATLAB programs integrated with the OrcaFlex high-level programming interface (OrcFxAPI [9]). The program calculates the initial SCR configurations using the catenary equations and creates the OrcaFlex SCRs models on flat seabed. The static calculation is then conducted to obtain the SCRs static TDPs coordinate on the flat seabed. The TDP coordinate and the seabed slope are then used to calculate point B and C using equations (6) and (7), such that the straight line from B to C passes through the calculated flat seabed static TDP coordinate (see Figure 2). The linear profile defined by line BC is then used to develop and update the seabed profile, inducing the sloped seabed profile on the configurations of SCR initially resting on the flat seabed. The program repeats this for other SCRs across the three groups, generating the required models. The storm and fatigue irregular wave loads (see Table 2) are modelled using the JONSWAP spectrum and simulated for all SCRs throughout 1200sec. The vessel RAOs and riser pipe content are set as well. The simulation period of 1200sec was considered to be sufficient since the study is a comparative one, same wave loads are imposed on all SCR models across the three groups, and the possibility of resonance in the SCRs are not considered. Numerical results post-processed by the program include the SCR configurations, effective tensions, stress utilisation, and fatigue damage along the SCRs.
The SCRs stress utilizations are calculated using the DNV-OS-F201 combined load resistance factor design criteria. Detailed information about the DNV-OS-F201 criteria can be found in [8]. The fatigue damage is computed from the variation of stresses in the risers. The rain flow counting technique [10] is applied to express the varying SCR stress spectrum as a histogram of stress reversal. The Miner’s rule, presented in equation (8) is applied to calculate the cumulated fatigue damage, $D$.

$$D = \sum_{i} n_i / N_i$$

(8)

Where $n_i$ is the $i^{th}$ stress range amplitude components of the stress range histogram, $N_i$ is the number of cycles to failure associated with the $i^{th}$ stress range as obtained from the S-N curve [11].

4. Results and discussions

4.1. Static touch down point (TDP) offsets

Figure 4 presents the static TDP arc length locations of the SCR on sloped seabed ($\alpha$) relative to the static TDP arc length for the same SCR on flat seabed ($\alpha$0deg). The relative static TDP arc lengths ($\alpha - \alpha_{0deg}$) is the offsets of the TDP on the sloped seabed from the static TDP on flat seabed, and can be seen as the error incurred when flat seabed are assumed rather than sloped seabed around the SCR TDZ. Positive lengths indicate longer static TDP arc lengths from hang-off (HO) relative to the flat seabed static TDP arc length, and negative lengths indicate shorter TDP arc lengths relative to the flat seabed static TDP arc length.

From Figure 4, it is observed that the SCRs will first touch the seabed (i.e. at shorter arc length from HO) on the negatively sloped seabed. The trend shows a progressive increase in TDP offset as the riser hang-off angle increases, and as the seabed slope increases in both positive and negative sense. TDP offset between 40m and 100m is possible for seabed slope between ±4deg and ±10deg. For deeper water where the SCR TDP is farther from the HO, the TDP offset can be even more significant. The SCR TDP offset errors occur when a flat seabed is assumed during riser design rather than the realistic sloped seabed. Such errors can impact on the design of the SCR whose sections around the TDP are to be cladded with carbon resistive alloys (CRA) to reduce corrosion induced fatigue damage. The cladding of the internal riser section with CRA is expensive and requires accurate estimation of the arc length positions of the sections to be cladded. This underpins the importance of seabed slope consideration during the SCR design.
4.2. Static top tension

The static top tension of SCR is a combination of the weight of its hanging section, including its content (600kg/m³ used in this study), less its displacement (buoyancy). The external and internal pressure effects are accounted for in the case of effective tension calculation. The difference in the lengths of the hanging section (from HO and TDP) caused by the seabed slope can result in a difference in the static top effective tension ($T_{eff}$). The difference between the static top tension of SCRs on the sloped seabed and those of SCRs on the flat seabed are presented in Figure 5. Table 4 in the appendix presents the numerical values of the top tension. It could be observed from these results that both positively and negatively sloped seabed can cause an increase in the top tension compared with SCRs on the flat seabed. The increase in top tensions is higher for SCRs on seabed slope beyond ±4deg. However, the top tension increase is observed to be smaller in magnitude for positively sloped seabed when compared with SCRs on the negatively sloped seabed. For example, with seabed slope of -10deg, the static top tension of SCRs on the flat seabed can be increased by more than 20kN, when compared with flat seabed SCRs. The bar chart plot trend also indicates that the change in top tension of each sloped seabed SCRs relative to their corresponding flat seabed SCRs increase and decrease respectively for negatively and positively sloped seabed, as the SCR HO angle increases.

Recall that the SCRs on negatively sloped seabed touched down first (i.e. TDP occurs at shorter arc length from HO) before those of positively sloped seabed, with the flat seabed SCRs in between (see Figure 4). This is supposed to mean that the top tension of SCR on the negatively sloped seabed will be smaller than the same SCR on the positively sloped seabed. However, as can be seen in Figure 5, this is not the case. A detailed look at Figure 6 which is the configuration plot for SCR with 16deg HO angle resting on ± 10deg sloped seabed, reveals the reason why it is so. Although the TDP of the riser on negative seabed touches down first, the riser section beyond the TDP on the seabed still contributes to the SCR hanging weight until the riser seabed frictional force cancels it. On the other hand, the weight beyond the TDP of the SCR resting on the positively sloped seabed is applied on the seabed, not the hanging riser section.

![Figure 5. Percentage change in static top tension of SCRs on sloped seabed relative to SCRs on a flat seabed.](image-url)
4.3. Dynamic analysis – Maximum top effective tension

The range graph maximum effective tension is the vector of nodal maximums over the simulation time. The maximum top tension occurs during the upward motion of the vessel where the SCRs are pulled upward, causing a longer hanging section of the SCRs. It is observed from Table 5 and Figure 7 of the appendix that the negatively sloped seabed SCRs have higher top tension when compared with the flat and positively sloped seabed SCRs. For example, the results presented in Table 5 and Figure 7 indicate more than 5% increase in SCR top tension for SCRs on -10deg sloped seabed compared with SCRs on the flat seabed. Top tensions of positively sloped seabed SCRs have values slightly less than SCRs on the flat seabed. SCRs top tensions are seen to be more sensitive to increasing negatively sloped seabed than positively sloped seabed. The hang-off tensions are also observed to be higher relative to SCRs on the flat seabed for increasing HO angles. These observations can be translated to some sort of positive (for positively sloped seabed) or negative (for negatively sloped seabed) impact on the design of topside supporting structures for the SCRs when a flat seabed is assumed during the SCR design rather than the profiled seabed. As the water depth increases, the top tensions are expected to increase. Similarly, the impact on top tension of flat seabed SCRs by an imposed negatively sloped seabed is expected to also increase.

Figure 6. Expanded view of TDZ sections for SCR with HO angle = 16deg, seabed slope = -10deg and +10deg.

Figure 7. Percentage change in maximum dynamic top tension of sloped seabed SCRs relative to SCRs on a flat seabed.
Note: Negative values mean reduction in maximum top tension in the sloped seabed SCRs relative to the flat seabed SCRs.

4.4. Dynamic analysis – TDZ compression
The negativity of the effective tension value around the SCR TDZ is an indication of riser compression. As observed in Table 6 in the appendix and Figure 8, the SCR TDZ compression is sensitive to seabed slope around the TDZ. The level of compression for flat seabed SCRs are significantly amplified for a small increase of inclination of the negatively sloped seabed. On the other hand, compression observed for flat seabed SCRs is improved (or reduced) significantly when the seabed becomes positively sloped. Note that the abscissa of Figure 8 contains both positive and negative values, where, the positive values indicate an increase in compression (increased negativity of effective tension in the sloped seabed SCRs) relative with the flat seabed SCRs, and the negative values represent the converse. As mentioned earlier, the SCRs resting on negatively and positively sloped seabed have smaller and larger seabed incidence angle (β) respectively, compared with incidence angle on flat seabed SCRs. Under the dynamic condition, this appears to have translated to higher SCR TDZ compressions or higher buckling tendencies for SCRs having smaller β as will be seen later in the most critical compressive point on the riser presented in Figure 11 (b) and (c) of section 4.6. Increased compression for negatively sloped seabed SCRs may be critical for SCRs designs where TDZ buckling is a major challenge. The results show that we under- and over-predict the TDZ buckling when we assume a flat seabed rather than the profiled seabed around the SCR TDZ for negatively and positively sloped seabed, respectively. For example, SCR of HO angle 16deg, encountering -4deg seabed slope around its TDP, can have up to 500% increase in TDZ compression unaccounted for if we assumed a flat seabed profile for the design. On the other hand, with a positively sloped seabed profile, a significant benefit in the form of reduced TDP compression or buckling is observed. In general, it is observed for SCRs resting on the same sloped seabed, that compression increases with decreasing hang off-angle

![Figure 8](image-url)

**Figure 8.** Percentage change in SCR TDZ compression relative to SCRs on a flat seabed.

Note: Negative values mean reduction in compression in the sloped seabed SCRs relative to the flat seabed SCRs.

4.5. Dynamic analysis – Stress utilisation
The range graph maximum of the DNV-OS-F201 dynamic stress utilisation around the SCR TDZ are presented in Figure 9 (a), (b) and (c).
Figure 9. Maximum DNV-OS-F201 stress utilization in TDZ for risers: (a) HO angle = 8deg, (b) HO angle = 12deg, (c) HO angle = 16deg.

The stress utilisation is a combination of stress component contributed to by the axial tension, bending moment and pressure loads. The most dominating component of the stress utilisation around the TDZ is the bending moment component. Since higher buckling tendencies were observed in the TDZ
of SCRs resting on the negatively sloped seabed, it is expected that the stress utilisation within this region is higher for the negatively sloped seabed. This is confirmed by the results presented in Figure 9 (a), (b), and (c). It can be observed that SCRs resting on negatively sloped seabed incur higher TDZ stress utilisation compared with same SCRs resting on the flat seabed. The converse is the case for the positively sloped seabed. It is also observed in general (both static and dynamic cases) that the point of highest TDZ stress utilisations shifts towards the HO direction for increasing negatively sloped seabed and towards the seabed anchor direction for the positively sloped seabed. This again is an indication of the challenge that may be encountered during the design specification of clad (CRA) section on the SCR TDZ if the seabed slope around the TDZ is not correctly considered. For SCRs on the flat seabed, the TDZ stress utilisation is observed to be higher for risers with smaller HO angles since this implies smaller $\beta$ and higher bending stress. However, it is possible to have higher TDZ stress utilisation for SCRs with larger HO angle compared with SCRs with smaller hang off-angle if the seabed slope on which the former risers rest result in smaller $\beta$ than the later risers. This may imply that $\beta$ value, which is driven by a combination of HO angle and the seabed slope ($\alpha$) is the single parameter indicator of the level of bending moments, stress and buckling around the TDZ.

![Figure 10. Percentage change in SCRs TDZ stress utilisation relative to SCRs on a flat seabed.](image)

Note that the negative values mean reduction in stress utilisation in the sloped seabed SCRs relative to the flat seabed SCRs. Like the observations made on results for SCRs maximum top tensions and TDZ compressions, the positively sloped seabed provides benefits in the form of the reduction in stress utilisation. On the other hand, assuming a flat seabed in SCR design, when indeed the seabed is negatively sloped around the SCR TDZ, stress utilisation can be underestimated.

4.6. Dynamic analysis - Time history of the most critical point

Compression or buckling in the SCR TDZ depends on the velocity of the TDZ section during riser excitations. The magnitude of the global vertical component of the SCR TDZ velocity (GZ velocity) gives an indication of the level of impact energy and deformation of the SCR when it contacts the seabed at every load cycle. TDZ compression can occur when the difference between the downward velocity of the riser TDZ section are higher compared with the section terminal velocity, and when the TDZ section impact on the seabed at higher acceleration. The time history of the seabed incidence angle ($\beta$), the GZ velocity, the effective tensions and stress utilisation at the critical points within the SCRs TDZ sections are presented in Figure 11(a), (b), (c) and (d).
The critical points are the arc lengths along the SCRs measured from the HO, where the highest stress utilisation occur for the SCRs. It is observed that $\beta$ have the smallest values at the time when the downward GZ velocities are highest. This indicates a correlation between the impact velocity and the resulting SCR curvature characterised by $\beta$. On the other hand, value of $\beta$ are higher for lower values of downward GZ velocities. Hence, higher impact velocities at these points on the seabed resulted in lower values of $\beta$, which in turn causes higher dynamic curvature, bending moments, compressions, and stress utilisation. The positively sloped seabed is characterised by smaller $\beta$ than flat seabed and negatively sloped seabed in that order, and hence reduced compression and stress utilisation in the same order.

4.7. Fatigue analysis – fatigue damage

The range graph fatigue damage per year for the SCRs are presented in Figure 12 (a), (b) and (c). The results revealed that with increasing positively sloped seabed (increasing $\beta$), the fatigue damage reduces compared with same SCRs on the flat seabed. The converse is the case for negatively sloped seabed with smaller $\beta$. The percentage change in the fatigue damage of the sloped seabed SCRs relative to the flat seabed SCRs are presented in Figure 13. Numerical values of Figure 13 are presented in Table 8 of the appendix. These results indicate imposed benefits on the SCRs fatigue lives by the positively sloped seabed and reduction on the SCRs lives by negatively sloped seabed around the SCR TDZ. The results indicate that we may be under- and over-predicting the TDZ fatigue damage when we assume a flat seabed rather than the profiled seabed around the SCR TDZ for negatively and positively sloped seabed respectively. For example, it could be observed from the results that positively sloped seabed can reduce the fatigue damage response by more than 50%, for SCRs resting on the positively sloped seabed of 10deg. On the other hand, the fatigue damage can be increased by more than 20% for the same SCR configurations, relative to the flat seabed SCRs fatigue damage response. This may indicate that a deliberate imposition of positively sloped seabed through modification of the riser TDZ – seabed contact profile can improve the SCR fatigue response around the TDZ.
Figure 12. Fatigue damage around riser TDZ for riser groups: (a) HO angle = 8deg, (b) HO angle = 12deg, (c) HO angle = 16deg Configuration.
Figure 13. Percentage change in SCRs TDZ stress utilisation relative to SCRs on a flat seabed.

Note: Negative values mean reduction in fatigue damage in the sloped seabed SCRs relative to the flat seabed SCRs.

5. Conclusion
The impact of seabed slope on SCR TDP offset, TDZ compression, stress utilisation and fatigue response have been investigated in this work. The study considers SCR design scenarios were flat seabed are assumed rather than the realistic profiled seabed around the TDZ for SCR design analysis, and then investigate the impact on the SCR TDZ responses for such design assumption. The positively and negatively sloped seabed of different slopes, \( a = (0, \pm 2, \pm 4 \pm 7 \pm 10) \) deg were imposed on SCR configurations initially modelled on the flat seabed. Three SCRs groups were considered with HO angles of 8deg, 12deg and 16deg. For flat seabed SCR configurations, it is possible to relate the stress and fatigue response at the SCR TDZ to variation in the SCR HO angle, since it is highly likely that smaller HO angle will cause higher TDZ stress utilisation and fatigue damage than higher HO angle. However, when the seabed is sloped, a combination of the HO angle and seabed slope drives the SCR TDZ response. This can be related to a single parameter resulting from such combination, referred to in this work as the SCR incidence angle on the seabed, \( \beta \). Positively sloped seabed SCRs are characterised by higher \( \beta \) values resulting in lower TDZ stress utilisation and fatigue damage. The converse is the case for the negatively sloped seabed.

Increasing values of \( \alpha \) for an actually sloped seabed within the vicinity of the TDP can result in higher TDP offsets compared with an equivalent model where the seabed is assumed to be flat. This can cause errors in the arc length specified for internal cladding of the SCR as well as errors in the arc length at which the maximum compression, stress utilisation and fatigue damage occur along with the SCR. Care should be taken during SCR design in the assumption of the seabed profile around the SCR TDZ.

In ongoing work, the possibility of introducing the structural form to impose a positively sloped seabed-like profile within the SCR TDZ is being investigated. The objective is to access the benefits (on SCR TDZ response) of the imposed positive sloped seabed on the SCR TDP vicinity.

6. Recommendation
A simplified linear seabed profile is assumed in this study, and a one-directional wave load is imposed on the model in the riser azimuth direction (beam sea), where the roll and heave components of the vessel response is expected to be highest. However, the seabed profile can be more complex than the assumed linear and contains local undulations within the SCR TDZ. This is worth investigating, as well as different wave load data and direction of impact on the host platform.
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Appendix

Table 4. Change in static top tension of sloped seabed SCRs relative to their respective flat seabed SCRs.

| Seabed slope (deg) | Static top tension T_eff (kN) | % change in static top T_eff relative with flat seabed risers |
|--------------------|-------------------------------|---------------------------------------------------------------|
|                    | HO = 8deg                     | HO = 12deg                  | HO = 16deg                  | HO = 8deg                     | HO = 12deg                  | HO = 16deg                  |
| 0                  | 2436.01                       | 2646.48                     | 2892.39                     | 0.00                           | 0.00                           | 0.00                           |
| 2                  | 2437.10                       | 2647.49                     | 2893.21                     | 0.04                           | 0.04                           | 0.03                           |
| -2                 | 2435.88                       | 2646.58                     | 2892.70                     | -0.01                          | 0.00                           | 0.01                           |
| 4                  | 2438.69                       | 2649.01                     | 2894.48                     | 0.11                           | 0.10                           | 0.07                           |
| -4                 | 2437.34                       | 2648.54                     | 2895.06                     | 0.05                           | 0.08                           | 0.09                           |
| 7                  | 2441.16                       | 2651.28                     | 2896.11                     | 0.21                           | 0.18                           | 0.13                           |
| -7                 | 2444.24                       | 2657.19                     | 2905.16                     | 0.34                           | 0.40                           | 0.44                           |
| 10                 | 2442.84                       | 2652.52                     | 2896.26                     | 0.28                           | 0.23                           | 0.13                           |
| -10                | 2460.15                       | 2677.08                     | 2928.70                     | 0.99                           | 1.16                           | 1.26                           |

Table 5. Change in maximum dynamic top tension of sloped seabed SCRs relative to their respective flat seabed SCRs.

| Seabed slope (deg) | Maximum T_eff (kN) | % change in max. T_eff relative with flat seabed risers |
|--------------------|--------------------|----------------------------------------------------------|
|                    | HO = 8deg         | HO = 12deg                  | HO = 16deg                  | HO = 8deg         | HO = 12deg                  | HO = 16deg                  |
| 0                  | 3250.95           | 3543.84                     | 3918.20                     | 0.00                           | 0.00                           | 0.00                           |
| 2                  | 3239.66           | 3525.53                     | 3872.10                     | -0.35                          | -0.52                          | -1.18                          |
| -2                 | 3264.59           | 3577.08                     | 3972.48                     | 0.42                           | 0.94                           | 1.39                           |
| 4                  | 3229.84           | 3510.62                     | 3840.49                     | -0.65                          | -0.94                          | -1.98                          |
| -4                 | 3283.05           | 3628.04                     | 4037.24                     | 0.99                           | 2.38                           | 3.04                           |
| 7                  | 3218.00           | 3490.86                     | 3808.71                     | -1.01                          | -1.49                          | -2.79                          |
| -7                 | 3317.74           | 3727.86                     | 4160.45                     | 2.05                           | 5.19                           | 6.18                           |
| 10                 | 3206.50           | 3471.89                     | 3778.03                     | -1.37                          | -2.03                          | -3.58                          |
| -10                | 3413.68           | 3865.71                     | 4332.41                     | 5.01                           | 9.08                           | 10.57                          |

Table 6. Change in TDZ compression of sloped seabed SCRs relative to their respective flat seabed SCRs.

| Seabed slope (deg) | Minimum T_eff (kN) | % change in min. T_eff relative with flat seabed (compression) |
|--------------------|-------------------|---------------------------------------------------------------|
|                    | HO = 8deg         | HO = 12deg                  | HO = 16deg                  | HO = 8deg         | HO = 12deg                  | HO = 16deg                  |
| 0                  | -105.51           | -80.07                     | -24.60                      | -28.49                          | -54.29                          | -226.08                      |
| 2                  | -75.46            | -36.60                     | 31.02                       | 31.23                           | 58.91                           | 241.43                       |
| -2                 | -138.46           | -127.24                    | -84.00                      | -54.94                          | -104.73                          | -435.52                      |
| 4                  | -47.54            | 3.79                       | 82.54                       | 66.15                           | 123.89                          | 506.06                       |
Table 7. Change in stress utilisation of sloped seabed SCRs relative to their respective flat seabed SCRs.

| Seabed slope (deg) | Maximum U | % change in U relative with the flat seabed |
|--------------------|-----------|-------------------------------------------|
|                    | HO = 8deg | HO = 12deg | HO = 16deg | HO = 8deg | HO = 12deg | HO = 16deg |
| 0                  | 1.2       | 1.0        | 0.9        | 0.00      | 0.00       | 0.00       |
| 2                  | 1.1       | 1.0        | 0.9        | -4.48     | -5.51      | -5.90      |
| -2                 | 1.2       | 1.1        | 1.0        | 4.95      | 6.19       | 6.73       |
| 4                  | 1.1       | 0.9        | 0.8        | -8.59     | -10.38     | -11.05     |
| -4                 | 1.3       | 1.2        | 1.0        | 10.32     | 13.05      | 14.32      |
| 7                  | 1.0       | 0.9        | 0.8        | -14.24    | -16.84     | -12.10     |
| -7                 | 1.4       | 1.3        | 1.2        | 19.65     | 24.80      | 27.41      |
| 10                 | 1.0       | 0.8        | 0.7        | -19.25    | -22.34     | -12.15     |
| -10                | 1.5       | 1.4        | 1.3        | 30.55     | 38.19      | 41.71      |

Table 8. Change in fatigue damage of sloped seabed SCRs relative to their respective flat seabed SCRs.

| Seabed slope (deg) | Fatigue damage/year | % change in fatigue damage relative with the flat seabed |
|--------------------|---------------------|--------------------------------------------------------|
|                    | HO = 8deg | HO = 12deg | HO = 16deg | HO = 8deg | HO = 12deg | HO = 16deg |
| 0                  | 1.8E-04   | 5.9E-05   | 2.0E-05   | 0.00      | 0.00       | 0.00       |
| 2                  | 1.6E-04   | 5.3E-05   | 1.8E-05   | -11.07    | -10.38     | -10.49     |
| -2                 | 2.0E-04   | 6.6E-05   | 2.2E-05   | 9.89      | 10.18      | 8.67       |
| 4                  | 1.4E-04   | 4.6E-05   | 1.6E-05   | -22.92    | -22.20     | -20.63     |
| -4                 | 2.2E-04   | 7.0E-05   | 2.3E-05   | 18.47     | 18.24      | 14.71      |
| 7                  | 1.1E-04   | 3.7E-05   | 1.3E-05   | -39.06    | -38.51     | -35.34     |
| -7                 | 2.3E-04   | 7.3E-05   | 2.4E-05   | 27.85     | 22.87      | 18.97      |
| 10                 | 8.5E-05   | 2.8E-05   | 9.9E-06   | -53.64    | -53.27     | -50.21     |
| -10                | 2.4E-04   | 7.0E-05   | 2.5E-05   | 28.99     | 17.82      | 23.79      |

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