TOWARDS THE GLOBAL ANALYSIS OF SOIL AND RISER INTERACTION USING A DEGRADATION SOIL MODEL

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Abstract. In offshore industry as water depth gets deeper, the prediction of riser loads gets more complex, due to issues such as its interaction with seabed. The touchdown point (TDP) – where the riser touches the seabed for the first time – is a hot spot where the interaction is intense, and good predictions of TDP response is critical to the assessment of steel catenary riser (SCR) fatigue life. Therefore, the soil model plays an important role, because simplified models can overestimate the SCR curvature at TDP. Different types of soil have been studied from linear to nonlinear springs to represent the seabed. Nonetheless, linear springs cannot represent the real soil behavior, thus research focuses on P-y curves based in pipe-soil experimental results. Two models became widely studied: the non-degradation and degradation models. The former has been applied in general software analysis, but the degradation model has not. The degradation model is based on plastic soil deformation under cyclic loads, and it has other features such as consideration of soil- water mixing, erosion, and soil consolidation, which can drive the riser-soil separation and trench formation. The purpose of this article is to describe the implementation of a soil-riser interaction model considering degradation effects [1] on the in-house time domain global analysis software SITUA-Prosim. Two case studies are presented to validate the model and the proposed algorithm.

Keywords: Soil and riser interaction, coupled analysis, numerical analysis.

1 Introduction

In the context of deepwater O&G exploration and production, steel catenary risers (SCRs) have been an alternative configuration and structure that is favorable in technical and economic. SCRs are designed to satisfy structural integrity requirements, but they demand extra attention at two critical points: at the top and at the first point where the riser touches the seabed (TDP- Touch Down Point). At the top, the stress caused by environmental conditions, movement of the floating unit, and the weight itself are, without much effort in terms of engineering methods, well estimated. At the TDP, and around its vicinity, there are still relevant technical and technological gaps to be remedied. The structural behavior of the SCR at the TDP is associated with several phenomena, which impose complexity for the evaluation of local efforts. It is a critical point where interactions with other domains make it difficult to predict the strength, which is directly associated with uncertainties in the estimation of stresses generated for example in the interaction with soil, where the riser can dig deep trenches, due to a complex mechanism of interaction between riser, soil, and fluid.

This interaction is not restricted to a single point, because any change in the riser's global equilibrium implies the variation of tension, curvature, and even the variation of the TDP, generating a touchdown zone (TDZ). The development of these cyclic stresses can generate a fatigue build-up in the SCR, which in turn is strongly dependent on the soil model and soil stiffness [2], [3]. Thus, the soil model plays an important role and simplified abstractions of the riser-soil interaction can overestimate the riser curvature in the TDZ. Different soil models have been proposed over the years by various researchers, many of them based on linear and nonlinear springs, which fail to depict many phenomena in the riser-soil interaction. Therefore, more recent research has focused on p-y curves calibrated by experimental work, from which two families emerge: non-degradable soil model and degradable soil. The degradation model considers the plastic deformation of soil under cyclic loads, along with other features such as consideration of soil-water mixing, erosion, and soil consolidation, which can lead to trench formation.

Thus, this work describes the implementation of the nonlinear soil model with strength degradation property proposed by [1] into in-house program SITUA/Prosim [4]. To test the ability of the soil model in generating strength and soil characteristic response within the finite element program, case studies were performed using the

SITUA/Prosim global analysis associated with the implemented routine to address the degradable soil model.

2 Modelling Riser-Soil Interaction

The riser-soil interaction in the TDZ is complex with highly nonlinear soil response. To represent it, nonlinear models follow the contact and update the stiffness, penetration, and reaction force. Several studies have sought to represent seafloor in riser contact. Experiments such as those of [5]–[7] have given rise to several nonlinear soil models. Nonlinear models, relying on discrete soil modeling, have become viable alternatives as they can represent most of the soil characteristics in riser interaction, of which the resistance and deflection (P-y) curves are the most studied. Through results of experiments, in the cooperative projects CARISIMA and STRIDE [6], formulated four basic stages in the interaction mechanism; from the subsidies collected there several models emerged to represent the stages of soil behavior in riser interaction as shown in Figure 1: (1) soil without penetration, (2) initial penetration, (3) riser elevation (4) partial separation and (5) repenetration.

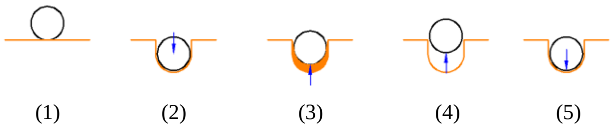


Figure 1: Basic schematic of riser-soil interaction[8]

Two groups can be highlighted: models with and without degradation. In the models without degradation, studies have focused on the representation of nonlinear models with hysteresis cycles for cyclic loading, highlighting features such as suction and trench formation. Of which, the RQ [9] and AB [10] models are highlighted, widely used for riser structural analysis, particularly for fatigue design in the TDP. These models agree in the general aspects about undegraded soil behavior and differ in the mathematical treatment of the problem and representation of some characteristics during riser-soil interaction, as shown [1], such as: both present the power law of the backbone curve to treat penetration into virgin soil and a hyperbolic response at unloading. They differ in the treatment of uplift; the RQ model does not present the explicit treatment of separation at contact loss. Both models do not develop an explicit treatment of soil degradation.

The group of soil models with degradation property are those that besides all the mentioned characteristics, present resistance decreases with load cycles. These models can arise from the adaptation of AB model as suggested [11] and [12]. However, the model presented by [1] (ZGR) represents degradation in a single model and features trenching and uses a single formulation for the different stages of soil response. Although it is more sophisticated, there are few references of this model in global riser analysis.

2.1 Zargar Soil Model

The ZGR model overcame some of the deficiencies of the previous models. It has in its formulation the basic riser-soil interaction scheme (Figure 2), differing in the way it represents the reshaped soil, implementing two response curves to address this aspect. The model then relies on seven stages: (1) Initial Penetration (IP); (2) Uplift Rebound (UR); (3) Uplift Separation (US); (4) Detachment (DT); (5) Repenetration- Remodeled (RR); (6) Partway Uplift and Repenetration (PU & PR); and (7) Repenetration Semi Intact (RS). These seven stages are represented in Figure 2.

2.1.1 Initial Penetration (IP)

The initial IP penetration curve is modeled by the backbone curve [10] which is based on a collapse load of a cylinder buried in the soil and represented by Eq. (1) and (2).

$$p = N_c S_u \tag{1}$$

$$S_u = S_{u0} + \rho y D \tag{2}$$

The soil bearing load Nc defined in Eq. (3) is variable sensitive to the trench width and provides shear resistance at the base trench. It is assumed that the width of the trench formed by the pipe is equal to the pipe diameter w/D = 1. The parameters a and b are dependent on the pipe roughness that can be found in [10]. The stiffness in the curve is the tangent stiffness, k_{IP}.

$$N_c = a y^b \tag{3}$$

$$k_{IP} = a y^{b-1} b (S_{u0} + \rho y D) + a \rho y^b D \tag{4}$$

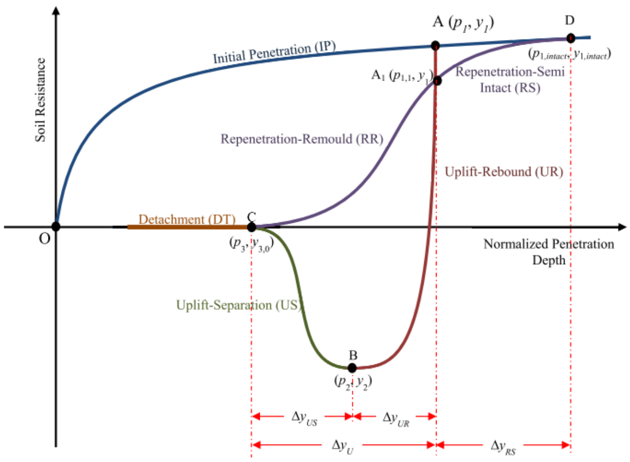


Figure 2:Schematic of the p-y curve of Zargar[1]

2.1.2 Uplift Rebound (UR)

After the change of motion at A (p_1, y_1), Figure 2, the riser begins to lift, and the soil behaves as a rebound (UR mode) which effectively starts the ZGR model. This curve is defined by equation (5) and with associated parameters found in [1]. The elevation mode (UR) has the upper boundary point A and the lower boundary point B in Figure 1, where point B is defined by equations (8) and (9). Equation (9) refers to the point of maximum suction, where φ is the suction factor that, through the results of Hodder & Byrne[7], [1]calibrated a linear regression with depth, given by Eq. (12), where the constants m and c are 0.09 and 0.53, respectively.

$$p(y) = p_m + \{\frac{\alpha}{[1 + C^{k(y-y_m)}]^{\nu}} + \beta\}\xi|\Delta p_m| \quad (5)$$

$$\xi = \frac{\gamma}{\frac{\alpha}{1+C^{k(y-y_m)}} + \beta} \quad (6)$$

$$k_{UR} = \frac{2K_{max}}{(1+\varphi)ln\,(C)} \quad (7)$$

$$y_2 = y_1 - \Delta y_{UR} \quad (8)$$

$$p_{2,1} = -\varphi p_{1,1} \quad (9)$$

$$\varphi = m(y) + c \quad (10)$$

2.1.3 Uplift Separation (US)

From the maximum suction, if the riser continues with the lifting motion, observed from point B to C in Figure 1, the model is governed by the partial separation mode of the riser from the soil, where the trajectory is modeled by the US curve, which uses the same Eq.(5), with the appropriate parameters for this level found in [1] . The US mode ends at depth y_3, Eq. (11), which represents the point at which the riser separates from the soil. Here the stiffness is the same as in the UR mode multiplied by a stiffness factor, given by Eq.(12).

$$y_{3,0} = y_1 - \Delta y_{U,0} \quad (11)$$

$$k_{US} = c_{US}\kappa_{UR} \quad (12)$$

2.1.4 Detachment (DT)

Rising riser movement, if no forces change its separation path, reaches point C, where the beginning of total separation of the riser from the seabed is observed. This separation continues until point O, as shown in Figure 2, then from this point the riser is totally separated from the soil (DT). At this stage, the resistance and stiffness of the soil are zero.

2.1.5 Repenetration- Remodeled (RR)

There is a change in the movement of the riser, and it repenetrates the soil, this behavior is represented by the curve that starts at point C. This repenetration of the riser is given by a different curve than that of IP and, because it finds remodeled soil, this rise is steeper than that of initial penetration (IP). The remodeled repenetration (RR) curve has the upper contour the point A_1, where, due to soil degradation, which the equations can be found in [1] , this contour resistance is lower than the resistance achieved at initial penetration. Thus, the P-y curve of the ZGR model, for a complete cycle, is formed by the following sequence of the modes: IP - UR - US - DT - RR.

2.1.6 Partway Uplift and Repenetration (PU & PR)

If, in the lift and soil separation (UR and US) modes, in the repenetration (RR) mode, the riser has a sudden reversal of motion, the soil reacts with the partial repenetration (PR) curves - for repenetration at uplift, and partial separation (PU) - for uplift at penetration. These curves also use the same formulation (5), with variation in the parameters in [1] . The stiffnesses in these modes are similar to the one used in the UR mode. Since the areas under the curves in PU and PR modes are smaller than the curve area generated by RR mode, it is considered as incomplete cycles, so the degradation is lower. And, to capture the actual degradation, [1] uses Eq. (18) to count the actual cycle. Where n is integer value of the full cycle before the incomplete mode and AR is the ratio of resistance in the incomplete cycle to the resistance in the full cycle. More advanced explanations and formulations can be found in [1].

2.1.7 Semi-Intact Soil Repenetration (RS)

RS refers to the part of soil that has neither been fully disturbed nor is fully virgin, and its upper contour refers to the point at which it joins bend IP. These modes are given by a single hyperbolic-exponential formulation, Eq. (5), changing some model parameters to form the right direction of the curve. If the riser continues to penetrate the soil, either exiting the RR or PR mode, above the maximum deformation (y_1) as shown in Figure 1, it encounters part of the soil that is not fully virgin and remold, so the response for this behavior is given by the semi-intact (RS) curve. For further formulation governing this mode reach [1].

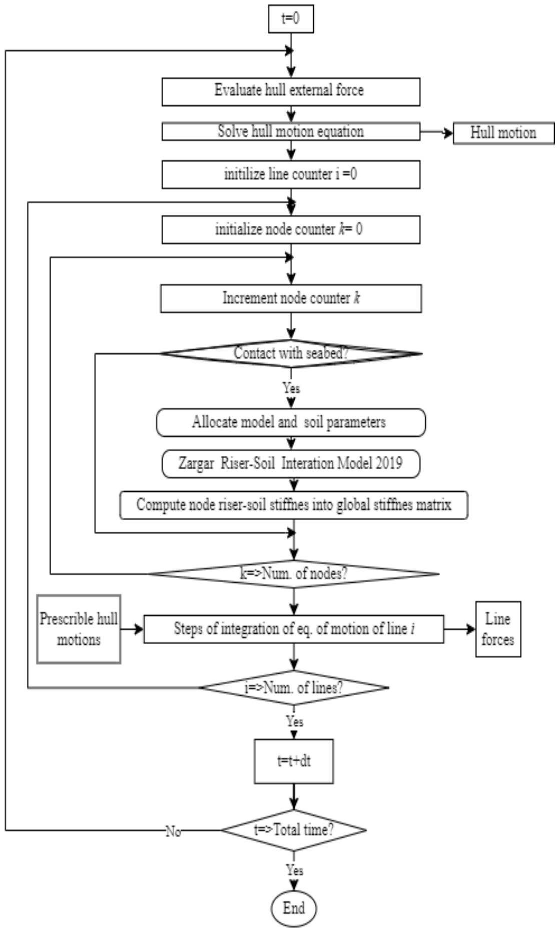
2.2 Modelling Zargar Soil Model in Global Analysis

The ZGR model [1] was implemented numerically as a Fortran subroutine in the SITUA/Prosim [4] global analysis code for offshore structures and systems, developed by the Laboratory of Computational Methods and Offshore Systems (LAMCSO) team. This program simulates the coupled global response of floating systems, mooring lines, and risers.

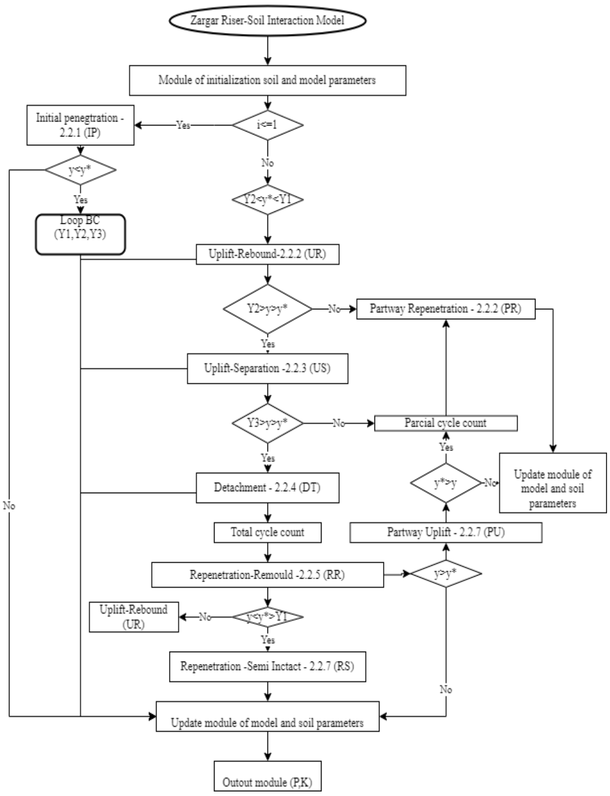
Flowchart 1 presents the main steps from the calculation of the environmental loads acting on the hull, through the calculations of the hull movement, through the solution steps of the equation of movement of the lines.The ZGR soil model was incorporated into the Prosim framework for vertical interaction, considering the soil as a flat surface and dependent on loading history. All data and simulation time-dependent loading histories, which form the loading and unloading loop of the model were incorporated within the structure of each element/node of SITUA/Prosim. The main advantages of the model proposed by [1] are that it can clearly show the trench formation at pipe uplift, while for example the widely used [9] model does not, thus providing a more realistic modeling of risers and degradation with load cycles. Thus, with the implementation of this model in the FE SITUA program it will be possible, for example, to use the model for a long-term fatigue analysis of the riser TDP.

Once allocated and initialized all the necessary parameters for soil-riser interaction analysis, the ZGR model is activated. This model is represented by the algorithm in Flowchart 2. The routine is called when the riser touches the soil. At this first touch, as the interaction mechanism explains, the soil is virgin and begins to be disturbed at the initial penetration (IP) stage, Flowchart 2. Note that, $y^* = y_n$ is the soil penetration at the current load step and y the penetration at the previous load step, $y=y_{n-1}$, in this way it is possible to capture the direction of the riser direction.

When it reaches the maximum soil deflection with the change of riser movement, the routine generates three contour points (Y1, Y2 and Y3) which are the point of maximum penetration, maximum suction, and the point of separation of the riser from the soil respectively. After formation of the hysteresis curve loop contours, the riser is in elevation, and the UR mode is activated, this mode starts with high resistance and drops rapidly to zero, from there the resistance becomes negative with a not so sharp decrease as it approaches the maximum suction Y2. If, prior to depth Y2, the riser, rising from the soil undergoes a change of motion from elevation to penetration $y>y^*$, the model should revert to the for repenetration (PR) mode. However, if this elevation continues until penetration is equal to, or less than, Y2, the algorithm should trigger partial separation (US) mode, as shown in Flowchart 2. As with UR mode, if there is a reversal of movement from separation to penetration of the riser into the soil, the algorithm redirects to (PR) mode. In this case there is an incomplete cycle count and calculating the degradation of the soil parameters.



Flowchart 1: Riser analysis module of the finite element program [4]



Flowchart 2: Algorithm for soil modeling

If there is no change and the separation movement continues, the riser goes into full separation mode (DT). If there is penetration movement of the riser, after exiting DT mode, there is cycle counting of model degradation, as shown in Flowchart 2. If the riser begins to penetrate the soil again, then the algorithm triggers the repenetration mode for the reshaped soil (RR). As the riser penetrates the soil, the resistance increases rapidly unlike the IP mode, and stiffness in this RR mode. If there is a change in movement, before reaching the upper contour y > y* < Y1 the algorithm triggers the elevation at penetration (PU) mode, Flowchart 2. Otherwise, the movement of for in the direction of burrowing further into the soil and reaching the maximum depth reached at virgin soil penetration (Y1), the soil mode switches to the remodeled soil repenetration mode of semi - intact soil (RS). After this point, any penetration the soil is considered as virgin.

Soil output module makes the effective link between the implemented model and the global Prosim framework, receiving the current soil resistance and calculates the model's secant stiffness.

3 Case Studies

To validate the implementation of the soil model into the SITUA/Prosim software, some existing examples in[1] have been reproduced. Two initial cases were studied, which use the same soil properties and model parameters varying only the load. Case A refers to a horizontal bar penetrating the soil with a diameter of 1 m and thickness of 0.25 m and harmonic motion of period 100 seconds and unit amplitude 2m. In this study, the soil was modeled as presented in Table 1, using the same data used by [1]. The power parameters as a function of duct roughness, for backbone curve, the values of a rough duct were adopted. For this study the soil data are as given in Table 1, type A.

This example shows a bar penetrating the soil, with the result in Figure 3 below where the abscissa corresponds to the depth of the bar buried in the soil and the ordinate to the resistance generated at the soil surface.

The result shows the resistance variation in two load cycles. With a resistance of 32 kPa in the first cycle and 24 kPa in the second cycle, evidence that there was degradation or reduction of resistance and showing all the stages of a characteristic P-y curve, with trench formation and the repenetration curve more pronounced than the initial penetration, as well as the reduction of suction with the number of load cycles.

Case B also comprises a horizontal beam with harmonic loading, but now with monotonic growth. The bar has 0.3 m diameter, soil parameters are presented in Table 1, type B. The goal was to test the algorithm with ten cycles of 1D penetration and 0.5D elevation. In the tenth cycle the penetration goes up to 2D and with the same elevation, repeated for 10 cycles. The results are presented in Figure 4. The first evidence of the curve lies in the number of load cycles and with monotonically increasing cycles; comparing with the curve proposed in [1], it is seen in Table 2 that the behavior is very close. The soil resistance values reached by [1] are marked on the Figure 4 with sign (+). Tested the responsiveness of the model under request of very number of displacement cycles, the algorithm responds by coherently decreasing the soil resistance. At the first displacement group the degradation has reached its maximum level and remains constant. After the tenth cycle the bar penetrates the soil one diameter above the maximum penetration previously and, in the middle of the two cycles, the RS mode starts in the tenth cycle where the resistance is lower and it is possible to observe that its beginning happens exactly at the lowest resistance value and grows until it joins the curve for penetration in virgin soil, evidencing a non-remodeled soil.

Table 1: Soil data

Soil data		A	B
Undrained Resistance RSD (kPa)	Su_0	2,5	2,5
RSD gradient (kPa/m)		1,5	1,5
Max. slope in UR mode	Δyur	0,3	0,2
Max. initial slope at elevation	Δyu	1	0,5
Max. normalized stiffness	K_{max}	200	200
Coefficient of stiffness in US	c_{us}	0,5	0,5
Stiffness coefficient in RR mode	c_{RR}	0,5	0,5
Degradation parameter	ρ_0	0,4	0,4
Degradation parameter	ε	0.8	0.9
Exponential basis	C	1,2	1,2
Secant stiffness coefficient in y1	μ	2	1,4

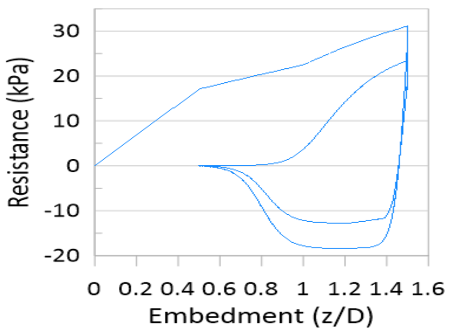


Figure 3: Typical P-Y curve generated for 1 load cycle.

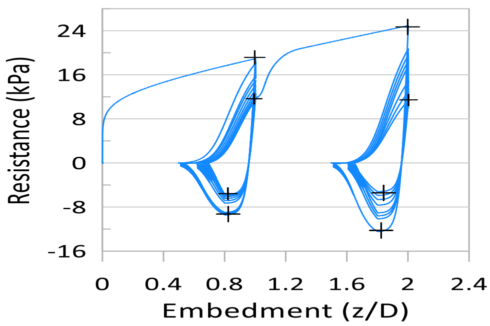


Figure 4:Typical P-Y curve generated for more than 1 load cycle.

The levels of resistances at maximum penetration and suction are the same in the example reproduced in this paper. Thus, one can observe maximum soil resistance of approximately 19 kPa and suction of approximately -9 kPa in the first loading group and 24 kPa maximum resistance and suction of approximately -12.5 kPa in the second loading group. The model in this study consistently reduced strength with cycle number in degradation, which can be seen in Figure 3 the reduction of approximately 16 and 22 kPa in the two motion groups for the first loading cycle.

Table 2 Comparison with results from Figure 14 [1]

		Before the soil degrade		After the soil degrade	
		Zargar (+)	Current work	Zargar (+)	Current workr
First load cycle	Max. resist	19	19	11	10
	Min Resist	-9	-9	-6	-5
Second load cycle	Max. resist	25	25	20.5	20.5
	Min Resist	-13	-13	-8	-7

4 Conclusions

This work presented the implementation of a riser-soil interaction model considering the soil degradation effects under cyclic loading, as well as a single government formulation for all stages of soil response, into a global analysis finite element software. In the case studies, the implementation has been validated by the good agreement with the results presented in [1] as shown in Table 2. Prescribed displacements were used, representing harmonic loading, controlling for maximum penetration or maximum initial soil displacement as hysteresis onset parameters. This strategy becomes convenient when the loading is known in advance.

In future works, once implemented the ZGR model [1], it is intended to follow with the implementation of a non-degraded soil model and perform a global SCR analysis coupled to a floating production system, comparing the effects of the different models for structural analysis and the impact on riser fatigue life.

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5 References

[1] E. Zargar, M. Kimiaei, and M. Randolph, "A new hysteretic seabed model for riser-soil interaction," *Marine Structures*, vol. 64, no. May 2018, pp. 360–378, 2019, doi: 10.1016/j.marstruc.2018.08.002.

[2] R. Thethi, "SOIL INTERACTION EFFECTS ON SIMPLE CATENARY".

[3] M. S. Hodder, D. J. White, and M. J. Cassidy, "Analysis of Soil Strength Degradation during Episodes of Cyclic Loading, Illustrated by the T-Bar Penetration Test," *International Journal of Geomechanics*, vol. 10, no. 3, pp. 117–123, 2010, doi: 10.1061/(asce)gm.1943-5622.0000041.

[4] B. P. Jacob, L. D. Franco, M. V. Rodrigues, F. N. Correa, and B. M. Jacovazzo, "Parallel implementations of coupled formulations for the analysis of floating production systems, Part II: Domain decomposition strategies," *Ocean Engineering*, vol. 55, pp. 219–234, 2012, doi: 10.1016/j.oceaneng.2012.06.018.

[5] N. R. T. Willis and P. T. J. West, "Interaction between Deepwater Catenary Risers and a Soft Seabed: Large Scale Sea Trials," *Technical paper*, pp. 9–25, 2001, doi: 10.4043/13113-ms.

[6] C. Bridge and N. Willis, "Table 2 – Summary of Test Rig Parameters".

[7] M. S. Hodder and B. W. Byrne, "3D experiments investigating the interaction of a model SCR with the seabed," *Applied Ocean Research*, vol. 32, no. 2, pp. 146–157, 2010, doi: 10.1016/j.apor.2009.09.004.

[8] A. Nakhaee and J. Zhang, "Trenching effects on dynamic behavior of a steel catenary riser," *Ocean Engineering*, vol. 37, no. 2–3, pp. 277–288, 2010, doi: 10.1016/j.oceaneng.2009.10.005.

[9] M. Randolph and P. Quiggin, "Non-linear hysteretic seabed model for catenary pipeline contact," *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, vol. 3, pp. 145–154, 2009, doi: 10.1115/OMAE2009-79259.

[10] C. P. Aubeny and G. Biscontin, "Seafloor interaction with steel catenary risers," *Proceedings of the International Offshore and Polar Engineering Conference*, no. 510, pp. 110–117, 2008.

[11] A. NAKHAEE, "Study of the Fatigue Life of Steel Catenary Risers," no. December, 2010.

[12] J. Chen, X. Bai, and M. A. Vaz, "Dynamic behavior of steel catenary riser at the TDZ considering soil stiffness degeneration and trench development," *Ocean Engineering*, vol. 250, no. March, p. 110970, 2022, doi: 10.1016/j.oceaneng.2022.110970.

[13] M. S. Hodder, "Geotechnical analysis of offshore pipelines and steel catenary risers," no. December, p. 229, 2009.

[14] E. Zargar, "A new hysteretic seabed model for riser-soil interaction," School of Civil, Environmental and Mining Engineering, The University of Western Australia, 2017. [Online]. Available: 10.4225/23/59f9222f76868