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Artificial neural network development for stress analysis of steel catenary risers: Sensitivity study and approximation of static stress range

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ABSTRACT

Fatigue design of steel catenary risers (SCRs) is an important challenge especially in the touchdown zone (TDZ). Numerous parameters affect the fatigue damage in the TDZ, including those pertaining to riser motions, riser characteristics and soil properties. So far, only a few sensitivity studies have been published with limited applications, considering small ranges, investigating only a selection of input parameters or failing to examine the interactions between input parameters.

This paper aims to test the robustness of previous research and extend the ranges of the input parameters for SCR systems under static loading, by means of numerical simulations. An approximation of the critical stress range in the TDZ defined by the authors previously was refined to assist the sensitivity studies. A large database was created using an automation subroutine coded in Python programming language that links the marine analysis software OrcaFlex and the optimisation software modeFRONTIER. Design of experiment techniques were used for post-processing and quantify the relative effects of the various dimensionless groups and their interactions. An approximation using a series of artificial neural networks is presented; it successfully approximates over 99% of the cases of the database with an accuracy of ±5%.

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1. Introduction

Fatigue damage of steel catenary risers (SCR) is influenced by a large number of parameters, rendering SCR fatigue design a challenging task, particularly in the touchdown (TDZ) – the area of dynamic riser-soil interaction [1]. Previous parametric studies have investigated the individual effects of some of these parameters, such as the effect of the hang-off angle, the inside diameter and the wall thickness [2], the effect of the soil parameters when using a nonlinear soil model [3–5] or the effect of the loading parameters [4]. The individual effects of the dimensionless groups that were shown to influence the fatigue damage in SCRs [6] were also examined [7]. These studies used the one-factor-at-a-time approach where only one of the input parameters is varied and the other input parameters are fixed to arbitrary values. This approach can however lead to misinterpretation of the results by failing to capture the potential effects of interactions between input parameters (“*an interaction occurs when two or more factors acting together have a different effect on the quality characteristic than the effect of each factor acting individually*” [8]). The robustness of previous published results should therefore be tested and the ranges of some of the input parameters extended. The work reported here is consistent with advice in riser design guidelines [9] to investigate the influence of different parameters, particularly where their value is uncertain. A more quantitative understanding of the effects of input parameters on the maximum stress range will assist the use and refinement of current numerical models and consequently will improve confidence in SCR fatigue design.

Fatigue damage in the touchdown zone arises due to the variation of axial stress under cycles of imposed motion, resulting mainly from the action of waves on the floating facility. The fatigue life in the TDZ is controlled by the maximum stress range (*Max* $\Delta\sigma_{TDZ}$) occurring there for a given motion, accounting for the number of cycles, and evaluating the cumulative fatigue damage over the full range of motion. For this reason, one of the objectives of this paper is to evaluate the relative effects of the input dimensionless groups and their interactions on the variation of *Max* $\Delta\sigma_{TDZ}$, considering large ranges of the relevant groups. The key dimensionless groups for fatigue design of SCRs are selected as the inputs for the sensitivity studies rather than the individual input parameters to enhance the applicability of this research [6,10,11].

The main purpose of this paper, however, is to develop an efficient method able to approximate the maximum stress range in the

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Table 1
Summary of the selected dimensionless groups.

Category	Notation	Dimensionless group	Comment
Output characteristic	π_1	σ/E	Strain in the riser wall
	π_{16}	$s/\Delta z$	Location along the SCR
Varied dimensionless group	π_2	$H/\Delta z$	Motion amplitude; vertical and horizontal perturbations of the catenary are defined by π_2 and π_3
	π_5	$D_o/\Delta z$	Riser outside diameter relative to water depth
	π_6	D_o/w_t	Riser outside diameter relative to wall thickness
	π_7	$p/(E\ \Delta z)$	Riser unit submerged weight
	π_9	$T_o/(E\ \Delta z^2)$	Riser tension
	π_{11}	k_s/E	Soil stiffness
	π_{15}	$g\ \Delta z\ \rho_{steel}/E$	Water depth
Unvaried dimensionless group	π_3	$\Delta\theta_m = 0°$	Motion direction relative to the hang-off angle
	π_8	$\nu = 0.293$	Poisson's ratio
	π_{10}	$\mu = 0.5$	Soil friction coefficient
	π_{14}	$\rho_{steel}/\rho_{water} = 7.66$	Relative steel and water densities
	π_{17}	$\beta = 0°$	Angular location on the SCR circumference
Irrelevant dimensionless group in this study	π_4	$H/T\sqrt{\rho_{steel}/E}$	Velocity of input motion relative to wave propagation speed in SCR
	π_{12}	C_D	Drag force coefficient
	π_{13}	C_A	Added mass coefficient
	π_{18}	t/T	Time during one cycle of applied motion

where β, angular position on the SCR circumference; Δz, vertical difference between hang-off point and seabed; $\Delta\theta_m$, angle of the motion relative to the hang-off angle (θ_{HO}); μ, soil friction coefficient; ν, Poisson's ratio; ρ_{steel},ρ_{water}, steel and water densities; σ, axial stress; C_D, C_A, drag and added mass coefficient; D_o, w_t, riser outer diameter and wall thickness; E, Young's modulus; g, gravity acceleration; H,T, Heave amplitude and period of the input motion; k_s, soil stiffness; p, unit submerged weight; s, arc length (measured from the hang-off point (HOP)); t, time; T_o, horizontal tension component.

TDZ in order to assist sensitivity studies. A pilot study described in [12] aimed to determine what model of response surface was best suited for SCR fatigue design and demonstrated the usefulness of the artificial neural network (ANN) approach. In this paper, the response surface method (RSM) using the ANN approach is applied to refine the approximation of the maximum stress range in the TDZ normalised by the Young's Modulus ($Max\ \Delta\sigma_{TDZ}/E$ as defined in [12]) and achieve a reasonable level of accuracy, defined here as a relative difference of ±15% between the ANN predictions and the results from OrcaFlex [13] simulations over the entire selected ranges of the input dimensionless groups. For this purpose, additional cases (i.e. particular combinations of SCR configuration and loading condition) were added to the original database of 4800 cases developed in [12] using the same in-house subroutine to automate pre-processing, running and post-processing of the numerical models.

In total, 57,023 cases were used with the aim of representing the majority of realistic SCR configurations and static loading conditions. Such a large database was developed to increase the chances of capturing all underlying interactions between the dimensionless groups. Also, the training and testing sets were selected using an improved technique that leads to similar statistical properties between the two sets of cases. This ensures that the testing set gives a reliable representation of the training set (assuming the training set itself is a reliable representation of the design space) in order to test the accuracy of the approximation within the entire design space. Once a suitable approximation was achieved, it was used to obtain a series of design charts.

This study is currently limited to static loading only (no inertia or damping effects), although it forms part of ongoing research aiming to simplify fatigue design of SCRs in the conceptual and basic design stages by using dynamic amplification factors (DAFs) to quantify the dynamic response in the TDZ relative to the static response [14]. Future work will extend the ANN approach directly to dynamic conditions, accounting for hydrodynamic and inertia effects as longitudinal and transverse waves travel along the riser. The study is limited to the SCR response under in-plane motions only with the motions applied by imposing a displacement to the floating vessel. The current profile in the sea column, rotational

Table 2
Selected extreme values of the individual input parameters.

Varied input parameter	Minimum value	Maximum value
Water depth, Δz	400 m	2000 m
Outside diameter, D_o	0.1524 m	0.762 m
Wall thickness, w_t	$D_o/15$ if $0.1524\ m \le D_o < 0.36\ m$ $D_o/20$ if $0.36\ m \le D_o < 0.56\ m$ $D_o/25$ if $0.56\ m \le D_o \le 0.762\ m$	$D_o/9$ if $0.1524\ m \le D_o \le 0.36\ m$ $D_o/12$ if $0.36\ m < D_o \le 0.56\ m$ $D_o/15$ if $0.56\ m < D_o \le 0.762\ m$
Content density, ρ_{cont}	0 kg/m^3	1025 kg/m^3 if $0.1524\ m \le D_o \le 0.46\ m$ 800 kg/m^3 if $0.46\ m < D_o \le 0.762\ m$
Horizontal tension component, T_o	Such that: $\theta_{HO} = 17°$ if $400\ m \le \Delta z < 950\ m$ $\theta_{HO} = 9°$ if $950\ m \le \Delta z < 1500\ m$ $\theta_{HO} = 7°$ if $1500\ m \le \Delta z \le 2000\ m$	Such that: $\theta_{HO} = 20°$ if $400\ m \le \Delta z \le 950\ m$ $\theta_{HO} = 17°$ if $950\ m < \Delta z \le 1500\ m$ $\theta_{HO} = 11°$ if $1500\ m < \Delta z \le 2000\ m$
Heave amplitude, H	0.1 m	7.5 m
Soil stiffness, k_s	11.4 kPa	228 kPa

stiffness at the hang-off point, flow rate of the contents, pipe coating and structural damping are not taken into account. A summary of the dimensionless group definitions and their physical descriptions is shown in Table 1 while an illustration of the key parameters is shown in Fig. 1. Since the study is limited to static loading, the dimensionless groups presented in [6] related to the velocity of imposed motion, time within a cycle of applied motion or to the hydrodynamic coefficients (as current is also neglected) are not relevant here. The ranges for the individual input parameters along with relevant design criteria are summarised in Table 2, with the resulting ranges for the dimensionless groups given in Table 3. Gravity acceleration ($g = 9.81\ m/s^2$), Young's Modulus for the SCR ($E = 2.12E8$ kPa), water density ($\rho_{water} = 1.025\ te/m^3$) and steel density ($\rho_{steel} = 7.85\ te/m^3$) remain unchanged in the study.

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