Engineering Structures 92 (2015) 172–185

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Approximation of the maximum dynamic stress range in steel catenary risers using artificial neural networks

Lucile M. Quéau *, Mehrdad Kimiaei, Mark F. Randolph

Centre for Offshore Foundation Systems, The University of Western Australia, Crawley, WA 6009, Australia

ARTICLE INFO

Article history:
Received 9 February 2015
Revised 11 February 2015
Accepted 12 February 2015
Available online 25 March 2015

Keywords:
Steel catenary risers
Fatigue
Sensitivity analyses
Design of experiment
Artificial neural network

ABSTRACT

Adequate assessment of fatigue damage in steel catenary risers (SCRs) is essential, and usually evaluated with time consuming numerical analyses. Simplified design strategies would improve the efficiency of the screening tasks in the early design stages.

As part of on-going research aiming to define a simplified fatigue design procedure for SCRs in the touchdown zone (TDZ), the sensitivity of fatigue damage to various parameters is explored using a large database (>40,000 cases). An approximation of the maximum stress range in the TDZ is established using several artificial neural networks and predicts well the fatigue life of selected example SCRs.

1. Introduction

The depletion of shallow water hydrocarbon reserves has focused the oil and gas industry increasingly on reserves in deep water, where steel catenary risers (SCRs) represent one of the most widely used option to convey the oil and gas from subsea to the surface. The main drawbacks of SCRs however is their high sensitivity to environmental loading that generates fatigue damage, especially in the area where the riser is in contact with the seabed, namely the touchdown zone (TDZ) (e.g. [1,2]). An accurate estimation of SCR fatigue life is fundamental to ensuring riser integrity over the life of the project while keeping costs low.

The fatigue damage is often estimated through time domain analyses to account for SCR nonlinearities (material and geometrical for instance) and by performing a series of time consuming numerical simulations [3–5]. A riser design standard [5] therefore encourages the use of simplifying techniques, especially for the early stages of design, to improve the efficiency of computer analyses and support engineering judgement. It states that "*numerous simplified analyses will normally produce more information regarding overall static and dynamic system behaviour when compared to a reduced number of advanced analyses*."

In light of these facts and recommendations, the authors have been aiming to develop a simplified riser fatigue analysis procedure for the early stages of SCR design, avoiding the need to perform time consuming analyses. The present paper details part of that research, focusing on defining an approximation of the maximum dynamic stress range of SCRs in the TDZ (*Max* $\Delta\sigma_{TDZ}$) valid for a wide range of input parameters. *Max* $\Delta\sigma_{TDZ}$ is used as, together with the number of cycles of each magnitude of motion applied, it controls the fatigue damage. The method followed to develop the approximation is the same as in Quéau [6] and Quéau et al. [7] where an approximation, namely '9-ANNs static approximation', was defined for the maximum static stress range in the TDZ.

The sensitivity of *Max* $\Delta\sigma_{TDZ}$ to the variation of design input parameters was investigated by performing a large amount of numerical analyses. A similar in-house automation subroutine as presented by Quéau et al. [7] was used for the pre and post processing tasks. It consists in linking the marine analysis software OrcaFlex [8] with the optimisation software modeFRONTIER [9] to generate a large database of SCR cases selected through design of experiment (DoE) techniques. A case is defined as a SCR configuration under a given dynamic displacement. The flowchart of the automation subroutine is shown in Fig. 1 using the notation from Quéau et al. [10] as adopted hereafter. The dimensionless groups shown to influence SCR stress range in previous work [10] constitute the input parameters so that the function f to be modelled is defined as

$$\frac{\mathrm{Max}\Delta\sigma_{TDZ}}{E} = f\left(\frac{H}{\Delta z}, \Delta\theta_m, \frac{H}{T}\sqrt{\frac{\rho_{steel}}{E}}, \frac{D_o}{\Delta z}, \frac{D_o}{w_t}, \frac{p}{E\Delta z}, \nu, \frac{T_o}{E\Delta z^2}, \mu, \frac{k_s}{E}, C_D, C_A, \frac{\rho_{steel}}{\rho_{water}}, \frac{g\Delta z\rho_{steel}}{E}, \beta\right) \quad (1)$$

With

* Corresponding author. Fax: +61 8 6488 1044.
E-mail address: lucile.queau@gmail.com (L.M. Quéau).

http://dx.doi.org/10.1016/j.engstruct.2015.02.025
0141-0296/© 2015 Elsevier Ltd. All rights reserved.

ρ_{steel}, ρ_{water}	steel and water densities
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
T_o	horizontal tension component
Δz	vertical difference between hang-off point and seabed
s	arc length (measured from hang-off point)
$H/\Delta z = \pi_2$	dimensionless riser displacement amplitude
$\Delta\theta_m = \pi_3$	angle of the motion relative to the hang-off angle (θ_{HO})
$\frac{H}{T}\sqrt{\rho_{steel}/E} = \pi_4$	dimensionless riser displacement velocity
$D_o/\Delta z = \pi_5$	dimensionless riser outside diameter
$D_o/w_t = \pi_6$	riser outside diameter to wall thickness ratio
$p/(E\ \Delta z) = \pi_7$	dimensionless riser unit submerged weight
$\nu = \pi_8$	Poisson's ratio
$T_o/(E\ \Delta z^2) = \pi_9$	dimensionless riser tension
$\mu = \pi_{10}$	soil friction coefficient
$k_s/E = \pi_{11}$	dimensionless soil stiffness
$C_D = \pi_{12}$, $C_A = \pi_{13}$	drag and added mass coefficient
$\rho_{steel}/\rho_{water} = \pi_{14}$	relative steel and water densities
$g\ \Delta z\ \rho_{steel}/E = \pi_{15}$	dimensionless water depth
$s/\Delta z = \pi_{16}$	location along the SCR
$\beta = \pi_{17}$	angular position on the SCR circumference

An illustration of an example SCR configuration and some of the individual input parameters are shown in Fig. 2.

The response surface method is applied with the artificial neural network (ANN) to find the function approximating the relationships between the various design input parameters and the output. The aim is to define a function that could approximate *Max* $\Delta\sigma_{TDZ}$ results from OrcaFlex software within ±5% relative error, which is regarded as negligible error for practical applications [11]. The use of ANN is not common for SCR design, although the ANN approach has been applied successfully in other engineering fields, e.g. in geotechnical engineering [12], mechanical engineering [13] or in civil engineering [14,15].

The same simplifying assumptions and parameter definitions as in Quéau et al. [7] are used here. The study is limited to the SCR response under in-plane motions only with the loading applied by imposing a sinusoidal displacement to the floating vessel. The current profile in the sea column, the rotational stiffness at the hang-off point, the flow rate of the contents, the coating and the structural damping are not taken into account. A linear soil response (defined by a spring stiffness) is adopted. Also, some of the input parameters remain unchanged throughout the study, with values presented in Table 1.

2. Initial database characteristics

A large database of 43,745 cases was established to capture most realistic SCR dynamic behaviours. Dynamic time history analyses were carried out to calculate (steady-state) values of *Max* $\Delta\sigma_{TDZ}$ over a single cycle of motion. All the numerical models have a fine segmentation along the riser length with refinement in the TDZ where segments vary from 0.5 m to 2.5 m depending on the SCR configuration and the severity of the imposed displacement.

2.1. Selected ranges of the dimensionless groups

The selected ranges of the individual input parameters in SCR design are shown in Table 2. The same design criteria as in Quéau et al. [7] were used in the choice of extreme values for the wall thickness (w_t), the content density (ρ_{cont}) and the horizontal tension component (T_o) to be consistent with industry practices. Design criteria specific to the dynamic cases were also implemented between the heave amplitude (H) and the period (T) of the imposed vessel motions. These values were established through numerical experiments using typical SCR configurations and different wave spectra (from Gulf of Mexico) to cover a wide range of vessel motions in response to calm and to very harsh sea states. However, a narrower range of H values are usually the dominant ones for fatigue design purpose.

The ranges of the dimensionless groups are presented in Table 3 as deduced from the chosen values of individual input parameters. Particular cases were defined by selecting appropriate combinations of dimensionless groups, respecting the design criteria on the individual input parameters.

2.2. Cases forming the overall database

DoE techniques were used to establish the database in an attempt to capture the boundaries of the input design spaces while providing homogeneous coverage over the entire domain. The detailed explanation of DoE techniques is well covered in the literature (e.g. [9,16–19]). In short, DoE is a method that is applied to gain as much knowledge as possible from 'experimental' results through a limited number of experiments by using various statistical techniques. The methods used in this paper are (i) the full factorial approach, consisting in discretising the ranges of the input design parameters in a number of levels and testing the effects of every possible combinations of the levels of the input design parameters on the output; and (ii) a quasi-random approach, aiming at spreading the cases within the design space.

A total of 12,288 cases were obtained with a full factorial design while the remaining cases were obtained through quasi-random techniques. The full factorial design cases were derived from the cases developed for the static study [7]. Additional levels of H and two levels for T were selected to account for the selected design criteria on the extreme values of T, as presented in Table 2. This led to the following levels, with the superscript $^{\pm}$ referring to the fact that values of those input parameters either side of the extremities of the ranges involved in the design criteria were tested for the various possible ranges of the dependent parameters (e.g. Δz = 1500 m was tested with values of θ_{HO} corresponding to the intervals relevant for both Δz just less than 1500 m ($9° \leqslant \theta_{HO} \leqslant 17°$) and Δz just greater than 1500 m ($7° \leqslant \theta_{HO} \leqslant 11°$)):

- Δz: 6 levels selected: 400 m; $950^{\pm}$ m; $1500^{\pm}$ m; and 2000 m.
- D_o: 8 levels selected: 0.1524 m; $0.36^{\pm}$ m; $0.46^{\pm}$ m; $0.56^{\pm}$ m and 0.762 m.
- π_6: = D_o/w_t: two levels selected: appropriate minimum and maximum values with respect to the value of D_o.
- ρ_{cont}: two levels selected: empty and full with appropriate content density value with respect to the value of D_o.
- T_o: two levels selected: appropriate minimum and maximum values determined through the value of θ_{HO} with respect to the value of Δz.
- H: eight levels selected: 0.1 m; $1^{\pm}$ m; $3.5^{\pm}$ m; $5.5^{\pm}$ m and 7.5 m.
- k_s: two levels selected: 11.4 kPa and 228 kPa.