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Analytical estimation of static stress range in oscillating steel catenary risers at touchdown areas and its application with dynamic amplification factors

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ABSTRACT

Steel catenary risers (SCRs) are dynamically sensitive structures and their fatigue design in the touchdown zone is challenging. The dynamic response of SCRs is traditionally assessed by performing a series of long time history analyses but a simplifying approach has recently been proposed. The simple method is based on the use of dynamic amplification factors that quantify the dynamic response for a given perturbation at the hang-off point relative to the static response. The determination of the static response of SCRs is therefore a prerequisite to this approach. In this paper, an existing analytical model is extended to accommodate the displacement at the hang-off point of the SCR and predict the static stress range. The results of this analytical model are validated against numerical simulations. Then, using this simple and efficient analytical model, various sensitivity analyses are performed to explore the impact of key dimensionless groups on the static stress range in the touchdown zone.

1. Introduction

Steel catenary risers (SCRs) have been used extensively in the past decades for offshore oil and gas developments in deepwater. They are a cost effective solution but are very sensitive to the hydrodynamic loading and the vessel motions, which generate fatigue damage concentrated at the vessel hang-off point (HOP – where the riser is connected to the floating facility) and in the touchdown zone (TDZ – the area of dynamic riser soil interaction (Bridge, 2005)) (Bai and Bai, 2005; Campbell, 1999). An accurate estimation of the fatigue life of SCRs is fundamental as failure would have high economical and environmental impacts. The structural response of SCRs is usually assessed by carrying out dynamic time history analyses but they are time consuming and they need high computational effort (Xia et al., 2008). In an attempt to simplify the early stages of fatigue design (i.e. conceptual or preliminary design stages), the authors have proposed an approach based on dynamic amplification factors (DAFs) (Quéau et al., 2011). DAFs are defined as the ratio of the maximum dynamic stress range to the maximum static stress range occurring in the TDZ under application of given wave packs. They are an efficient alternative to explicit numerical analysis as they allow determination of the maximum dynamic response amplitudes directly from the static response. The dimensionless groups of input parameters influencing the DAF values can be deduced from those impacting the axial stress occurring in SCRs, merely omitting the groups that involve time and position within the SCR. Thus the relevant groups for axial stress (σ_t) and DAF may be expressed as (Quéau et al., 2013)

$$\frac{\sigma_t}{E}=f_1\left(\frac{H}{\Delta z},\Delta\theta_m,\frac{H}{T}\sqrt{\frac{\rho_{steel}}{E}},\frac{D_o}{\Delta z},\frac{D_o}{w_t},\frac{p}{E\,\Delta z},\nu,\frac{T_o}{E\,\Delta z^2},\mu,\frac{k_s}{E},C_D,C_A,\frac{\rho_{steel}}{\rho_{water}},\frac{g\,\Delta z\,\rho_{steel}}{E},\frac{s}{\Delta z},\beta,\frac{t}{T}\right) \tag{1}$$

$$DAF=f_2\left(\frac{H}{\Delta z},\Delta\theta_m,\frac{H}{T}\sqrt{\frac{\rho_{steel}}{E}},\frac{D_o}{\Delta z},\frac{D_o}{w_t},\frac{p}{E\,\Delta z},\nu,\frac{T_o}{E\,\Delta z^2},\mu,\frac{k_s}{E},C_D,C_A,\frac{\rho_{steel}}{\rho_{water}},\frac{g\,\Delta z\,\rho_{steel}}{E}\right) \tag{2}$$

where:

H, T	Heave amplitude and period of the input motion
$\Delta\theta_m$	Angle of the motion relative to the hang-off angle (θ_{HO})
Δz	Vertical difference between hang-off point and seabed (directly related to water depth based on HOP location on the vessel)
E	Young's modulus
	Steel and water densities

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ρ_{steel}, ρ_{water}
D_o, w_t Riser outer diameter and wall thickness
p Unit submerged weight
ν Poisson's ratio
T_o Horizontal tension component
k_s Soil stiffness
μ Soil friction coefficient
C_D, C_A Drag and added mass coefficients
g Gravity acceleration
s Arc length (measured from the touchdown point (TDP))
β Angular position on the SCR circumference
t Time

The main aim of this paper is to establish an accurate analytical method to assess the static response of oscillating SCRs, as this is a fundamental input for the DAF approach. A simple analytical method commonly used to estimate the overall geometry of SCRs relies on the catenary based solutions that were developed for cables and which neglect bending stiffness and riser-soil interaction (Bridge, 2005). They provide a good approximation because SCRs have a high aspect ratio of suspended length over outside diameter. However, more sophisticated techniques are required to capture the shear force, bending moment and stress distributions in SCRs, in particular near the touchdown point (TDP), where the riser bending stiffness and the soil stiffness will impact the riser profile.

Aranha et al. (1997) and Pesce et al. (1998a,b) proposed more complex analytical equations to smooth the curvature variation close to the TDP by taking into account the riser bending stiffness in a small section near the TDP that is referred to as the “boundary layer”. The length of the boundary layer zone is indicated by the flexural length parameter $\lambda = (EI/T_o)^{0.5}$, where I is the second moment of area (Love, 1892). One of their models can also account for the effect of a linear soil stiffness (Pesce et al., 1998b). This model was used by Shiri and Hashemi (2012) to estimate the maximum fatigue damage in the TDZ at least in an approximate way. However, Shiri and Hashemi (2012) neglected the effect of tension in the SCR and also approximated the maximum variation of bending moment as the product of the maximum shear force in the SCR, before application of any motion, with the maximum range of motion of the TDP for the given cycle. In addition, while the model from Pesce et al. (1998b) was used to estimate the maximum shear force, the maximum range of motion of the TDP was assessed by means of standard catenary relationships, thus neglecting the effect of the riser bending stiffness.

By contrast, the model developed in this paper accounts for a linear soil stiffness and the boundary layer effect systematically. It also evaluates the maximum static stress range by assessing the static stress distribution along the riser length, combining changes in both tension and bending moment, when the HOP is relocated under a cycle of static loading.

The model is based on the “three-fields model” (TFM) from Lenci and Callegari (2005) that is able to model continuous displacement, slope, tension (approximately), bending moment and shear force everywhere along the riser length for SCRs in an equilibrium configuration (i.e. before any motion is applied). This model has been adopted here and any reference to the TFM acknowledges the work of Lenci and Callegari (2005). The TFM is extended in order to accommodate the displacement of the hang-off point and predict the static stress range along the riser length. For validation, results of the extended analytical model are compared with numerical simulations. Also, the proposed extended model is used to evaluate the sensitivity of the static stress range in SCRs to the dimensionless groups of input parameters as part of on-going research on the DAF approach. This will assist the future sensitivity analyses aiming to establish quantitative relationships between the dimensionless groups and the DAF.

The following assumptions are used to simplify this study: it is limited to 2D conditions with no account taken of the current profile in the sea column, the soil friction, the rotational stiffness at the HOP, the flow rate of the contents and the coating. Also, it is chosen to work at a fixed position around the SCR circumference, $\beta = 0^\circ$ corresponding to the bottom of the riser, for the post-processing of the numerical models.

2. Analytical assessment of axial stress in SCRs

The TFM divides the riser into three zones having different behaviour: (i) the suspended part away from the TDP where the standard catenary relationships developed for cables are used, (ii) the boundary layer zone (suspended part of the riser close to the TDP), where the riser bending stiffness is taken into account, and (iii) the zone where the riser is in contact with the soil and where a Winkler-type deformable soil model is used. An illustration of the TFM and the relevant notations are presented in Fig. 1. Using the TFM, the riser elevation measured from the seabed, z, can be calculated through the following system of equations:

$$\begin{cases} z(x) = -w_1(x) = -\left[\frac{p}{k_s} + c_1\, e^{\alpha x}\cos(\beta_1 x) + c_2\, e^{\alpha x}\sin(\beta_1 x)\right]; & x \le 0 \\ z(x) = -w_2(x) = \frac{p}{2\,T_{BLE}}x^2 - c_3 - c_4 x - c_5 \sinh(\gamma x) - c_6\cosh(\gamma x); & 0 < x \le L_1 \\ z(x) = y(x - L_1) = c_7 + \frac{1}{\delta}\cosh(\delta(x - L_1) + c_8); & L_1 < x \le L_1 + L_2 \end{cases} \quad (3)$$

$$\alpha = \frac{1}{2}\sqrt{2\sqrt{\frac{k_s}{E\,I}} + \frac{T_{BLE}}{EI}},\ \beta_1 = \frac{1}{2}\sqrt{2\sqrt{\frac{k_s}{E\,I}} - \frac{T_{BLE}}{EI}},\ \gamma = \sqrt{\frac{T_{BLE}}{EI}} \quad (4)$$

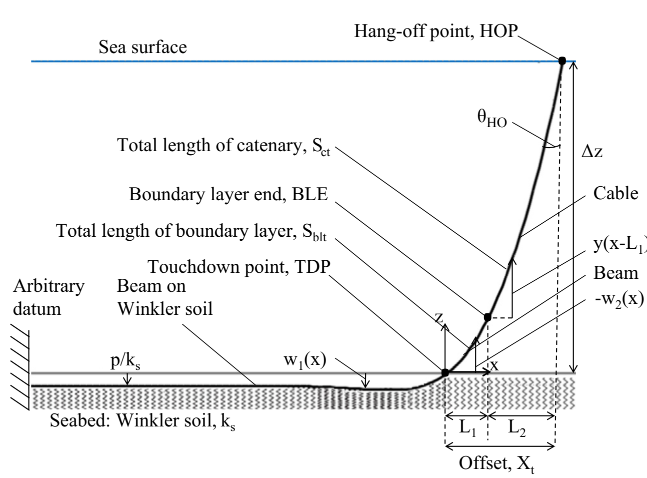

Fig. 1. Scheme of the three-fields model proposed by Lenci and Callegari (2005).