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Performance of non-linear seabed interaction models for steel catenary risers, part I: Nodal response

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A B S T R A C T

Non-linear hysteretic riser-seabed interaction models have been developed and implemented into business software packages within recent years to simulate the riser penetration into the seabed and its influence on fatigue life in the touchdown zone (TDZ). These models have shown significant impact on ultimate fatigue damage and users shall take caution while using the models paying particular attention to the selection of model parameters. The oscillation of steel catenary riser (SCR) in the touchdown zone can be quite complex, where neighbor nodes go under different episodes and magnitudes of penetration and uplift at the same time. Therefore, it is necessary to evaluate the non-linear soil models consistency in nodal performance. This paper comprehensively examined the nodal performance of a popular non-linear hysteretic riser-seabed interaction model through developing a global numerical riser model in ABAQUS and a user-defined subroutine (UEL). The model shows a dominantly strong nodal performance. However, nodal response violations and model malfunctioning were observed in the proximity of trench bottom towards the vessel, which is the most fatigue prone section of SCR in the touchdown zone. Also, it was identified that the model over-estimates the penetration and suction resistance and consequently the fatigue damage in the TDZ.

1. Introduction

Steel catenary risers (SCR) are one of the most attractive elements in the development of deep offshore oil and gas fields as their construction and installation cost is less than other riser families (Maclure and Walters, 2007; Lim and Gauld, 2003). These risers are naturally subjected to cyclic motions due to environmental loads, and consequently susceptible to fatigue damage both in SCR attachment point to the floating system and in the touchdown zone (TDZ). However, the estimation of the SCR fatigue life in the TDZ is the most challenging issue in its design because of highly complex riser-seabed interaction and range of inherited uncertainties. The survey results obtained by remote operating vehicles (ROV) have proved the complex non-linear seabed response to riser fluctuations in the TDZ, where SRC penetrates into the seabed and cyclically creates trenches often with several diameters deep (Bridge and Howells, 2007). Different mechanisms with a range of uncertainties contribute to the riser-seabed interaction and the trench development underneath the riser. The oscillatory motions of SCR in the touchdown zone result in a complex riser interaction mechanism with surrounding media including seawater and soil. Some of the influential parameters contributing to these non-linear hysteretic interactions are as follow:

- soil stiffness degradation under cyclic loads and riser penetration into the seabed,
- mobilization of suction force within uplift motions of the riser,
- trench base softening and damping,
- the erosive mechanism by water velocity field around the SCR in the TDZ and consequent variation of the flow pattern of displaced water,
- the riser dynamics influenced by internal multi-phase flow regimes and also vessel motions (velocity and frequencies),
- vortex induced vibration (VIV).

These complexities cause several major uncertainties in the prediction of fatigue life and the SCR design procedure (Jacob, 2005). Advanced non-linear hysteretic seabed models have been developed within the recent years, enabling automatic simulation of the different stiffness in the seabed response through the TDZ (Randolph and Quiggin, 2009; Aubeny and Biscontin, 2009). In continuation to exploring the significance of nonlinear soil response in fatigue performance of SCRs (Shiri and Hashemi, 2012; Shiri, 2014), the current paper (Part I)

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comprehensively examined the nodal performance of one of the most popular nonlinear hysteretic soil models (i.e., Randolph and Quiggin (2009), called R-Q model from now on). The main objective was to explore the consistency and the extent of the model validity that has never been accomplished before. The R-Q model defines evolutionary non-linear hysteretic soil stiffness represented by springs connected to the nodes on the SCR within the TDZ. Therefore, the nodal response of the model which is the basis for longitudinal stress profiles has significant importance in fatigue response. In this paper, a numerical model was developed in ABAQUS, and the R-Q model was coded in FORTRAN as a user-defined element (UEL). A comprehensive study was conducted focusing on the nodal performance of the model within various seabed parameters and different locations on the SCR. The pros and cons of the R-Q model along with its extent of functionality was discussed. The performance of the R-Q model regarding fatigue response and longitudinal stress profiles in the TDZ will be presented in a sister paper as Part II.

2. Seabed soil modeling strategies

Simplified beam-spring models and also constitutive soil models combined with different numerical approaches are two main strategies in modeling the riser-seabed interaction. The latter approach results in higher accuracy and higher computational cost at the same time. Increasing the computational effort, particularly in coupled analysis makes this approach less attractive for industrial applications. However, using the constitutive soil models with proper numerical approaches such as continuum finite element models (e.g. (Clukey et al., 2008)) can provide a strong tool to explore the different aspects of the riser-seabed interaction mechanisms through research projects. In beam-spring strategy, the soil response is represented by simple springs. This approach seems to be an oversimplification from the geotechnical standpoint, where some particular aspects of the soil such as dilatation and creep are lost within the soil discretization process. However, the beam-spring approach results in considerable mitigation of computational cost with no significant loss of accuracy, particularly when the soil stiffness parameters are properly adjusted. The simplicity and reasonably acceptable accuracy of this method has caused the industry to apply this approach to a range of design challenges widely. The results interestingly show good agreement with experimental data and continuum models. The Complexity of the riser-seabed interaction and the need for simultaneous modeling of vessel excitation, riser dynamics and non-linear seabed response within fatigue analyses have caused the industry to show more interest in SCR beam-spring modeling approach.

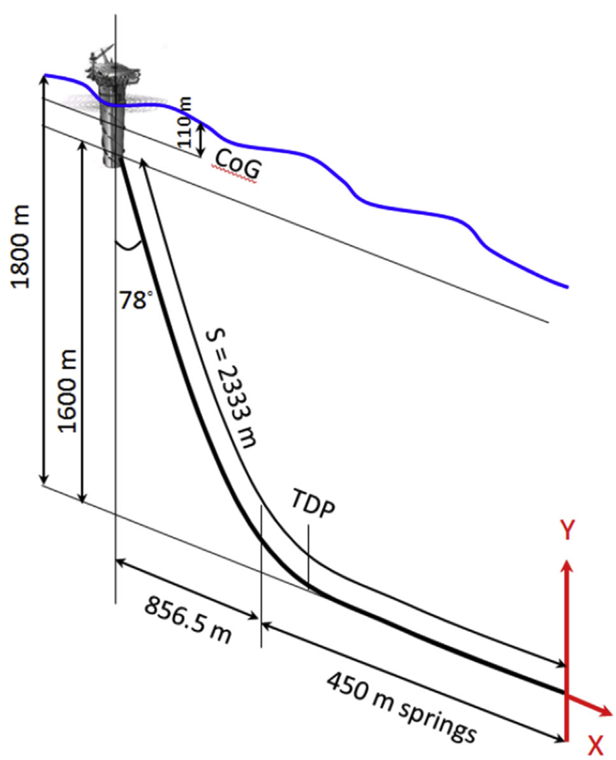

Fig. 1. The global geometry of SCR modeled by ABAQUS.

Various SCR design codes have traditionally proposed Linear soil springs in the touchdown zone. After the first experience of SCR technology in the Auger field of the Gulf of Mexico (Phifer et al., 1994), the STRIDE and CARISIMA JIPs (1999–2001) (Giertsen et al., 2004) were the first organised attempts to investigate the need for more sophisticated riser-seabed interaction models (Theti and Moros, 2001). Bridge et al. (Bridge and Howells, 2007) examined the test data from the CARISIMA and STRIDE JIPs and also conducted a range of full-scale harbour tests, laboratory model tests and numerical simulations. A series of soil stiffness models was developed for static penetration, small and large displacements, and cyclic loading for use in finite element analysis programs. These studies included assessment of the influence of suction during uplift, and also the presence of a trench, on the performance of SCRs particularly with respect to fatigue in the TDZ. The hyperbolic model proposed by Bridge et al. (Bridge and Howells, 2007) captures various non-linear aspects of soil behaviour characteristics within the applicable displacement stages, including initial penetration, uplift, suction mobilization, breakout and re-penetration. The hyperbolic curve of the model was developed based on the hyperbolic force-displacement interaction curve for sand developed by Audibert et al. (1984). It is similar in form to the hyperbolic pipe-soil interaction curve developed by Hardin and Drnevich (1972) that was originally proposed for clay by Kondner (1963). The soil suction during uplift was modeled based on the test data obtained from the STRIDE and CARISIMA JIPs. In order to calculate the dynamic soil stiffness, the model used the bearing load as opposed to the touchdown point reaction force. Hence, the model does not account for soil softening due to repeated cycles, resulting in a conservative modeling in the TDZ, even though the soil behaviour in this region is highly nonlinear. Jiao (2007) proposed a non-linear discrete soil model for SCR response analysis in the TDZ. The model introduced two non-degrading and degrading schemes for different soil conditions. More recently, Aubeny & Biscontin (Aubeny and Biscontin, 2009) and Randolph & Quiggin (Randolph and Quiggin, 2009) proposed two advanced nonlinear soil models for SCR analysis in the TDZ. Aubeny & Biscontin (Aubeny and Biscontin, 2009) proposed a simplified model consisting of four different equations that represent the soil spring characteristic in each load cycle. The first curve in this model simulates the intact soil response as a backbone curve. The second scenario is the elastic rebound curve, which simulates the soil response to SCR uplift process. The partial separation of the riser and soil within the uplift episode is modeled with a third curve until complete detachment. A reloading curve then models the riser re-penetration in the disturbed soil. More intermediate equations are modeling the local load cycles. The incapability of this model in predicting comprehensive soil degradation was resolved by Nakhaee and Zhang (2008) through proposing an updated version. Randolph and Quiggin (2009) proposed a nonlinear model to predict the hysteretic soil response to SCR up and down oscillations. The model combines the hyperbolic and exponential functions within four main episodes of riser-seabed cyclic contact: initial penetration, uplift, separation, and re-penetration. Shiri and Randolph (2010) implemented the model into ABAQUS through developing user-defined elements to explore the SCR fatigue performance and automated trench generation mechanism. This model was implemented into Orcaflex software in 2009 and is currently amongst the most popular non-linear models to predict the hysteretic riser-seabed interaction. Shiri (2014) used the model to study the influence of trench creation on fatigue performance of SCR in the TDZ. Zargar and Kimiaei (2015) conducted a comparative study to investigate the advantages and disadvantages of the models proposed by Aubeny and