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Response of steel catenary risers on hysteretic non-linear seabed

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ABSTRACT

The methodologies recommended by existing codes and standards for design of steel catenary risers are considering linear springs in the seabed while it is publicly accepted that the non-linear riser-seabed interaction can have vital influence on stress variation in touchdown area and consequently fatigue performance during the cyclic motions of the riser as the latter is excited by vessel motions under environmental loads. In this study an advanced hysteretic non-linear riser-seabed interaction model has been implemented into the seabed enabling the automatic simulation of different stiffness in the seabed response through the touchdown zone and gradual embedment of riser. Then the impacts of this model on fatigue calculation procedure and fatigue performance in touchdown area has been studied.

1. Introduction

The non-linear response of the seabed has already been proved through the ROV survey results of steel catenary risers showing considerable embedment of the SCR in the touchdown zone often with trenches several diameters deep formed [1], a fact that has been ignored in current design codes mainly due to high complexity and less-known nature. The uncertainties associated with non-linear riser-seabed interaction particularly its effect on fatigue performance has caused engineers to rely on oversimplified methodologies recommended by design codes, though the design codes are expected to be simple and conservative. In this paper the effects of incremental embedment of the riser and the mobilization of suction resistance during uplift on fatigue performance of SCR under cyclic perturbation of floating facilities has been investigated through extensive numerical simulations using a hysteretic non-linear seabed model [2]. The influence of the seabed model on contact stress and shear force distributions within the TDZ, and the profile of cyclic von Mises stress range that is the basis of fatigue damage calculation in tubular elements, are examined. It is worth mentioning that the internal and external pressures have not been considered in the constructed model, so taking into account the limited magnitude of the shear force the von Mises stress is almost same as longitudinal stress resulted from axial force and bending moment. The application of Miner's rule for superposition of damage from separate wave packets for non-linear seabed response is discussed, and the effect of different ordering of the wave packets is investigated.

Taking into account the complex nature of the riser-seabed interaction, the study has been conducted in two phases. In the first phase, the main emphasis of the work was set to explore the relative effects of different assumptions for the non-linear vertical seabed response. Therefore, the analyses were limited to 2D planar quasi-static (cyclic) perturbations of the SCR only. In the second phase, dynamic analyses were performed to investigate the influence of riser dynamics and consequent stress changes on the fatigue life. In order to allow clear principles of the vertical riser-seabed interaction to be identified, the impact of lateral riser-trench interaction in the 3D nature has been excluded from analyses. All of the analyses have been conducted as displacement-controlled, where the floating vessel has been excited using the combination of a generic SPAR RAO and a wave scatter diagram from Gulf of Mexico giving the vessel's 2D offsets. The floating vessel dynamic is already included in given RAO, but the riser dynamics including drag force, inertia and added mass has been modeled inside the AQUA module of ABAQUS.

2. Hysteretic non-linear seabed model

The seabed response to cyclic loading inserted by pipeline has been widely studied over the years through extensive number of numerical and experimental research programs and various pipeline-seabed interaction models have been proposed in the literature [3–9]. The hysteretic non-linear riser-seabed resistance model proposed by Randolph and Quiggin [2] for an SCR oscillating up and down in the TDZ has been selected and implemented in this study as a sophisticated model inserting the gradual soil softening, suction force mobilization and riser progressive embedment into the seabed over the load cycles. It is worth mentioning, that due to valuable features and advantages of this model, Orcina Ltd. has implemented it into Orcaflex series 9.6, a commercial software used worldwide by pipeline and riser industry. The generic form of the proposed model has been schematically shown in Fig. 1 where the model starts in "initial penetration" mode

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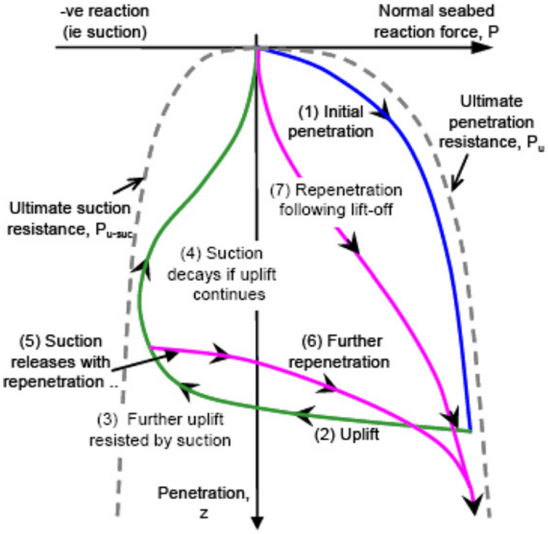

Fig. 1. Non-linear soil model characteristics for different modes [2]. (For interpretation of the references to color inthe text, the reader is referred to the web version of the article.)

as shown by the blue line. Increasing the penetration depth, the resistance asymptotically approaches the ultimate penetration resistance P_u. By reversing the riser penetration direction, the model enters uplift mode and the reaction force decreases rapidly with a high initial secant stiffness, K_{max} (note 2, Fig. 1). Further uplift takes the model into the suction region with negative reaction force. The suction resistance reaches its maximum value approaching the ultimate suction resistance, $P_{u\text{-suc}}$ (note 3, Fig. 1). The magnitude of ultimate suction resistance is a fraction of the ultimate penetration resistance controlled by parameter f_{suc}. With further uplift, the suction resistance decays to zero over a distance controlled by parameter λ_{suc} (note 4, Fig. 1). Re-penetration after an entire break out follows an initially convex curve reflecting the soil softening beneath the riser during uplift (note 7, Fig. 1). The re-penetration resistance approaches the ultimate penetration resistance at a penetration depth greater than the previous maximum penetration depth, as controlled by parameter λ_{rep}. Re-penetration may also occur when the suction resistance is partially mobilized (note 5, Fig. 1). In such a case, the suction resistance reduces rapidly and the model enters the positive reaction region. Further cycles of uplift and re-penetration would give further episodes of uplift and re-penetration modes and so give hysteresis loops of seabed resistance with incremental penetration at each cycle [2].

In summary, the model's main features are as follows:

- The seabed normal resistance is modeled using four penetration modes, namely not-in-contact, initial penetration, uplift and re-penetration.
- In each penetration mode the seabed reaction force per unit length, $P(z)$, is modeled using an analytic function of the non-dimensional penetration z/D, where z is the penetration (pipe invert) and D is the pipe diameter.
- For each mode, the analytic formula use a hyperbolic term, which provides a high stiffness response for small reversals of motions, but ensures that the resistance $P(z)$ asymptotically approaches the soil ultimate penetration resistance (for penetration) or ultimate suction resistance (for uplift), as the penetration z increases or decreases from its value when this episode of penetration or uplift started.

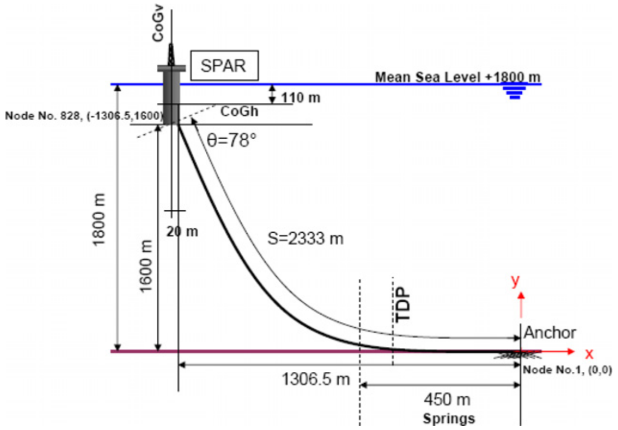

Fig. 2. Global geometry of modeled SCR.

Since the model formulation includes extensive number of complicated mathematical terms requiring detail explanations, so the details not been presented here can be found in the original paper given by Randolph and Quiggin [2]. The suggested default values for model parameters can also be found in the same reference where comprehensive discussion has been given about the parameters.

3. Numerical model configuration

The general-purpose finite element software, ABAQUS and its AQUA module have been used for 2D planar numerical simulations. A generic configuration of an SCR attached to a SPAR system has been considered, Fig. 2. The non-linear hysteretic seabed model implemented in the study is conceptually works based on the nodes position and their moving direction on the riser body at every time increment throughout the load cycles. The riser dynamics is believed to have important contribution to fatigue performance, so the dynamic effects of the riser itself including the drag, inertia and added mass has also been included for more realistic investigation. The system has been studied through displacement-controlled, quasi-static and dynamic analyses with the SPAR excitation based on generic RAOs from the Gulf of Mexico and the impact of riser dynamics on riser fatigue performance has been explored. The riser itself has been modeled using Euler–Bernoulli beam elements (B21 of ABAQUS element library). The element length in the first 450 m of the riser from anchor side is 1 m where the riser is seating on the seabed and 5 m for the rest of hanging part (Fig. 2) [10]. It is worth mentioning, since all of the analyses are displacement-controlled, the floating vessel is excited based on the 2D offsets extracted from generic RAO and the applied sea states through selected wave scatter diagram. Therefore, no hydrodynamic software is needed to extract vessel RAO under environmental loads, which is usually a common practice in load-controlled analyses.

4. Numerical analysis steps

As for any finite element software, ABAQUS allows the user to define various steps for accurate modeling of the system behavior during different stages of loading. Three steps have been defined to model the SCR connected to the floating system as follows:

- Step 1: pipe end lift-up.

  The SCR is initially modeled as a straight pipe, laid on the seabed, partially supported by linear elastic, tensionless springs, with a simple support at the vessel end and fixed at the anchor end. At this stage, no gravity loading has been applied on the pipe. At the start of Step 1, for quasi-static analysis, the submerged weight is applied to the riser and the vessel end of the riser is lifted up simultaneously to the level equal to the height of the