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Numerical modelling of a steel catenary riser section in the touchdown zone under cyclic loading

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A B S T R A C T

The fatigue life of steel catenary risers is significantly influenced by cyclic riser–seabed–water interaction in the touchdown zone. In this study, the penetration and extraction of a shallow embedded riser section, subjected to cyclic vertical loading, are simulated using a computational fluid dynamics approach with ANSYS CFX. An empirical strength degradation model is proposed for soil softening due to undrained remoulding and clay–water interaction in the highly sheared interface, termed 'shear wetting.' The combined effects of strain rate and softening on the mobilized shear strength of deepwater offshore clay are implemented in CFX. A sufficiently large number of loading cycles is simulated using this computationally efficient numerical technique to achieve a stable response. A significantly large reduction of vertical resistance of a shallowly embedded riser section due to cyclic loading, as observed in physical model tests, is obtained using the proposed strength degradation model with shear wetting, which cannot be explained simply by undrained remoulding.

1. Introduction

Steel catenary risers (SCRs) — long flexible pipes of typically 150–600 mm diameter — are widely used in deepwater to transport hydrocarbons from seabed well systems to floating platforms or surface vessels. Environmental loading, such as surface waves or currents, causes cyclic motion of the riser. One of the key concerns in the design is the fatigue response of risers near the touchdown point (TDP), the point where the riser first touches the seabed. The fatigue response is significantly influenced by riser–seabed–water interaction in the touchdown zone (TDZ), the zone where cyclic riser–soil interaction exists. In the current industry practice, the fatigue performance is mainly evaluated modelling the seabed as a linear/nonlinear spring or rigid surface. Large-scale field and laboratory tests (e.g., Bridge et al., 2003; Hodder and Byrne, 2010; Wang et al., 2014) and reduced-scale centrifuge tests (e.g., Hu, 2010; Elliott et al., 2013a, b, 2014) were conducted to understand the response of a riser under cyclic loading. Still, this complex behaviour is not well understood.

Environmental loading could cause six degrees of motion; however, the vertical motion of the riser is the most critical because the penetration near the TDP could increase the curvature and bending moment (Clukey et al., 2005). Moreover, suction under the riser during uplift also increases fatigue damage (Clukey et al., 2007; Ting et al., 2010). Therefore, the focus of the present study is to investigate the response of an SCR subjected to cyclic vertical motion only, although it is understood that the response might be influenced by the motions in the other directions in several ways, such as altering trench shape/size and water flow mechanisms.

A riser separates from the seabed near the TDP when lifted upward during cyclic motion. The degree of separation is high during storm events because of the large-amplitude vertical motion. Further away from the TDP in the buried zone, the amplitude of motion reduces and therefore the maximum vertical displacement may not be sufficient to cause separation of the riser from the seabed. Compared to their large-amplitude motion during storm events, risers generally experience much more frequent day-to-day small-to medium-amplitude cyclic motions over a long period, which governs the fatigue design (Bridge, 2005; Clukey et al., 2005, 2007).

Model tests have been conducted to understand riser–seabed–water interaction under cyclic loading. In these tests, the invert of a model pipe section of diameter D is first penetrated into the seabed to the desired depth (w_{in}) and then cyclic vertical displacements of amplitude a are applied. Tests were conducted under the submerged condition in order to investigate the effects of water on vertical resistance. The

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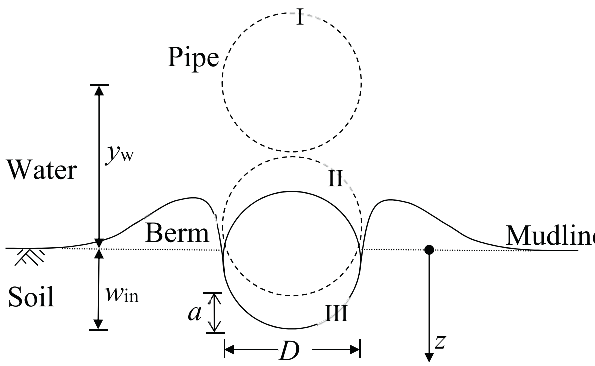

Fig. 1. Problem statement.

depth of embedment (w) represents the vertical distance between the invert of the pipe and mudline (Fig. 1). For brevity, the symbols $\hat{w} = w/D, \hat{w}_{in} = w_{in}/D$ and $\hat{a} = a/D$ are used in the following sections. In most of the tests, cyclic loading started from a shallow initial embedment ($\hat{w}_{in} \leq 1.2$) (Bridge, 2005; Clukey et al., 2005; Aubeny et al., 2008; Langford and Aubeny, 2008a,b; Langford and Meyer, 2010); however, some researchers conducted tests for larger $\hat{w}_{in}$ (Clukey et al., 2008b; Hu et al., 2010; Yuan et al., 2016). When the pipe is not fully covered by soil during cyclic loading, the available 'free water' could interact with seabed sediment at the interface between water and clay.

The following were the key observations in the experimental programs when free water was available. The resistance decreased rapidly with the number of cycles when the pipe/T-bar broke away from the seabed in large-amplitude cyclic motions (Hodder et al., 2008, 2009; Langford and Meyer, 2010; Yuan et al., 2016). A large number of small or medium-amplitude cyclic motions reduced the vertical resistance significantly, even in the tests without pipe/T-bar breakaway (Clukey et al., 2005, 2008b; Ganesan and Bolton, 2013). Soil and free water mixing near the interface exacerbate the strength degradation process. The degradation of vertical resistance in free water cases is much higher than that resulting from undrained remoulding in T-bar tests, when the cyclic motion is applied under a fully embedded condition.

Recognizing the complex nature of riser–seabed–water interaction, mathematical models in the form of a *P-y* curve, where *P* is the vertical resistance per unit length of riser and *y* is the vertical displacement, have been proposed for practical engineering purposes (Bridge et al., 2004; Aubeny and Biscontin, 2009; Randolph and Quiggin, 2009). A number of empirical model parameters are required in these models and the authors proposed the ranges for these parameters based on two-dimensional model test results (Dunlap et al., 1990; Bridge, 2005; Aubeny et al., 2008). The degradation of shear strength due to cyclic loading is not considered in these models. These models have also been used to investigate the fatigue response of risers (e.g., Shiri and Randolph, 2010; Ting et al., 2010; Li and Low, 2011). Nakhaee and Zhang (2010) incorporated the degradation of resistance due to plastic deformation during cyclic loading in the *P–y* curve; however, they neglected the effects of water entrainment, possible erosion and reconsolidation of softened sediment, as reported from physical experiments (Hodder et al., 2013; Sahdi et al., 2017). Aubeny et al. (2015) proposed a revised *P-y* curve where the effects of amplitude and number of loading cycles have been incorporated using a set of empirical equations.

Numerical modelling could provide further insights into the mechanisms and can explain some of these experimental observations. Finite element (FE) simulation of cyclic penetration and extraction processes in a fully embedded (deep) condition is available in the literature (Zhou and Randolph, 2009). Similarly, FE modelling of penetration of a shallowly embedded pipeline has been presented by a number of researchers (Wang et al., 2010; Chatterjee et al., 2012; Dutta et al., 2014). However, numerical modelling of extraction behaviour at shallow depths is very limited. Clukey et al. (2008a) demonstrated some advantages of Eulerian simulations for modelling riser–seabed–-water interaction in the presence of free water. They suggested that soil and free water mixing might be incorporated in the strength degradation model, although it was not considered in that study. Moreover, simulations have been performed only for one loading cycle instead of simulating a sufficiently large number of cycles. Using a finite element limit analysis program, Martin and White (2012) calculated the lower- and upper-bound limit loads of 'wished in place' pipes for rough/smooth and fully-bonded/unbonded cases. The soil has been modelled as rigid-plastic material without softening. Again, cyclic loading was not simulated in that study. The authors of the present study used the Eulerian solution technique in ANSYS CFX to model penetration of a pipe into a soft clay seabed (Hawlader et al., 2015a). They also implemented a simplified strength degradation model as a function of distance from the riser in CFX and simulated only one loading cycle (Hawlader et al., 2015b). Comparing with previous model tests and FE results, it was shown that CFX can simulate both penetration and extraction processes.

In summary, when subjected to cyclic loading, the response of shallowly embedded SCR is very different from the response of a fully embedded T-bar. The numerical modelling of SCR subjected to cyclic displacements near the seabed, where free water could play a major role, is not available. In the present study, numerical simulations in a Eulerian framework are performed using ANSYS CFX software which can accommodate both geotechnical and hydrodynamic aspects of the problem. A soil strength degradation model is proposed and implemented in CFX to simulate the reduction of soil resistance under cyclic loading for a range of model parameters and loading conditions. Using this computationally efficient technique, simulations are continued over a sufficiently large number of cycles.

2. Problem statement

A section of pipe located at a distance y_w above the seabed is displaced downward to $w = w_{in}$ and then a sinusoidal cyclic displacement of amplitude a is applied maintaining an average velocity v_0 during penetration and extraction (Fig. 1). The depth of a soil element from the mudline is z.

3. CFD model development

The general purpose ANSYS CFX 14.0 software is used for numerical modelling (ANSYS CFX, 2012). The computational fluid dynamics (CFD) approach has been used in the past not only for modelling fluid but also for the problems involved in soft seabed sediments including debris flows, glide blocks and out runner blocks modelling (De Blasio et al., 2004a; b; 2005; Gauer et al., 2005, 2006; Harbitz et al., 2003; Zakeri, 2009; Zakeri et al., 2009; Zakeri and Hawlader, 2013). The basic principle of CFD modelling, the similarity and differences between solid mechanics, which is the basis of FE formulations, and the advantages of CFD over FE methods to simulate riser–seabed–water interaction have been discussed in Hawlader et al. (2015a,b).

Fig. 2 shows the CFX model used in the present study. As CFX allows only three-dimensional modelling, the analysis is performed only for one element of 10 mm thickness in the out of plane direction. A riser section of $D = 350$ mm and $L = 10$ mm is placed in water above the seabed at $y_w = 1.0D$. The soil and water domains are discretized into a three-dimensional mesh. Previous FE analyses and model tests for shallow embedded conditions show that the soil elements more than $1.5D$ from the pipe surface do not experience significant deformation during vertical displacement (Dutta et al., 2014). A subdomain of $1.5D$ thickness, the shaded zone in Fig. 2, is created where mesh deformation is not allowed and therefore the size and shape of the mesh in the subdomain do not change with loading. However, mesh distortion is