A Review of the Research on Interaction between Deepwater Steel Catenary Risers and a Soft Clay Seabed

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Abstract

Steel catenary risers (SCR) have become an enabling technology for deepwater environments. A comprehensive review is introduced about the recent research on interaction between deepwater steel catenary risers and a soft clay seabed, including the STRIDE (STeel Risers In Deepwater Environments) and CARISIMA (CAtenary Riser Soil Interaction Model for global riser Analysis) Joint Industry Program's test data and information from existing papers.

Key words: Steel Catenary Riser (SCR), Touchdown Point, Soft Clay Seabed

Introduction

Steel Catenary Risers (SCR)

A SCR is a long steel pipe that hangs freely between the seabed and a floating production system. The top of a SCR is connected to the floating production system, where it hangs at a prescribed top angle. The riser is free-hanging and gently curves down to the seabed to the touchdown point (TDP). At the TDP, the SCR buries itself in a trench and then gradually rises to the surface where it rests, and is effectively a static pipeline. SCRs may be described as consisting of three sections as shown in Figure 1, below:

- Catenary zone, where the riser hangs in a catenary section
- Buried zone, where the riser is within a trench
- Surface zone, where the riser rests on the seabed

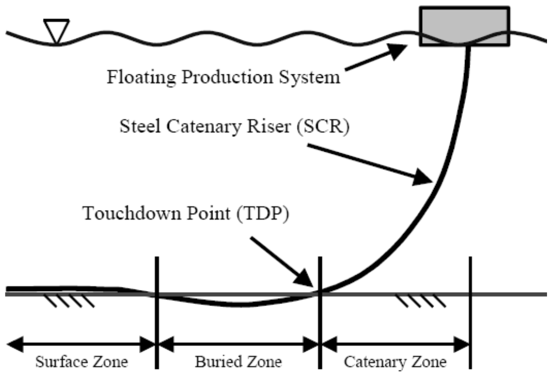

Figure 1: General Catenary Arrangement [1]

Predicting the shape and general forces on a SCR is a relatively simple process, the most basic of which is to solve standard catenary equations. More detailed analysis of risers can be conducted using non-linear finite element analysis programs. Most specialist state-of-the- art riser analysis codes use either rigid or linear elastic contact surfaces to simulate the seabed, which model vertical soil resistance to pipe penetration, horizontal friction resistance and axial friction resistance. A rigid surface generally gives a conservative result since it is unyielding, while the linear elastic surface is a better approximation of a seabed.

Touchdown Point

Deepwater oil and gas fields usually have seabeds of soft clay. ROV surveys of installed SCRs have shown deep trenches cut into the seabed beyond the TDP. The mechanisms that create these trenches are unknown, however they are thought to be produced by the dynamic motions of the riser combined with the scouring and sediment transportation effects of the seabed currents.

Storm and current action on a deepwater production vessel can pull the riser upwards from its trench, or laterally against the trench wall. This interaction could cause an increase in the local riser stresses (due to tighter riser curvatures and higher tensions) than those predicted ignoring the seabed trench.

1 Full Scale Model Tests of Seabed Interaction

The first, the full-scale test to research the 3D effects of fluid/riser/soil interaction around the touch down point (TDP) was conducted over 3 months at Watchet Harbor in the west of England by the STRIDE Ⅲ JIP, 2H Offshore Engineering Ltd in 2000 [2]. The purpose of the full-scale test was to estimate the significance of fluid/riser/soil interaction and to develop finite element analysis techniques to predict the measured response.

The riser, a 110m (360ft) long 0.1683m (6-5/8inch) diameter pipe was draped from an actuator on the harbor wall to an anchor point on the seabed. A programmable logic controller (PLC) to simulate the vessel drift and the wave motions of a platform in 1000m (3,300ft) water depth was used to actuate the top end of the pipe string. Tensions and bending moments were monitored by installing strain gauges along the pipe length.

The seabed is made up of soft clay with an undrained shear strength of 3 to 5 kPa, a sensitivity of 3, a plasticity index of 39% and a normally consolidated shear strength gradient below the mud layer. Table 1 shows the geotechnical parameters for seabed soil in detail.

Bridge et al. reviewed the results of full-scale riser test and concluded that the soil suction force, repeated loading, pull up velocity and the length of the consolidation time can affect the fluid, riser and soil interaction from the test data [1]. Also it stated the possible causes for mechanisms for the trench creation as follows:

Geotechnical Parameter	Value
Moisture Content, w	104.7%
Bulk Density, ρ	1.46 Mg/m^3
Dry Density, ρ_d	0.73 Mg/m^3
Particle Density, ρ_S	2.68 Mg/m^3
Liquid Limit, w_L	87.6%
Plastic Limit, w_P	38.8%
Plasticity Index, I_P	48.9%
Average Organic Content	3.2%
Specific Gravity, G_S	2.68
Undisturbed Shear Strength at 1D	3.5 kPa
Remoulded Shear Strength at 1D	1.7 kPa
Sensitivity of Clay at 1D	3.3
Coefficient of Consolidation, c_V at 1D	0.5 m^2/year
Coefficient of Volume Compressibility, m_V at 1D	15 m^2/MN

Table 1: Geotechnical Parameter of Clay Soil[4]

- The dynamic motions of the pipe applied by the actuator can form the trench. In addition, water rushing out form beneath the riser can scour out a trench.
- Scouring and washing away of the sediment around the riser may be caused by the flow of the tides.
- The vortex induced vibration (VIV) motions which was observed when the tide came in or went out can result in the flow of the seawater across the riser. The high frequency motion would act such as a saw, slowly cutting into the seabed.
- The buoyancy force causes the riser to lift away from the seabed when the test riser is submerged. Any loose sediment in the trench or attached to the riser would be washed away.

Bridge and Willis used pipe/soil interaction model for soil suction to predict and back-analyse the response of the harbour test rise of 2H Offshore Engineering Ltd [4]. The upper bound curve (Figure 2) based on the STRIDE 2D pipe and soil interaction analysis [2] was employed as the soil suction curve in the analytical modeling. They stated that the soil suction curve consists of three parts which are suction mobilization, the suction plateau and suction release like Figure 2.

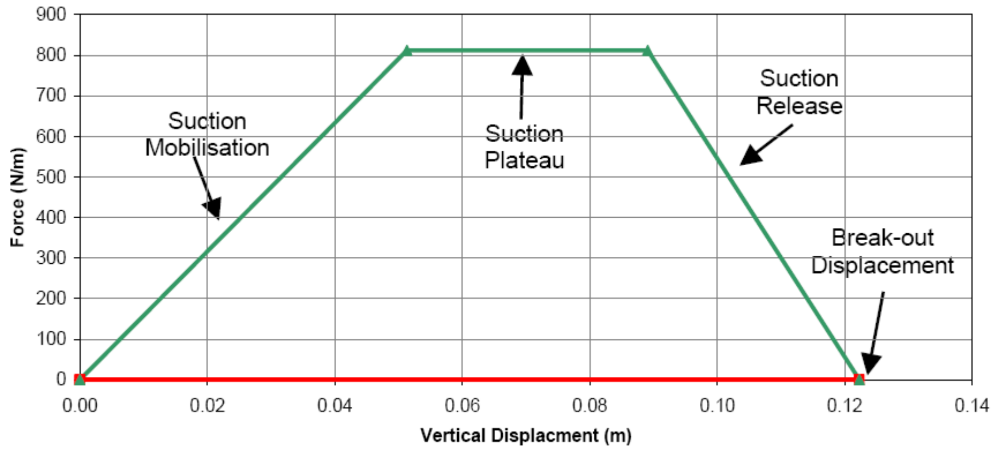

Figure 2: Soil Suction Model [4]

In addition, the each test measurement from a strain gauge location was compared to that of a similar point on the analytical model. Computed bending moments were bracketed by analytical predictions for with suction and no suction. The results of comparison showed good agreement as illustrated Figure 3. Further, they compared pull up and lay down response owing to the difference in bending moment between two response occurred by soil suction. The results of these comparisons are as follows:

- A sudden vertical displacement of a catenary riser at its touchdown point (TDP) after a period at rest could cause a peak in the bending stress that travels along the riser.
- Soil suction forces are subject to hysteresis effects.
- The soil suction force is related to the consolidation time.
- Pull up velocity does not strongly correlate with the bending moment response on a remolded seabed.
- Soil suction can cause effects such as a suction kick.
- Following any actions resulting in pull-up, the mobilized soil suction will dissipate, and the riser will move into an equilibrium position with no or little no soil suction.

Thethi and Moros considered three aspects of soil-catenary riser interaction [3]: the effect of riser motions on the seabed associated the vertical movement of the riser, the effect of water on the seabed related to pumping action, and the effect of the seabed on the riser related to vertical, lateral and axial soil resistance. Because of the complexity of the problem, the authors recommend that trench depth and width profiles were selected in the riser analysis based on the deepest trenches and conservative soil strength assumptions.

Riser and soil response curves may be considered as a load path bounded by the backbone curve. The concept is illustrated in Figure 4. The characteristics of this riser-seabed load deflection curve depend on the burial depth as well as the soil and riser properties.

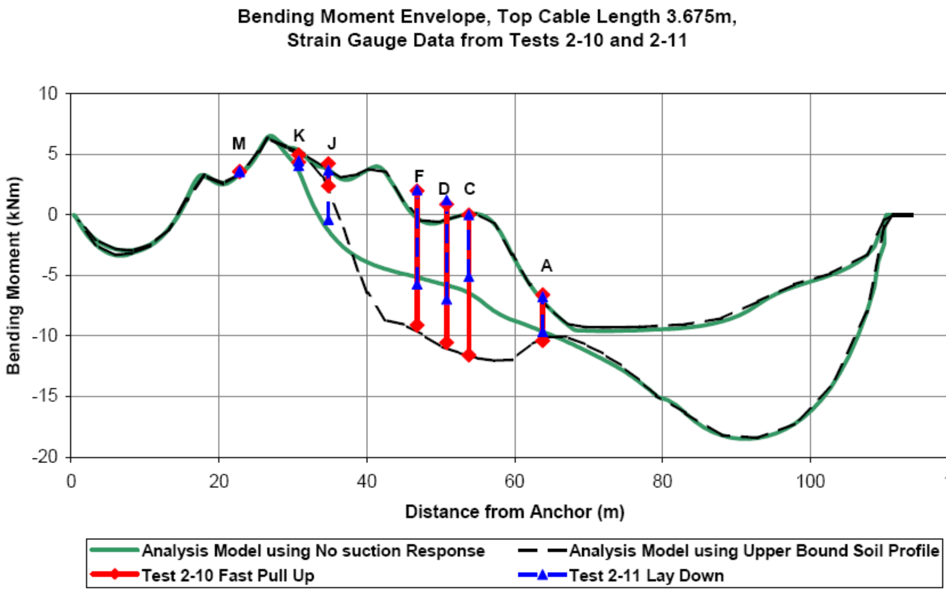

Figure 3: Comparison of Test Data and Analytical Bending Moment Envelope [4]

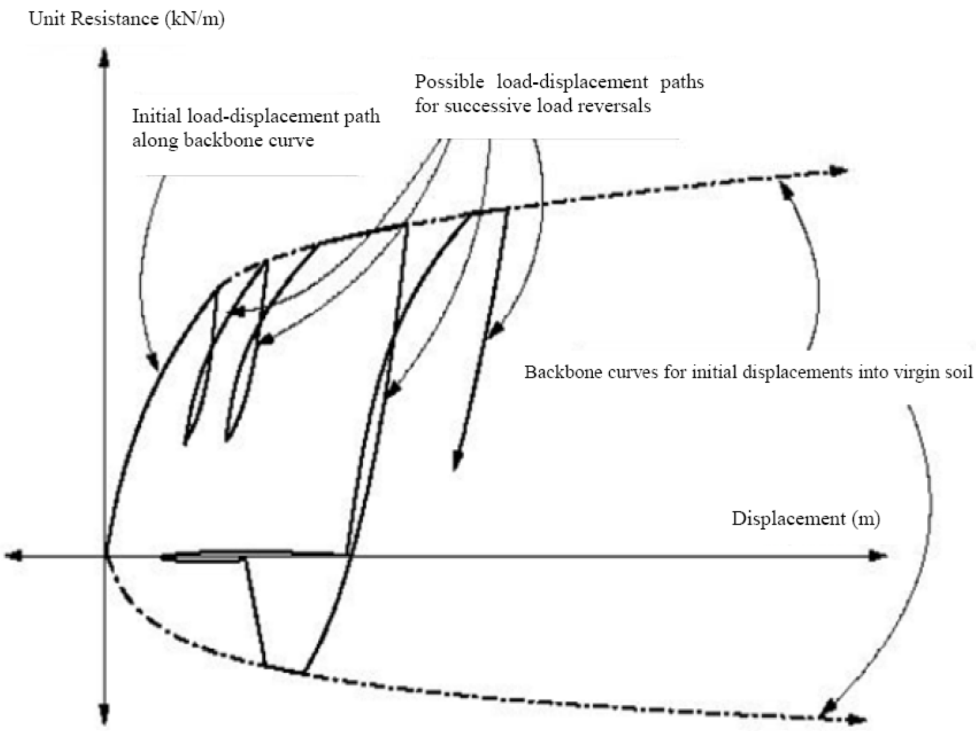

Figure 4: Concept of Backbone & Load-Deformation Curves [3]

Bridge et al. developed advanced models using published data and data from the pipe and soil interaction experiments conducted within the STRIDE and CARISIMA JIP's [4]. They describe an example of the development of a pipe and soil interaction curve with an unloading and reloading cycle, as presented in Figure 5 and the mechanism of pipe and soil interaction such as following steps:

(1)The pipe is initially in contact with a virgin soil.

(2)The pipe penetrates into the soil, plastically deforming it. The pipe and soil interaction curve tracks on the backbone curve.

(3) The pipe moves up and the soil acts elastically. The pipe and soil interaction curve move apart from the backbone curve, the force decreases over a small displacement.

(4) The pipe resumes penetrating the soil, deforming it elastically. The pipe and soil interaction curve follows an elastic loading curve.

(5) The pipe keeps going to penetrate into the soil, plastically deforming it. The pipe and soil interaction curve meets again with the backbone curve and tracks it.

In addition, they updated the force and displacement curve and consider the soil suction effect, as shown in Figure 6 and described below.

(1) Penetration – the pipe penetrates into the soil to a depth where the soil force equals the penetration force.

(2) Unloading – the penetration force reduces to zero allowing the soil to swell.

(3) Soil suction – as the pipe continues to elevate the adhesion between the soil and the pipe causes a tensile force resisting the pipe motion. The adhesion force quickly increases to a maximum then decreases to zero as the pipe pulls out of the trench.

(4) Re-penetration – the re-penetration force and displacement curve has zero force when the pipe enters the trench again, only increasing the interaction force when the pipe re-contacts the soil. The pipe and soil interaction force then increases until it rejoins the backbone curve at a lower depth than the previous penetration.

2 Numerical Model for SCR on Seabed

Jung Hwan You presented the initial stage of development of a simplified seafloor support model[6]. This numerical model simulates the seafloor-pipe interaction as a flexible pipe supported on a series of equivalent soil springs, as shown in Figure 7.

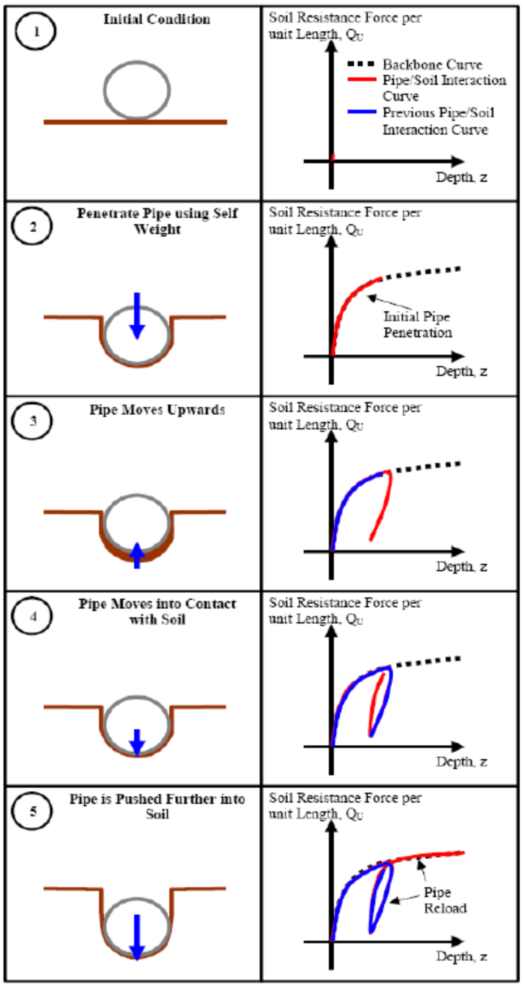

Figure 5: Illustration of Pipe/Soil Interaction [5]

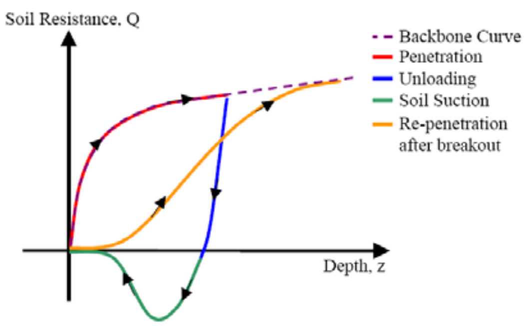

Figure 6: Re-penetration Pipe/Soil Interaction Curves [5]

Constants for the soil springs were derived from finite element studies performed in a separate, parallel investigation. These supports are comprised of elasto-plastic springs with spring constants being a function of soil stiffness and strength, and the geometry of the trench within the touchdown zone.

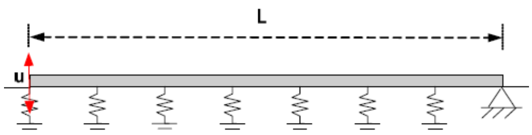

Figure 7: Simplified Spring Support Model

Deflections and bending stresses in the pipe are computed based on a finite element method and a finite difference formulation developed in this research project. The finite difference algorithm has capabilities for analyzing linear springs, non-linear springs, and springs having a tension cut-off. The latter feature simulates the effect of a pipe pulling out of contact with the soil.

The model is used to perform parametric studies to assess the effects of soil stiffness, soil strength, trench geometry, amplitude of pipe displacements, pipe stiffness, and length of touchdown zone on pipe deflections and bending stresses.

The preliminary studies indicate that the seafloor stiffness (as characterized by the three spring parameters), the magnitude of pipe displacement, and the length of the touchdown zone all influence bending stresses in the pipe. Also, the tension cutoff effect, i.e., the pipe pulling away from the soil, can have a very large effect on bending stresses in the pipe. Neglecting this effect can lead to serious over-estimate of stress levels and excessive conservatism in design.

3 Parametric Studies

C.P. Pesce, J.A.P. Aranha and C.A. Martins [7] researched soil rigidity effect in the touch down boundary layer of riser on static problem. Their work developed previous analysis performed on the catenary riser TDP static boundary-layer problem by considering a linearly elastic soil. A non-dimensional soil rigidity parameter was defined as follows:

$$K = \frac{k\lambda^4}{EI} = \frac{k\lambda^2}{T_0} = \frac{kEI}{T_0}$$

Where k = the rigidity per unit area.

EI= the bending stiffness.

T_0 = the static tension at TDP

λ = the flexural-length parameter representing the TDP boundary later length scale.

A typical oscillatory behavior for the elasticity on the supported part of the pipe line was showed by the constructed solution. Also, it indicated how this behavior matched smoothly the catenary solution along the suspended part, removing the discontinuity in the shear effort, attained in the infinitely rigid soil case. In that previous case, the flexural length parameter $\lambda = \sqrt{EI/T_0}$ had been shown to be a measure for the position of the actual TDP, with regard to the ideal cable configuration.

Unlike the previous case, in the linearly elastic soil problem, the parameter λ has been shown to measure the displacement of the point of horizontal tangency about corresponding TDP attained in the ideal cable solution, in rigid soil. Having K as parameter some non-dimensional diagrams have been presented, showing, for K⩾10, the local elastic line, the horizontal angle, the shear effort, and the curvature, as functions of the local non-dimensional arc-length parameter $\varepsilon = s/\lambda$. Also, another non-dimensional curve was presented, enabling the determination of the actual TDP position as a function of soil rigidity K.

4 Conclusions

The use of SCR in deepwater developments is becoming more popular with a number of SCR's already installed offshore Brazil and in the Gulf of Mexico, and West Africa. Current development of steel catenary riser technology have focused on better understanding of the touch down region and its interaction with the seabed. The interaction between steel catenary risers and the seafloor involves a number of complexities including non-linear soil behavior, soil yielding, softening of seafloor soils under cyclic loading, variable trench width and depth, a wide range of possible riser displacement amplitudes, and conditions in which the riser pipe can actually pull out of contact with the soil. In this paper, a comprehensive review is introduced about the recent research on interaction between deepwater steel catenary risers and a soft clay seabed, including the STRIDE (STeel Risers In Deepwater Environments) and CARISIMA (CAtenary Riser Soil Interaction Model for global riser Analysis) Joint Industry Program's test data and information from existing papers. It is helpful for the development of steel catenary risers in China.

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