Wellhead Fatigue Response Affected By Seabed Interaction

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ABSTRACT

Subsea wellheads are generally exposed to fatigue due to environmental loading, such as waves, current and wind which implies cyclic loading to the wellhead. The conductor-soil interaction may have significant impact on stress range variation in wellhead system and consequently on accumulative fatigue damage. In practice, the seabed soil is usually replaced with linear elastic springs to define lateral force-displacement curves.

In this study, the influences of a range of different lateral force-displacement models were examined through implementation into global riser analysis. The results showed that the selection of lateral p-y curve and the soil properties governing the soil stiffness may have significant influence on fatigue damage. In terms of riser dynamics, it was observed that the bending moment increases with current speed and decreases with lower wave height for different sea states, thus, resulting in reduction in wellhead fatigue damage.

RÉSUMÉ

Les têtes de puits sous-marines sont généralement exposées à la fatigue due aux charges environnementales, telles que les vagues, le courant et le vent, ce qui implique un chargement cyclique vers la tête de puits. L'interaction conducteur-sol peut avoir un impact important sur la variation de la plage de contrainte dans le système de tête de puits et, par conséquent, sur les dommages de fatigue accumulés. En pratique, le sol du fond marin est généralement remplacé par des ressorts élastiques linéaires pour définir les courbes force-déplacement latérales.

Dans cette étude, les influences d'une gamme de différents modèles de force-déplacement latéraux ont été examinées par la mise en œuvre dans l'analyse globale de la colonne montante. Les résultats ont montré que la sélection de la courbe p-y latérale et les propriétés du sol régissant la rigidité du sol peuvent avoir une influence significative sur les dommages dus à la fatigue. En termes de dynamique de la colonne montante, il a été observé que le moment de flexion augmente avec la vitesse du courant et diminue avec la hauteur de vague inférieure pour différents états de la mer, entraînant une réduction de la fatigue de la tête de puits.

1 INTRODUCTION

The subsea wellhead is a vital component of the drilling and production system and is located at sea bottom. It provides the suspension point and pressure seals for the casing strings that run from the bottom of the hole sections to the surface pressure control equipment.

Hydrodynamic forces acting on the drilling riser and drilling unit will cause dynamic movement which will be transmitted to the wellhead system and can lead to fatigue accumulation in the subsea wellhead. Fatigue damage also arises from stress changes in the conductor which are generated by environmental loads such as waves acting on the vessel and the riser. Structurally, the function of the subsea wellhead is for supporting the weight of the subsea BOP stack during the drilling operations. Hence, a structural failure in the wellhead might lead to blowouts which can cause catastrophic effects on the environment.

However, the most popular way of estimating fatigue damage of the subsea wellhead is to perform global and a local finite element analyses. The goal of a wellhead fatigue analysis is to predict the fatigue damage in system components for the life of the well. For this purpose, operational inputs are appropriately applied to engineering models of systems and sub-systems to predict local responses, which are then combined with material properties and damage models (DNV-RP 2015). Both the fatigue and strength analyses can be examined from a geotechnical point of view with inputs for seabed-structure interaction modelling. Furthermore, complex modelling requirements exist and numerous analysis methods exist for the wellhead system.

The soil response acting on the conductor is generally modelled using Winkler springs type which is defined as a function of the lateral soil-resistance displacement (P-y) relationship. The soil's stiffness is highly dependent on the soil type and the strength properties, and it directly affects the amplitude of stress cycles predicted in the subsea wellhead system.

The main objectives of this paper are as follows:

- To investigate the impact of seabed soil interaction on the subsea wellhead fatigue by performing a global riser model in OrcaFlex
- To perform a fatigue assessment in a subsea wellhead system based on the numerical models.
- To perform parametric studies in order to investigate their effects on estimated wellhead damage

2 SYSTEM DESCRIPTION

This section describes the drilling riser and the subsea wellhead system. During subsea drilling, the motion of the MODU causes cyclic bending moments on the wellhead as shown in figure 1. Hydrodynamic forces on the riser due to waves and current normally cause the dynamic loading in the drilling system which may have severe impact thereby leading to fatigue damage in the subsea wellhead.

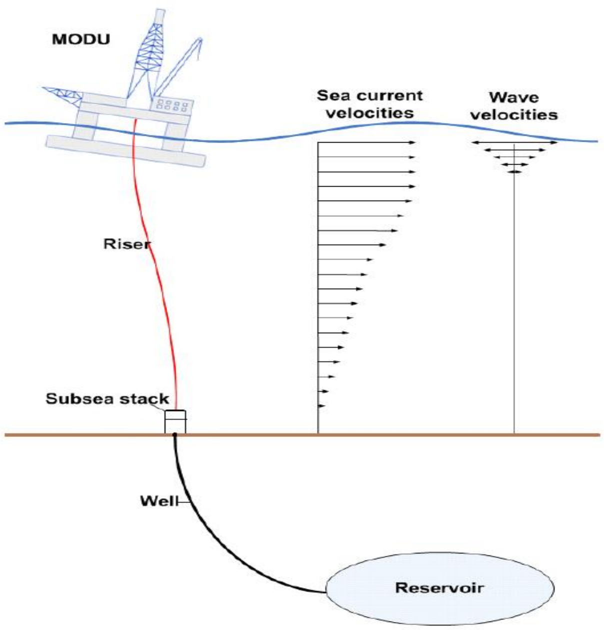

Figure 1: Schematic overview of the system (DNVGL-RP-0142, 2015)

2.1 Drilling Riser

Riser drilling is an essential and indispensable part of the offshore oil industry and are used in conveying fluids from the seafloor to an offshore floating production structure or a drilling rig. A drilling riser installed in 100m water depth operated by semi-submersible vessel also known as MODU was selected for this study. The rig is a complex equipment containing the lower marine riser package (LMRP), subsea BOP connected to the wellhead at the seabed, conductor, casing and other components needed to drill the oil well. A typical drilling system comprises of a Lower Flex Joint (LFJ) and Upper Flex Joint (UFJ). The UFJ makes up the topmost part of the LMRP. The function of the Flex joint is to allow rotation of the riser with minimal motion thereby reducing bending moments generated at critical structural interfaces. It also exhibits a non-linear behaviour which must be taken into account during the analysis to avoid non-conservative results.

2.2 Subsea Wellhead and Conductor Systems

The primary purpose of the subsea wellhead is to support the BOP and must be designed for a high structural loads imposed (i.e. maximum strength and capacities) during drilling, workover or well completion operations. The subsea wellhead system comprises the high pressure housing (HPH) also known as the wellhead housing and the conductor housing also called the Low Pressure Housing (LPH). The conductor housing is essentially the top of the casing conductor. In addition, the HPH provides pressure integrity for the well.
In this study, a simple two-pipe wellhead system comprising a conductor pipe (diameter 762mm, thickness 25.4mm) and a surface casing pipe (diameter 536.4mm, thickness 33.3mm) was considered. The conductor casing is welded to the base of the LPH while the surface casing is welded to the base of the HPH.
The properties of the conductor, surface casings and the cement are presented in Table 1. The annular space between the conductor and the surface casing is cemented from the casing bottom at 186.5m below the MWL to 10m below the seabed.

Table 1**:** Conductor and surface casing properties

Description	Conductor	Surface Casing
Outer diameter (m)	0.762	0.5364
Inner diameter (m)	0.7366	0.5031
Length (m)	48.3687	48.4042
Bending Stiffness (Nm^2)	1.76E+06	1.93E+05
Axial Stiffness (N)	6.28E+06	5.69E+06

3 ANALYSIS AND SIMULATION SOFTWARE

In this study the simulation software-OrcaFlex (Orcina, 2012) was used to perform the analysis. Both static and dynamic analyses was performed for each segment. Dynamic analysis is run with irregular wave (JONSWAP). The implicit method is used for the integration which requires longer time step for its stability. Simulation time was 120 seconds. There was no prescribed motion assuming the rig was anchored and neglecting drift-off. The simulation time was changed to 3600s to simulate the movements and the forces in the different parts with a time step of 0.25s chosen for the analysis.

3.1 Model Built-up

The numerical model was built using the FE analysis program: Orcaflex. The riser model is build up using lines, springs and buoys by using the graphical user interface in the program. This program has been used for the analysis of the wellhead on the seabed which is connected to the MODU by means of a top-tensioned riser.
In this model, the riser line starts at the Upper Flex Joint (UFJ) and ends at the wellhead. The tension cylinder connected to the tensioner ring is modelled as a spring. The springs that model the soil stiffness are connected to the wellhead.
The UFJ is connected to the inner barrel also known as the slick joint which is positioned above the tensioner ring. The tensioner ring is modelled as a body with six degrees of freedom. In Orcaflex the body is represented as a 6D buoy and can transfer both moment and translation motion to and from the body to the connected lines. The main function of the 6D buoy is to act as a connection point for the tensioners since the springs cannot be connected to nodes on a line but can only be connected to end points. There is also a 23m pup joint that connects the outer barrel to the 23m slick joint. Other components that make up the riser line are 23m buoyancy joint and a 3m pup joint connected between the buoyancy joint and the LMRP above lower flex joint (LFJ) center of rotation. The LMRP is fixed to the BOP. The lower packages (i.e. LMRP and BOP) are modelled using cylindrical shapes in OrcaFlex with defined geometry (length, diameter etc.) A similar connection line (space spool) is also stretched from the BOP to the wellhead datum. Figure 2 shows a schematic of the riser model build-up used in this studies.

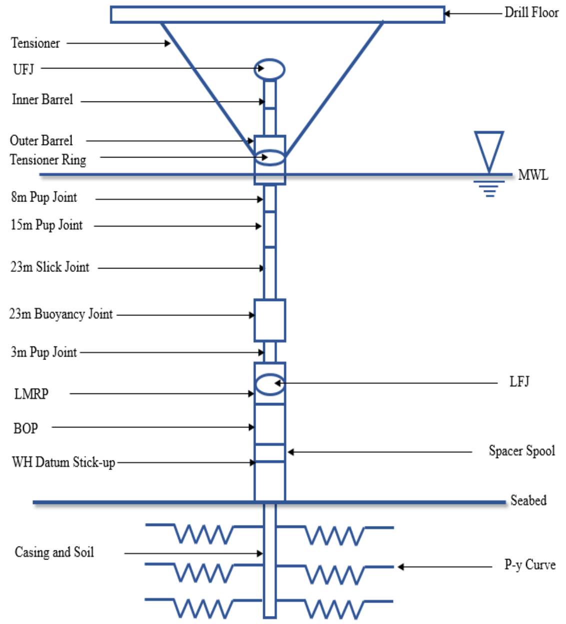

Figure 2: Schematic of Riser stack-up and Wellhead Model Created in OrcaFlex

3.2 Environmental Data

The drilling riser was installed at the location of 100m water depth. The global analysis is run with head sea, significant wave height (Hs) and peak spectral period (Tp). JONSWAP spectra is used to describe the irregular wave motion.

4. SOIL MODELS

This section attempts to investigate the accuracy of the different soil models in wellhead fatigue analysis. A literature review has been conducted to review the basis for the API springs, and alternative p-y curves as proposed by Jeanjean (2009) and Zakeri et al (2015). These soil models were reviewed and implemented in the global analysis to demonstrate the effect of soil stiffness in wellhead fatigue analysis.

Matlock-API soil model is the industry standard approach used in modelling soil response for piles also known as backbone p-y curves. The p-y curves was originally developed by Matlock for ultimate limit state design of pile foundations for steel jacket subjected to monotonic or cyclic storm or hurricane loading. It has been shown both experimentally and numerically to be too soft at a small displacement required for the estimation of fatigue. Fatigue, however, occur as a result of stress changes and are often well below the elastic yield stress of a typical conductor which corresponds to smaller soil deformation (Russo et al, 2016). As such, a reliable soil p-y model was proposed for accurate conductor fatigue analysis which led to determination of a more appropriate stiffness by considering the unload-reload stiffness (secant stiffness) of the soil once steady state conditions are reached. A vital aspect of developing p-y springs with the FE method is to develop a representative soil model for riser-conductor problems. Monotonic backbone P-y curves were obtained from series of tests at different depths as shown in Figure 3. The P-y curves developed with the FE approach are compared with API recommendations.

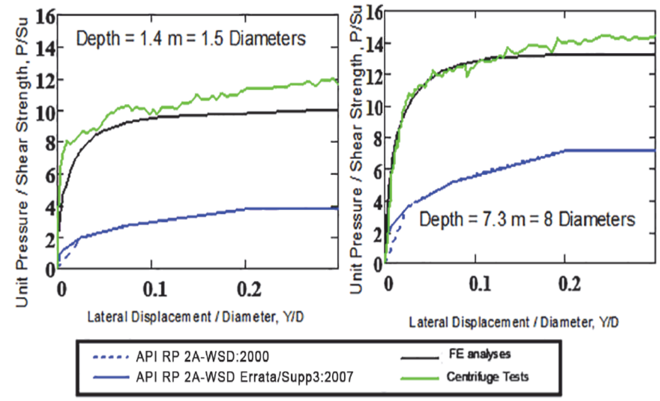

Figure 3: Comparison between p-y springs measured in centrifuge tests on kaolinite and computed using the FEA method with API recommendation (API, 2011)

Jeanjean (2009) also conducted some studies and deduced that the application of backbone curves for fatigue analysis is not appropriate. His curiosity led to the development of a more robust soil model for well conductor analysis. This model was developed specifically to improve the initial soil stiffness modelling and its effects on fatigue performance and was verified by extensive physical testing in a geotechnical centrifuge and numerical analyses. It was shown both numerically and experimentally that the API lateral soil springs are too soft at small displacements needed for wellhead fatigue assessment. In addition, the proper characterization fatigue should not be based on the backbone response. Jeanjean's model is stiffer than Matlock API and gives a robust soil model for wellhead fatigue analysis.
According to Jeanjean (2009), the relative soft soil reactions (soil springs) will lead to deeper penetration below the mudline resulting in maximum bending moment range while relative stiffer soil leads to the maximum bending moments range shifting closer to the mud line. Details of the methodology for physical modelling, test results and approach adopted are presented in later publications in 2016.
A new empirical equation was proposed from the equation inspired by O'Neil et al (1990) for p-y curves in stiff clay and the shape of the FEA-generated backbone curve has been fitted as shown in Figure 4:

$$P = N_p . S_u . \tanh\left[\frac{G_{max}}{100 . S_u}\right] . \left(\frac{y}{D}\right)^{0.5} \qquad [1]$$

where,

P	is the soil pressure per unit length of conductor
G_{max}	is the maximum soil shear modulus
N_p	is the bearing capacity factor
S_u	is the shear strength
$\frac{y}{D}$	is the lateral displacement, y, over pile diameter, D

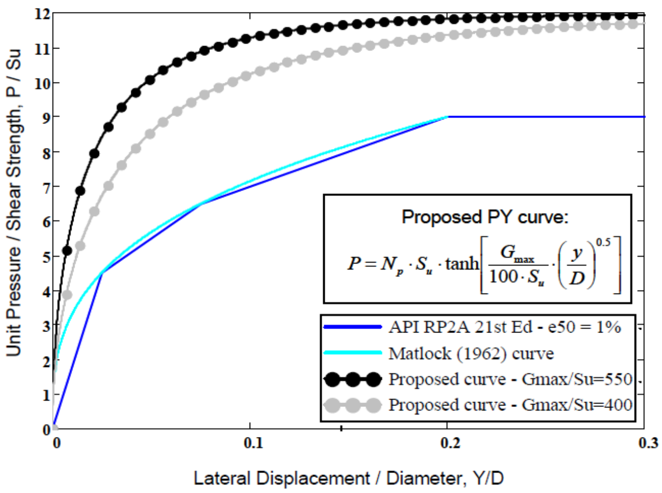

Figure 4: P-y curves as per equation 1, compared with API and Matlock curves for large embedment depths (Jeanjean, 2009)

The work conducted by Jeanjean also inspired Zakeri et al. (2015) to develop a model which focuses on the degraded cyclic soil response behavior. Soil degradation occurs during the high sea state affecting the well and BOP response after high loading is finished. The Zakeri et al. model exhibited stiffer response at small displacement and was validated by extensive centrifuge test and corresponding numerical analyses. The approach outlined by Zakeri et al. is based on the unload-reload stiffness of disturbed soil (degraded soil response) at the steady-state condition and was specifically developed for well conductor fatigue analysis. This model provides a more accurate fatigue life predictions than API soil p-y models since it has a higher initial stiffness and forms the basis for the development of soil constitutive p-y models for implementation into numerical analysis.
A simplified approach was developed based on the degraded soil secant stiffness at the steady-state condition and is recommended for both global and local analyses for normally to lightly over-consolidated clays and for medium-dense sands. The soil pressure per unit length of conductor, P, at each spring location is estimated using the equation below as proposed by Zakeri et al.

For normally to lightly over-consolidated clays, equation 2 is used

$$P = 0.5 \times 0.90 \times \tau \times (\tfrac{y}{D})^{-0.05} \qquad [2]$$

For medium-dense sands, equation 3 is used

$$P = 0.5 \times 730 \times \tau \times (\tfrac{y}{D})^{0.65} \qquad [3]$$

The 5Gmax Model has also been considered in this paper and was proposed as a simplified estimate of the initial stiffness corresponding to five times the maximum shear modulus in clay. The minimum displacement has been estimated based on the lateral pressure from Matlock-API and the displacement calculated based on an initial stiffness of 5Gmax (Gregersen et al, 2017).
Based on the laboratory test and field testing with CPT to determine the geotechnical properties of the soil in the well vicinity; soil p-y models were developed for the conductors installed in normally consolidated to lightly overconsolidated clays.

4.1 Lateral Soil-Structure Interaction (P-y) Model

A common way to describe the interaction of seabed and conductor is through p-y curves which relates the lateral resistance from the soil (p) to the displacement of the structure (y) at a given depth. The p-y curves is based on Winkler springs used to represent the soil stiffness which are highly dependent on the soil type, strength properties and its cyclic characteristic. The spring stiffness can be defined using the equation below:

$$K = K_{soil} . \Delta z \qquad [4]$$

where,

K is the spring stiffness
K_{soil} is the stiffness of the soil layer
Δz is the height that the spring support

Gregersen et al (2017) presented plots of a series of soil models obtained from different authors. The study was carried out to validate the soil models for wellhead fatigue analysis. The p-y curve plots as obtained by Gregersen et al (2017) was implemented in the numerical models as non-linear springs attached to discrete locations.
In this paper, our focus will be on the most popular soil models namely: Matlock API, Jeanjean and Zakeri et al. The soil model for original Matlock and Gmax will not be compared since their stiffness are very close to that of Matlock API and gives nearly same results with negligible variations. Figures 5 and 6 present the p-y curves for each of the five models for both large and small displacement.

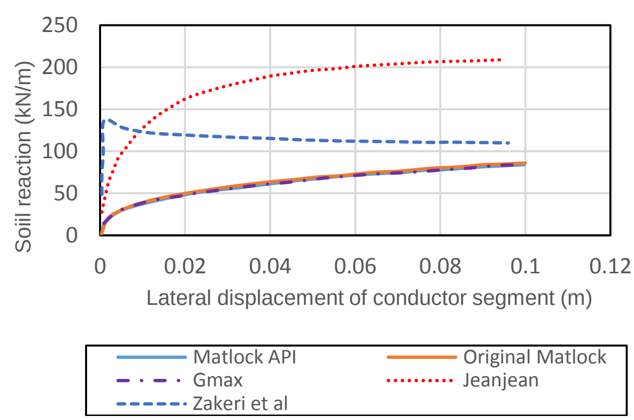

Figure 5: P-y Curve for large displacement (From Gregersen et al. 2017)

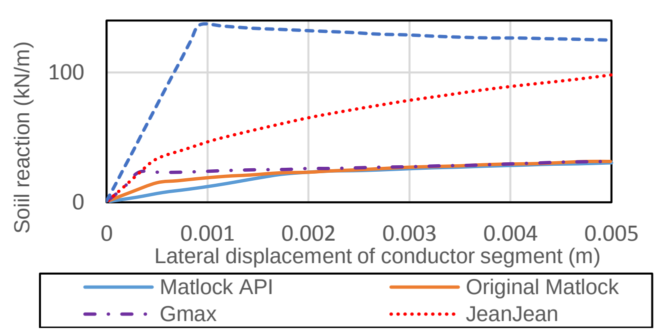

Figure 6: P-y Curve for small displacements (From Gregersen et al. 2017)

5 VERIFICATION OF NUMERICAL MODEL

Jaiswal et al (2016) performed a fatigue analysis for non-rigid locked wellhead using Abaqus software and obtained results for the modal analysis by performing both local and global analyses on the wellhead system. Similar results have been obtained for the modal analysis in this paper by performing only the global riser analysis using OrcaFlex software. The results obtained were compared with that obtained by Jaiswal et al (2016).

5.1 Modal Analysis

Modal analysis was computed from the global riser analysis based on Matlock-API soil model to calculate the undamped natural modes of the system. The first and second natural period are respectively 8.8s and 3.2s.

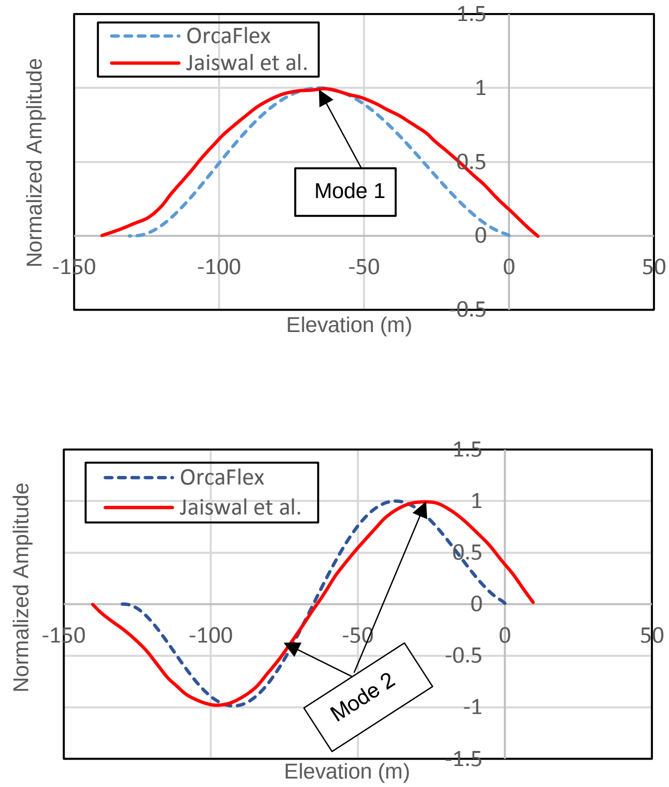

Figure 7: First two natural mode shapes

6 SOIL-MODELS INVESTIGATION

Global riser analysis is performed for the four additional soil models: Original Matlock, Jeanjean, Zakeri et al and 5Gmax. The results of the bending moment for the Zakeri et al and Jeanjean models at different sea states were compared with the result obtained from the global analysis using API recommendation soil model (Matlock-API) which served as the base case soil model. The results showed that the wellhead bending moment is affected by the soil stiffness.

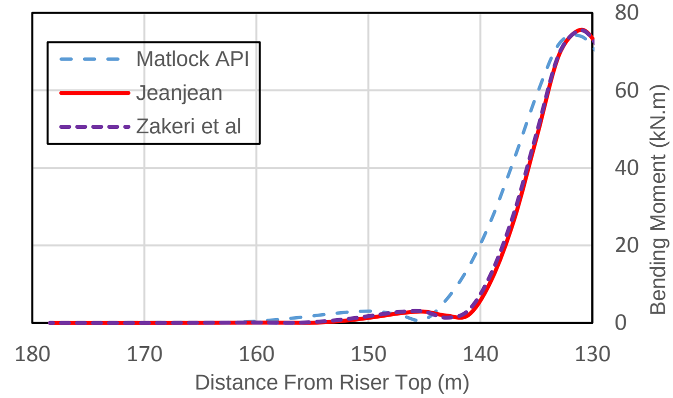

Figure 8: Wellhead Bending Moment for sea state 1 (Hs = 3.6m, Tp = 11s)

As can be seen in Figure 8, the bending moments are significantly influenced by the soil formulations. The softer the soil model the larger the bending moment. Similarly, the stiffer the soil model the smaller the bending moment. The bending moment at the wellhead region is 72.13kNm for the Matlock API model, 69.42kNm for Jeanjean model and 69.68kNm for Zakeri et al model for the lowest sea state.

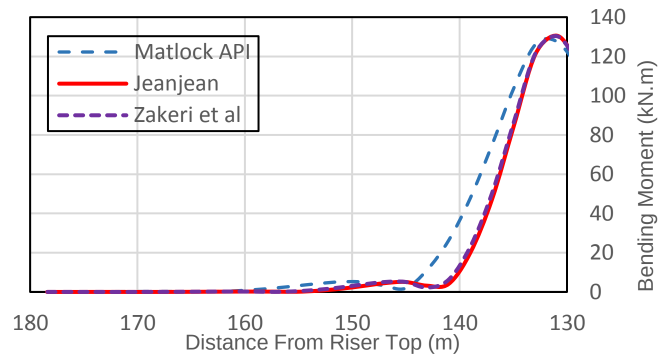

Figure 9: Wellhead Bending Moment for Sea State 2 (Hs = 6.5m, Tp = 8.5s)

The bending moments acting on the wellhead were also extracted from the FE model for the high sea state as shown in figure 9. As can be seen in Figure 10, the bending moments are significantly influenced by the high sea state. This is expected since larger waves typically excite larger forces. The bending moment at the wellhead region varies from 126kNm for the Matlock API model and 121kNm for Jeanjean and Zakeri et al models.

6.1 Comparison with Gregersen et al result

Gregersen et al. (2017) performed analysis to validate soil models for wellhead fatigue and presented the results for the bending moment for two different sea states. The results obtained by Gregersen et al. were compared with the results obtained from this research using OrcaFlex for three different soil models: Matlock API, Jeanjean and Zakeri et al. Lower sea state was simulated as shown in Figure 10, Figure 11 and Figure 12.

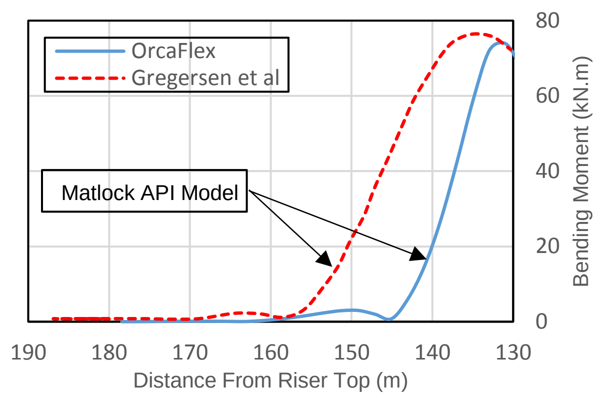

Figure 10: Bending Moment for Matlock API Model (Sea state 1: Hs =3.6m, Tp = 11s)

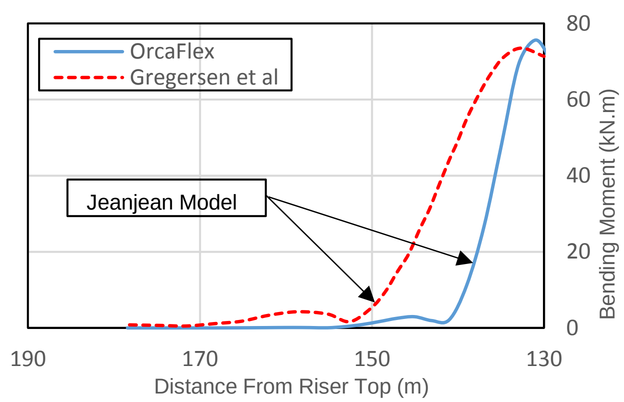

Figure 11: Bending Moment for Jeanjean Model (Sea state 1: Hs =3.6m, Tp = 11s)

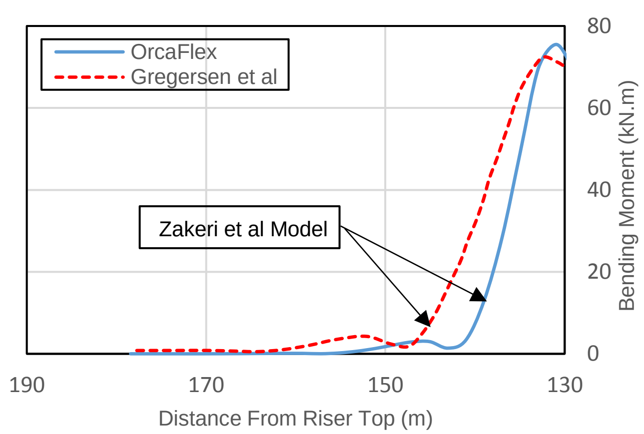

Figure 12: Bending Moment for Zakeri et al. Model (Sea state 1: Hs =3.6m, Tp = 11s)

The results from Gregersen et al. may not quite agree with that obtained from OrcaFlex due to variation in environmental data and geometric properties selected for this studies. This present studies considered a water depth of 100m while Gregersen et al.considered a water depth of 400m. The plots for the wellhead bending moment for the high sea state are shown below.

6.2 Effect of Current on wellhead

Application of velocity current in global response analyses was conducted as part of the studies to assess the relative difference in terms of estimated fatigue damage for the different soil models. Different current speeds were simulated for each of the proposed models and the results are presented below.

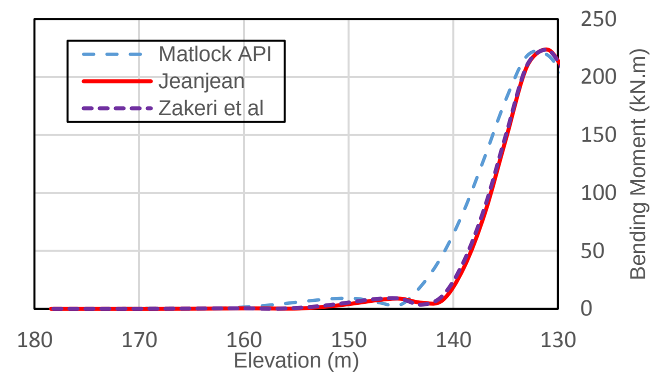

Figure 13: Wellhead bending moment at Current Speed = 0.72m/s

The bending moment generated from the different speeds for the three different soil models have been compared. The results showed that the current affects the riser response as shown in the bending moment diagrams. It can be seen in Figure 13 that the bending moment at location of the wellhead for Matlock API is 218kNm and that of Jeanjean and Zakeri et al models are found to be 209kNm and 210kNm respectively.

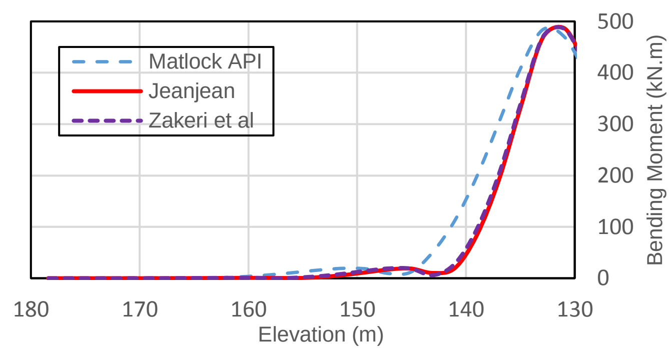

Figure 14: Wellhead bending moment at Current Speed = 1.25m/s

High current also affects the wellhead bending moment as observed in Figure 14. The higher the current the higher the bending moment and vice versa. Current will normally have an impact on the subsea wellhead which will also contribute to fatigue failure of the wellhead.

6.3 Modal Analysis

Modal analyses were computed for the different soil models and the results of the first five natural mode shapes and natural periods are presented below:

Table 2: Natural Period

Mode #	Natural Period (s)				
	Matlock-API	Original Matlock	5Gmax	Jeanjean	Zakeri et al
1	8.766	8.765	8.766	8.768	8.768
2	3.263	3.264	3.263	3.266	3.267
3	1.671	1.672	1.671	1.678	1.677
4	1.002	1.003	1.002	1.005	1.005
5	0.69	0.69	0.69	0.693	0.692

7 IMPACT OF SOIL ON WELLHEAD FATIGUE FROM ANALYSIS

The influence of seabed soil interaction model on wellhead fatigue was investigated in this paper. The results of the fatigue analysis at the wellhead datum for a 25 years period are presented. Two different sea states have been considered (low and high sea states).The results showed that the fatigue life of the wellhead decreases over the 25 years period for the different soil models with a more damage occurring in the soft soil than stiffer soil.
In the first analysis, the fatigue damage has been calculated for a period of 25 years for the low sea state by considering each of the proposed soil models. Figure 15 and Figure 16 show the comparison of the fatigue damage and fatigue life for the low sea state and for each of the different soil models.

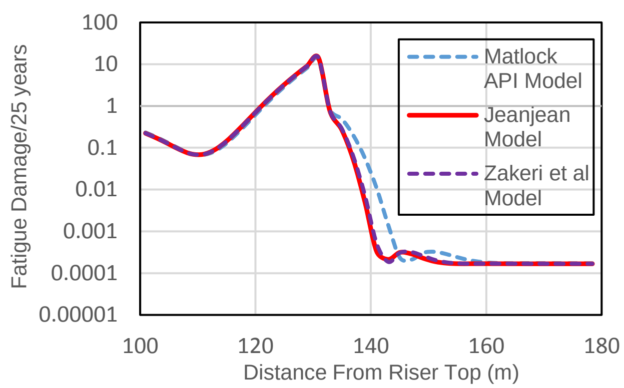

Figure 15: Fatigue Damage for Load Case 1 (Hs = 3.6m, Tp = 11s)

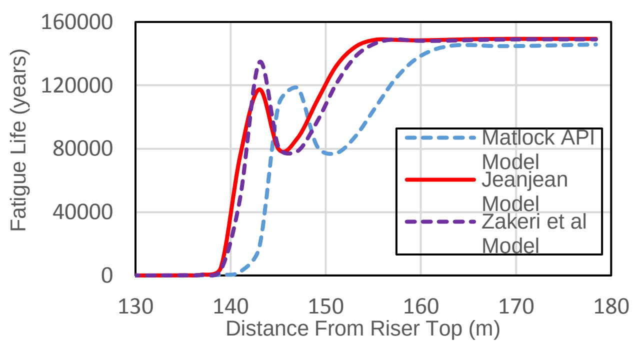

Figure 16: Fatigue Life for Load Case 1 (Hs = 3.6m, Tp = 11s)

By critically assessing the plots above, it is shown that the Matlock API model has an overall fatigue damage of 0.83 and fatigue life of 30.2 years at the location of the wellhead while the Jeanjean model has an overall fatigue damage of 0.75 and fatigue life of 33.3 years and Zakeri et al. model has an overall fatigue damage of 0.76 and fatigue life of 33 years. This is attributed to the fact that, the lowest soil stiffness (i.e. Matlock API, Original Matlock and Gmax models) leads to larger damage and decreased fatigue life whereas a stiffer soil (i.e. Jeanjean and Zakeri et al models) leads to lower damage and increased fatigue life.

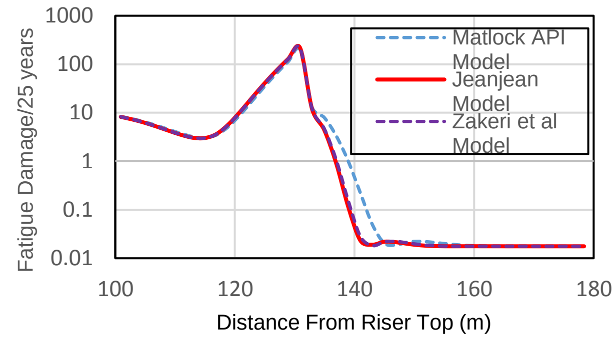

Figure 17: Fatigue Damage for Load Case 2 (Hs = 6.5m, Tp = 8.5s)

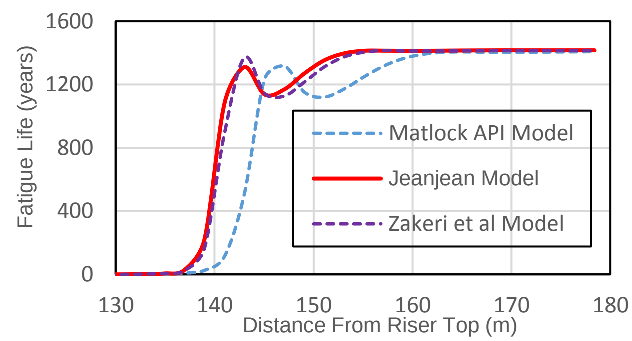

Figure 18: Fatigue Life for Load Case 2 (Hs = 6.5m, Tp = 8.5s)

In the second analysis, a high sea state was simulated over a period of 25 years for each of the soil models. Figures 17 and 18 show both the overall fatigue damage and fatigue life for the high sea state for each of the proposed soil models. Hence, a higher sea state leads to a more damage and decrease fatigue life.

8. CONCLUSIONS

In this study, the influence of seabed soil interaction on wellhead fatigue was investigated. From the results of the analyses, it is evident that the stiffer soil models will greatly reduce the bending moment at the wellhead datum which will further have beneficial impact on the fatigue life of the subsea wellhead system. Moreover, the softer soil model leads to more damage and decrease in fatigue life on the wellhead.
The global riser analysis performed for the different soil models showed that the Matlock-API soil formulation gives the largest fatigue damage due to the low initial soil stiffness (i.e. stiffness for the first few meters of displacement); secondly, the proper characterization for wellhead fatigue should not be based on the backbone response. The Zakeri et al. and Jeanjean soil models have higher initial stiffness and tend to give a low damage and increase fatigue life. Hence, the fatigue response of the wellhead from analysis is affected by the soil models.

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GLOSSARY OF TERMS

API	American Petroleum Institute
BM	Bending Moment
BOP	Blowout Preventer
CPT	Cone Penetration Test
5Gmax	Five times the maximum shear modulus in clay
HPH	High Pressure Housing
Hs	Significant Wave Height
JONSWAP	Joint North Sea Wave Project
LFJ	Lower Flex Joint
LMRP	Lower Marine Riser Package
LPH	Low Pressure Housing
MODU	Mobile Offshore Drilling Unit
MWL	Mean Water Level
Tp	Peak Period
Tz	Mean up-crossing period
UFJ	Upper Flex Joint
WH	Wellhead

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