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Application of an Alternative Material to the Portland cement for the Cementing of Wellbore Top Casings of Subsea Wellhead

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ABSTRACT

The Offshore Drilling Operations are moving to deep waters due to the continued demand for Fossil Fuels and the depleting Continental Shelf reserves. This has posed several new problems to the offshore or subsea engineers in the design of the various systems and equipment to be used for the exploration and exploitation of deep water resources due to harsh environmental conditions at deep oceans. One of the most affected systems due to this environmental condition is Subsea Wellheads or Subsea Wellhead-Conductor Systems experiencing more fatigue induced damage problems than their application in continental shelves. Subsea Wellhead serves as an access to the wellbore while the conductor is to sustain the wellbore integrity in all phases of an offshore field development until Plugging and Abandonment. In this paper, a case study on the application of alternate material, i.e. a Marine-Grade Resin for securing the wellbore top casings than the API Class G cement grout is studied at a deep water field named 'Kikeh' which is located offshore Sabah, East Malaysia in the South China Sea. This is to overcome various dis-advantages of the Portland cement in deep water oil/gas well applications. A model of a Semi-Submersible Drilling Rig with Drilling Riser System was developed in ORCAFLEX to obtain the Bending Moment, Shear Force and the Effective Riser Tension. The obtained results were then used to estimate the fatigue life of a De-Coupled 3D CAD Model of Soil – Wellhead-Conductor System developed in Creo Parametric 2.0 in ANSYS Static Structural Analysis Module. It has been found that the application of Marine-Grade Resin as an alternative return material is producing better fatigue life than placing the API Class G cement returns inside the annulus.

KEY WORDS: *API Class G Cement, Marine-Grade Resin, Offshore Deep Water Drilling, Wellbore Cementing, Conductor Casing Strings, Subsea Wellhead.*

1.0 INTRODUCTION

1.1 Description and Application

Subsea Wellhead is a compositely constructed structure placed above the Mudline (also called as Seabed) with a Stick-up height typically ranging from 2 to 4 m above Mudline. This wellhead along with the conductor casing or string is collectively called as wellhead-conductor system in the offshore oil and gas industry. This wellhead-conductor system acts as an access way to the reservoir through the wellbore drilled from typical floating type drilling platforms like Semi-Submersible Rigs or Drill-Ships. These platforms are also simply called as Floaters deploys a drilling riser extending all the way from the drill deck floor in the floater accesses the wellbore through this wellhead-conductor system to perform the drilling operations during the exploration, development drilling and completion phases of the offshore oil mining activities. The typical Subsea Wellhead-Conductor System is shown in the following Figure 1:

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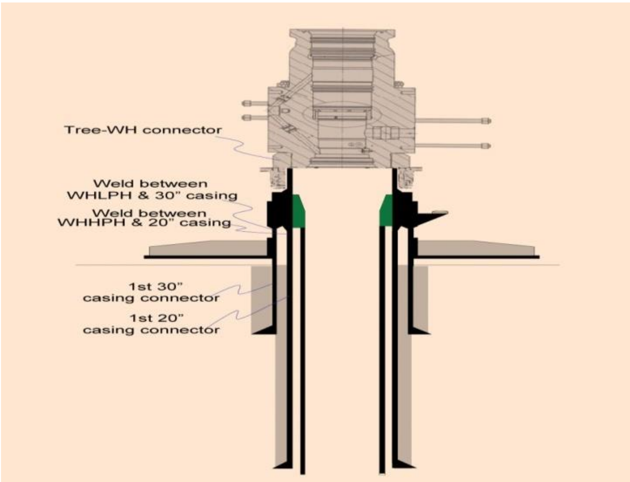

Figure 1: Typical General Arrangement of Wellhead-Conductor System with weld joints locations (www.drilling contractor.org)

1.2 Drilling Operation and its Loads

During the drilling operations, the wellhead is subjected to various loads acting on it due to the undersea current induced motion transferred to the wellhead through the riser systems, floater excursion and responses due to the wave and wind effects and also due to the continuing drilling operations of the wellbore which has a direct effect on the wellhead-conductor system as stated by Howells and Bowman (1997).These loads are subjected to change rapidly in magnitude with respect to time during the operational periods thus inducing loads of varying magnitude with respect to time on the wellhead-conductor system components which may eventually lead to the fatigue induced failure as the failure criterion to the subsea wellhead-conductor system components. Shen and Natarajan (2010) state that the VIV may cause excitation of the BOP and Conductor Systems combined natural frequency ranges and results in fatigue accumulation below the mudline in the conductor system. Shen and Natarajan (2010) also added that the fatigue damage accumulation reduced the failure margin for other operations like workover, intervention, etc.

Lim et al (2012) found that the equipment selections for subsea system applications are purely based on the experience and also not specific in application. They also add that the system fatigue performance is not given much importance during the conceptual design of the system. Lim et al (2012) also confirmed that connected drilling riser system induces cyclic lateral loads on the subsea wellhead, conductor and casing systems contributing to its fatigue accumulation and eventually leading to its failure

Milberg et al (1991) found that the environmental loading magnitude has increased continuously with the introduction of TLP based drilling operations because the drilling risers are connected to the subsea wellhead system in all the conditions which contributes considerably to the fatigue and the static loading on the systems in the mudline. This loading scenario has resulted in the wellhead extension premature failure due to their magnitude induced.

So this work will focus on the fatigue induced damage of the wellhead-conductor Systems installed on Kikeh, a deep water field (maximum water depths of around 1300 m) offshore Sabha, East Malaysia and simultaneously assessing the reliability of wellhead-conductor systems installed for the drilling purposes in this field will be taken for the study. The suitability of that alternate material will be studied.

The following Figure 1 describes the offshore drilling system with the current profile from the seabed, the wave velocity profile, the motion response of the floater and the riser system with respect to the wellhead and BOP Stack Position. It can be inferred from the Figure 2 that the access to the reservoirs beyond the continental shelf, in deep waters possess many challenges which has to overcome in order to explore and exploit the resources of the field for the ever increasing demand for the fossil fuel based energy sources and also for the benefit of the mankind.

1.3 Problem Statement

The deep water drilling operations as already mentioned possess many challenges due to the extremities of the marine environment and also due to the greater depth of water they are working on. The floaters motion responses to the surface effects such as wind, surface Currents and Waves inducing intricate forces which displace the rig from its original position in its six degrees of freedom typical to a floater.

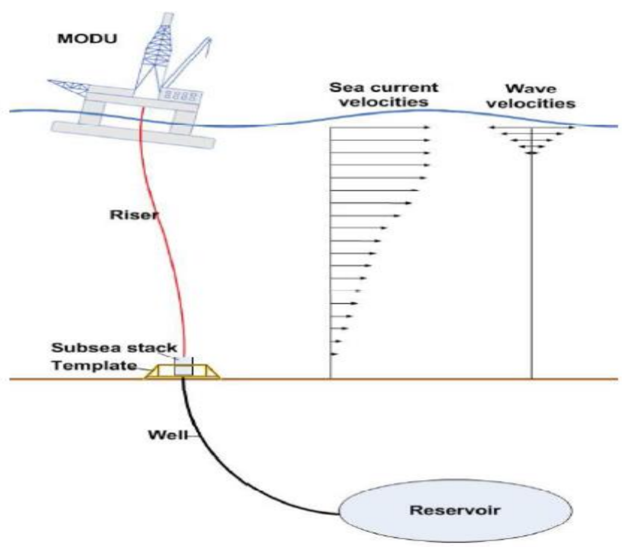

Figure 2: Offshore Drilling System with local Environmental Load Profile [DNVGL-RP-0142]

These motion induced force effects are transferred to the riser system through which the drill string passes connected to the platform through flex-joints at various locations along the pipeline up to the LMRP/BOP Stack and all the way to the Wellhead/Conductor System by Bai and Bai (2012). These transferred loads induce forces of varying magnitude and direction on the Wellhead-Conductor System leading to pre-mature failure of this system. But in practice, the Wellhead-Conductor System are designed to take up fatigue loads up to a

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certain limit based on the experience from previous successful drilling operations but pre-mature failure has been reported by various drilling operations conducted globally even though the design life after considering fatigue effects are very much greater than the actual time to the first failure of the system and very high safety factors in the range of 5 to 10 have been adopted in the overall design of these systems.

Ward et al (2013) state that positioning of wellhead just few meters above the seabed makes it to experience more stringent of the bending moments due to various loading effects and the most part is dissipated to the adjoining soil strata. The problem will be to find out that the kind of fatigue cycle involved i.e. ‘Low Cycle Fatigue or High Cycle Fatigue’ and also which type of loading contributing to which kind of fatigue cycle and also the effect of drilling operations induced loads on the Wellhead-Conductor System through the drill string inside the drilling riser. The deep water drilling operations experience have shown that VIV is higher in deep waters due to the greater under-water currents which are not something associated with the harsher environments and can occur any time in a year by Howells and Sworn (2003) and the problem of VIV contribution to the fatigue damage of the Wellhead-Conductor System will be analyzed. The suitability of cement as a sealing material will be assessed for its effectiveness as an ideal wellbore sealing material. An attempt to mitigate the reduced fatigue life problem will be solved by the usage of alternate materials for wellbore sealing other than the conventional cement slurry. Material properties will be the deciding factor for the selection of alternate wellbore sealing material. Figure 3 represents the typical subsea wellhead-conductor system with full cement returns, programmed shortfall and the proposed complete returns with the alternate sealing material.

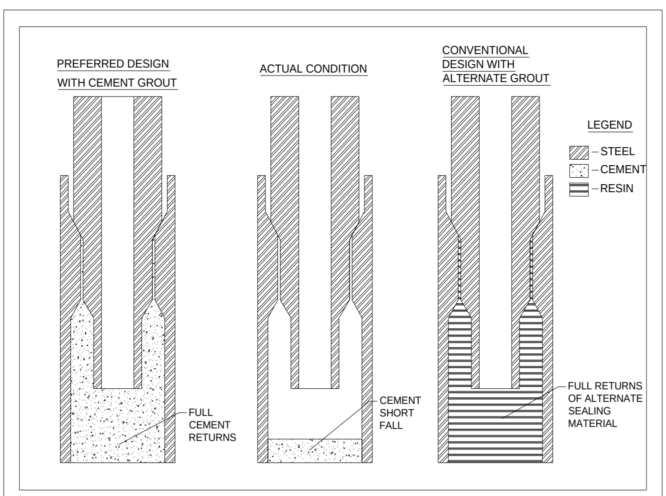

Figure 3: Wellhead-Conductor System with various annular material return conditions

2.0 LITERATURE REVIEW

The wellhead fatigue accumulation is of interest to most drilling contractors involved in drilling operations because of the unscheduled shutdowns and abandonments when a fatigue failure occurs. Considerable research has been done on knowing the exact phenomenon of wellhead fatigue damage. Many Researches focus on the damage caused to the conductor and surface casing strings near proximity to mudline of the wellbore than at greater depths.

Mcneill et al (2017) emphasize that local activities of wave at the site is the primary cause for fatigue damage. Mcneill et al (2017) stressed that the response due to the low frequency current forces does not have any significant contribution to the fatigue life of the wellhead system. Kebadez et al (2017) infer that the uncertainties associated with the development of the model affects the accuracy of the wellhead fatigue analysis negatively. Healy et al (2017) developed a fully coupled 3-D finite element model of the wellhead with the casing and soil and compared the obtained results with the simplified models.

Mercan et al (2017) developed mathematical models of Wellhead-Conductor Systems along with BOP stack which says that local stiffness of the soil and the methods adopted for the development of models limits the consideration of BOP stack's response to various motion induced due to the environmental loads on the riser system.

Mattey et al (2017) optimized the geometry at housing transition zones of three new wellhead conceptual models and tested in loose-sand and soft-clay soil types developed based on the generic load parameters and following the practices of DNVGL-RP-C203. They plotted M-N Curve for the developed three conceptual models of the wellheads and compared with the 36”x 2” WT (Wall Thickness) C1 quality girth weld which is considered as the best fatigue performance for a given wellhead system can achieve especially for conductor casing joints. They performed iterations of the models additionally during the analysis considering both with and without preload between the conductor housing and the wellhead housing. The results of their analysis were presented in the form of M-N curves for fatigue sensitive regions in the system. The first iteration results were in good agreement with the benchmark model. The single model selected for fatigue optimization analysis is a non-preloaded design which showed a solution to the fatigue resistance and structural capacity.

Reinaas L. (2012) developed analytical models considering the surface casing as boundary condition. He found that the inside annular gap between the high pressure housing and low pressure casing is caused due to the varying or cyclic bending effects induced on the wellhead-conductor System causes fatigue damage to the cemented casing and resulting in damage. The near field soil settlement also occurs.

The fatigue crack initiation is a local phenomenon which demands the consideration of “Geometric Stress Concentration” at potential fatigue critical locations. Suitable fatigue criteria based on the distribution of fatigue accumulation is to be identified. Generally, accumulation of fatigue is of two types. They are ‘constant stress range’ or ‘varying stress range’. The fatigue life is estimated as the multiples of required service life of the system based on the scatter and uncertainty of the fatigue analysis (Chakrabarti, 2005).

The soil behavior under the dynamic or cyclic loading is of

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more importance in determining the shear strength degradation and soil damping characteristics. Wave response of the floater causes the cyclic forces and moments in various directions degrading the resistance and strength of soil. 'Cyclic P-Y Curves' can be applied for the computation of the fatigue because of the disturbance of adjoining soil near the casing string with cyclic and smaller deflections continuously than 'Static P-Y curves' because of the greater accuracy of results it can produce (API-RP-2A-WSD).

During the well completion phase after the cement grouting work, the full cement returns are ensured through visual inspection of wellhead especially at its cement return ports near the top of the wellhead clogged with the lead cement which is pumped first. This type of arrangement of the wellhead-conductor system is for a means of transfer of the external loads to the cement, further to the conductor housing and finally to the adjoining soil. This supports the sharing of the total loads on the system. But due to Hydrostatic Pressure, the weak surface hole formations in the cement slurry are broken down leading the cement level to drop in the annulus. The cement level drop also occurs due to the lack of adequate bond between the walls of the strings in the annulus leading to the effective cement level well below the actual cement level (Britton and Henderson, 1988).

The load transfer path created by the cement short fall can enhance failures due to the fatigue effects at the casing string connectors and housing transition zones. The wellheads devoid of this load transfer system are more resistant to static overloads and damage due to fatigue effects by setting the cement level well below the mudline (or seabed). The wellhead body after the displacement pivots about the suspension shoulder until it contacts the conductor string at its upper and lower position transferring the induced bending to the conductor string, thus load sharing is initiated. The loads should be high enough to cause the contact of the upper and lower positions with the given loading spectrum affecting the wellhead-conductor system flexibility positively contributing to the system fatigue life (Britton and Henderson, 1988).

From the above review, it can be inferred that in the conventional cement returned wellhead system is facing many fatigue issues, so an alternative material returns which can reduce the dis-advantages associated with cement has become more interest for the oil and gas industry.

3.0 METHODOLOGY

3.1 'ORCAFLEX' Modeling and Site Conditions Simulation

The methodology of finding the fatigue life of a subsea wellhead is based on Computer Simulation Techniques. A commercial software package of 'ORCAFLEX' was used to model the deep water rigid riser system along with the Riser Tensioners and the Semi-Submersible Drilling Rig. The developed model is then simulated in the particular Met-Ocean Environment of Kikeh Field, Offshore Sabah, East Malaysia in the South China Sea. It is one of the Deep Water field off the Continental Shelf of East Malaysia currently producing oil for some of the wells developed. The following figure 5 shows the Geographical Location and table 1 shows the Met-Ocean Data for the Kikeh Field under Study:

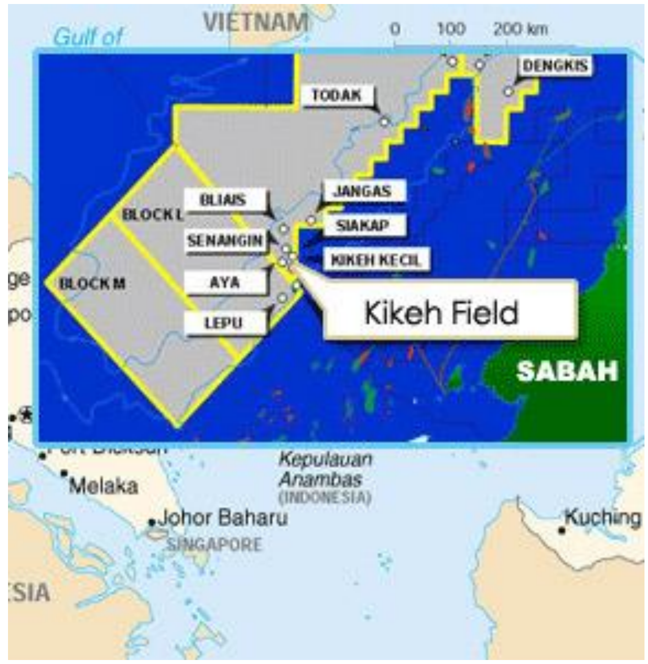

Figure 5: 'Kikeh' Field Geographical Location

The desired results of the analysis were the mean Bending Moment, mean Shear Force at lower flex joint.

3.2 3D CAD Modeling of the Wellhead-Conductor System

Three-dimensional (3D) Idealized Computer Aided Design (CAD) model of a typical wellhead-Conductor System in full scale with the subsea Soil Domain was developed using commercial CAD Software Package 'Creo Parametric 2.0'. The Wellhead and Conductor has been modeled as Pipe-in-Pipe system with solid models. The material return was ensured by filling the empty annuli with a solid model to resemble material returns. The isometric view of the assembly model has been shown in the following figure 6 and the close-up view of the wellhead-conductor system is shown in figure 7. The housing extension dimensions are assumed to suit the actual high pressure housing and conductor housing extension in applications in the offshore subsea wellbores. The surface and conductor casing strings are of standard sizes.

Table 1: 'Kikeh' Field Met-Ocean Particulars

Particulars	Description	Units
Water Depth	≈ 1300	m
Water Density	1025	kg/m^3
Sig. Wave Height	6	m

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Sig. Wave Period	11.7	s
Wave Spectrum	JONSWAP	
Wind Speed	19	m/s
Max. Current Speed	≈ 1.3	m/s

Figure 6: Isometric View of the Global Model of Wellhead-Conductor System with the adjoining Soil Domain

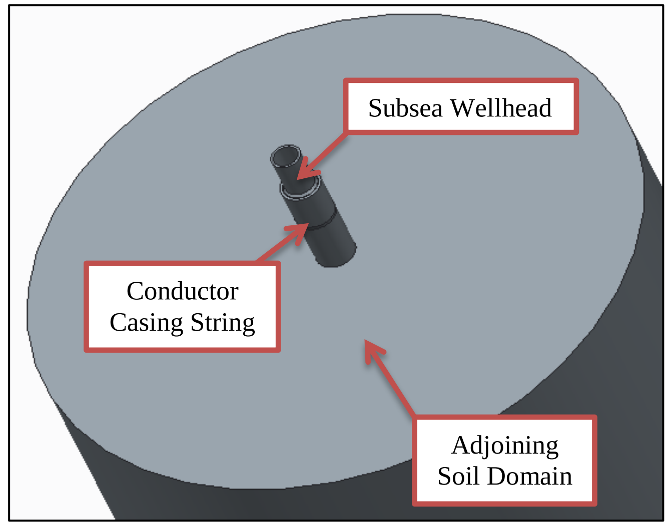

Figure 7: Close-up View of the Wellhead-Conductor System with the adjoining Soil Domain

3.3 Simulation in ANSYS

The results obtained from the 'ORCAFLEX' analysis is applied to the 3D CAD Model in ANSYS to simulate for the fatigue life results with full Marine-Grade Epoxy Returns than the Class G Portland cement for Offshore Oil Well Applications. The following figure 8 and figure 9 show the Finite Element Model of the Wellhead-Conductor System with the adjoining soil domain and detailed View of the type of finite element mesh generated by the automatic mesh generation system of the software. The statistics of the Finite Element mesh generated are:

<u>**No. of Elements:**</u> 255781
<u>**No. of Nodes:**</u> 58832
<u>**Type of Elements Generated:**</u> 8-Node Brick Elements and 6-Node Triangular Elements.

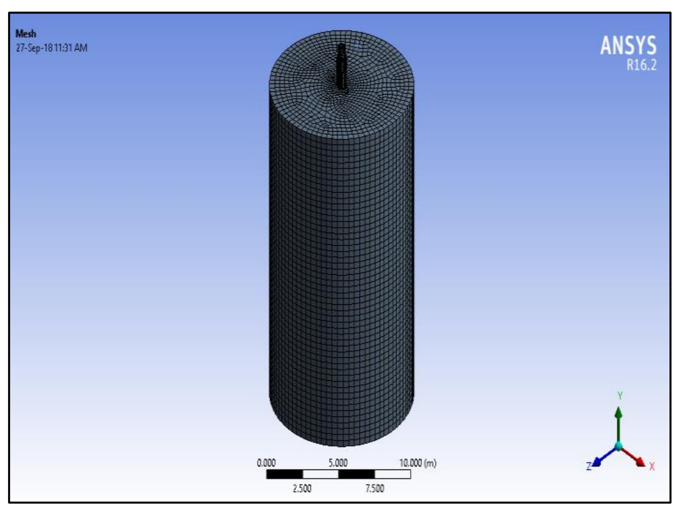

Figure 8: Finite Element Model of the Wellhead-Conductor system with adjoining Soil Domain

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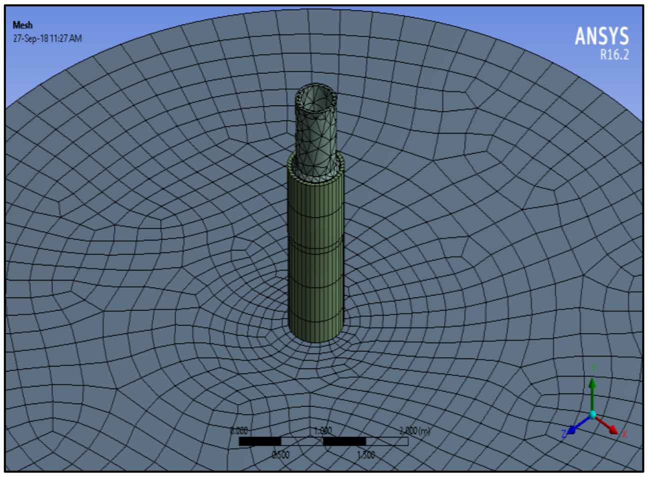

Figure 9: Close –up view Finite Element Mesh of the Wellhead-Conductor System with the adjoining Soil Domain at the Mudline

3.3.1 Material and Geometric Properties

The casing string material is taken as API Grade N-80 Steel whose mechanical properties are mentioned in the following table 2 and Mechanical Properties of API Class G cement grout and Marine – Grade Resin, both in fully cured condition is mentioned in subsequent tables 3 and 4 respectively.

Table 2: Mechanical Properties of Casing Material

Particulars	Description	Units
Yield Strength	551.6	MPa
Ultimate Strength	689.5	MPa
Poisson Ratio	0.5	-
Elasticity Modulus	200	GPa
Density	7850	Kg/m^3

Table 3: Mechanical Properties of API Class G Cement Grout

Particulars	Description	Units
Compressive Strength	58	MPa
Tensile Strength	10	MPa
Poisson Ratio	0.18	-
Elasticity Modulus	3.7	GPa
Density	3230	Kg/m^3

Table 4: Mechanical Properties of Marine-Grade Resin

Particulars	Description	Units
Compressive Strength	58	MPa
Tensile Strength	10	MPa
Poisson Ratio	0.35	-
Elasticity Modulus	2.24	GPa
Density	1180	Kg/m^3

The geometric properties of a 30 inch (762 mm) conductor with 1.5 inch (38.1 mm) wall thickness and 20 inch (508 mm) surface casing with 1.5 inch (38.1 mm) wall thickness apply. The annulus between the strings is provided with API Class G cement Grout (or Marine – Grade Resin) properties.

3.3.2 Boundary Conditions

The soil is a continuous domain and the wellbore extends all the way to the reservoir. Since only the wellhead near to mudline is subjected to excessive failures, a finite domain of soil adjoining the wellhead is taken for study. The boundary conditions are so applied to simulate the real world scenario. The outer limits of the soil domain and the bottom limit of the Casing Strings are fixed i.e. all the 6 DOF Motion has been constrained.

3.3.3 Loading on the Subsea Wellhead

The Subsea Wellhead is subjected to complex loading conditions like External Hydrostatic Pressure, Internal Drilling Mud Weight, Base Shear Force and corresponding Bending Moment, Effective Tension from the Riser and other Drilling Induced Loads. But among these loadings, the significant part contributing to its fatigue life reduction is the loads which are highly dynamic in nature. The near constant magnitude loads such as External Hydrostatic Pressure and Internal Drilling Mud Weight is negligible as far as fatigue damage is concerned. The total Bending Moment component is applied on the top of Subsea Wellhead which is considered as datum. The Total Shear Force is made to act on the idealized external surface of the wellhead. Pre-loading effects are ignored. Based on the Orcaflex simulation and considering the LMRP/BOP weight, the total bending moment and shear force acting on the system is calculated as follows:

Table 5: Mechanical Properties of API Class G Cement Grout

Particulars	Description	Units
Total Bending Moment	509	kNm
Total Shear Force	6.364	kN

3.3.3 Fatigue Life Estimation

The Fatigue analysis is conducted using an inbuilt 'Fatigue Tool' within the Static Structural Analysis Module of ANSYS. This tool generates a SN Curve based on the given ultimate tensile strength of the material whose fatigue life is of interest. The following are the input particulars for Fatigue Life Estimation:

Loading Type: Constant Amplitude Loading
Stress Ratio: -1 (Completely Reversed Loading)
Scale Factor: 3
Analysis Type: Stress-Life Approach
Mean Stress Theory: Gerber theory (Ideal for Ductile Materials)

3.3.4 Simulation Environment

In order to maintain the solution accuracy, real world data of subsea environment temperature of the 7°C is considered as per the general thermocline of the oceans. The Marine-Grade Resin is in completely cured condition with its maximum attainable strength in a given subsea environment.

4.0 RESULTS AND DISCUSSION

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The Fatigue Analysis Results for both full API Class-G cement returns and full Marine-Grade Resin returns conditions are given as follows:

Fatigue Life with API Class G cement: 7.23E4 cycles
Fatigue Life with Marine-Grade Resin: 7.23E4 cycles

From these results, it can be inferred that the fatigue life when full returns of marine-grade resin is ensured is equivalent to the life when full API class G cement returns. But full returns of cement never happen in practice even though the full cement returns are ensured at the cement return ports on the wellhead. Various reasons have been identified like shrinkage, less bonding strength, etc. through previous researches for the phenomenon occurring. So the actual top of cement or the cement level will be well below mudline which reduces the life of the Wellhead-Conductor System considerably by making it more vulnerable to dynamic loading effects. So, it can be proved that the fatigue life of the wellhead is subjected to increase when full returns of resin are ensured in the annulus of the wellhead-conductor annulus concentrating only on the top casing of the wellbore because of the action of the dynamic loadings is more near the mudline i.e. approximately up to a depth of 50 m from mudline (Reinaas, 2012)

5.0 CONCLUSION

From the modeling and simulation of wellhead, it can be stated that the resins can be considered as an alternative to the Portland cement. The Portland cement because of its poor ductility characteristics and subjection to dynamic loading effects gives up early after curing inside the annulus. This short- coming is overcome by the application of the resin based compounds which possess better ductility characteristics than the conventional Portland cement thus making it as an alternate ideal material for cementing wellbore top casings. The resin based compounds are already in application in recent past in offshore oil and gas wells but used only during the Plugging and Abandonment (P&A) phases of the well where Portland cement plugs are not effective enough to sustain the release of stray gases from an abandoned or de-commissioned wells.

6.0 RECOMMENDATIONS FOR FUTURE WORK

The fatigue analysis was conducted considering the dynamic effects of the Drilling Riser connected to the Subsea Wellhead. The dynamic load effects are considered transferred to the drilling riser through a transfer function. But other dynamic effects such as changes in internal hydrostatic pressure effects based on the changing level of fluid column inside the Riser is not considered in this study. But these effects also contribute to fatigue accumulation in smaller scale.

The soil taken for study is non-cohesive type which is of homogeneous **'Dense Sand'**. In real world, the soil type is subjected to vary from one site to another which can influence the fatigue effects. The soil types vary with the depth i.e. different soils layers at various depths. This can considered in future studies to expand the research on this field so that loss of well integrity issues can be completely avoided in the future drilled offshore deep water wells thus contributing to the safety and economics of the offshore deep water oil and gas exploitation attempts.

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