**Understanding the fluid-structure interaction from wave diffraction forces on CALM buoys: Numerical and analytical solutions**

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**Abstract**

This research fills the gap in understanding fluid-structure interaction (FSI) from wave diffraction forces on CALM buoys and cylindrical structures, based on the hydrodynamics with connections. Recently, there is an increased application of (un)loading marine hoses for Catenary Anchor Leg Moorings (CALM) buoy systems in the offshore industry due to the need for more flexible marine structures that are cost-saving, easier to install, and service. However, different operational issues challenge these hoses, like during hose disconnection. Also, the fluid behaviour was investigated based on the analytical and numerical models. The numerical modelling involves boundary element method (BEM) and Orcaflex line theory. Hydrodynamic analysis is conducted on the disconnection-induced load response of marine bonded hoses during normal operation and accidental operation under irregular waves. A comparative study on hose performance during normal operation and accidental operation is also presented. Results of statistical analysis on CALM buoy system shows good motion characteristics.

**Keywords:** Wave diffraction forces; Marine bondedHose; Ocean Waves Hydrodynamics; Disconnection-induced load; Catenary Anchor Leg Mooring (CALM) buoy; Fluid Structure Interaction

**Highlights**

* *Analytical solution on wave diffraction forces on CALM buoy systems.*
* *Understanding the fluid-structure interaction from wave diffraction forces*
* *Wave load and flow angle analysis as hydrodynamic loads on hose profiles on under irregular waves.*
* *Novelty in hydrodynamics on Lazy-S and Chinese-lantern configurations under normal and accidental operations.*
* *Wave diffraction analysis, and validation using statistical analysis in ocean environment.*

1.0 Introduction

In recent times, there has been an increasing trend in the application of marine bonded hoses in the ocean engineering and marine industry. This has resulted from the need for more flexible marine structures, easier to install, easier to service, and more cost-effective structures. Oil prospecting companies lost revenue due to the recent crash in oil price in 2016, which was similar to the one that occurred during the Gulf war in 1991 and following the recent COVID-19 pandemic in 2020. As such, the oil/offshore operators need to adapt more exploration activities with less cost. This adaptation subsequently influenced the increase in the application of these marine bonded hoses. These marine hoses have a short service life of about 25 years, although they are pretty reliable and, therefore, highly utilized. Some studies on the stiffness behaviour of hoses and CALM buoy motion are presented in literature (Amaechi et al. 2019a, 2019b, 2021a, 2021b, 2021c, 2021d, 2021e, 2021f). Also, buoy attachments can induce load response, such as the marine bonded hoses and mooring lines. These marine bonded hoses are designed for high-pressure ratings of 9 bar and 21 bar capacities. They have applications for loading and offloading purposes (Amaechi et al. 2021g, 2021h, 2021i, 2021j). The material development of marine tubular structures includes composite materials on composite risers (Amaechi et al. 2017, 2019c, 2019d, 2019e, 2019f, 2021k, 2021l, 2021m, Ye J. et al. 2021), and on marine hoses (EMSTEC 2016; Yokohama 2016; Trelleborg 2016, 2018; Continental 2020). Marine hoses are classified as single carcass and double carcass (Amaechi et al. 2021h, 2021i, 2021j, 2021n, 2021o, 2021p, 2021q). The primary function of marine hoses includes loading, transporting, transporting, discharging or offloading operations in the oil field (Amaechi et al. 2019a; Palmer et al. 2008; Guo et al. 2005; Bai & Bai 2005). A typical CALM buoy hose system is shown in Figure 1.

Generally, CALM buoys are offshore structures that display six degrees of freedom (6DoF) motions (Wang et al. 2015; Ryu et al. 2006; Duggal et al. 2005; Berteaux 1976, Bluewater 2009, 2011) and are usually restrained using mooring lines (Amaechi C.V. 2019a, 2019b, Wichers 2013; Ricbourg et al. 2006). They are also used in ocean environments, and their motions could be induced by water waves (Chandrasekaran 2015; Hirdaris et al. 2014; Sarpkaya 2014; Chakrabarti, 2001, 2005, 1972, 1975). Wave forces on offshore structures such as semisubmersibles (Bhosale 2017, Amaechi et al. 2021r, 2021s, 2021t, 2021u, Odijie et al. 2017a; 2017b; Zou 2014, 2013, 2008) and Wave Energy Converters (WEC) structures (Doyle et al. 2019, 2021; Gu et al. 2018; Pecher et al. 2014) are computed by considering both the inertial component and the drag component of the body as represented in Morison’s equation (Morison 1950; Amaechi et al. 2019a; Odijie 2016, Zhang et al. 2015). The complexities associated with the incident, scattered and diffusion wave potentials have been a subject of discussion in the offshore industry for quite some time. Useful applicable theories have been postulated to resolve some of these problems in theses works (Amaechi 2021n, Odijie 2016) and journal articles (Amaechi et al. 2021a,2021b,2021c,2019a). These forces direct some stress effects and lead to some motion instabilities due to complex potentials on the material (Brown & Elliot 1987, 1988, Brown 1985a, 1985b, Esmailzadeh & Goodarzi 2001). Some comparative studies have also been conducted based on configurations (Hasanvand et al. 2021, Amaechi et al. 2019b, 2021c, Pecher et al. 2014). Hasanvand et al. (2021) presented a comparative investigation on CALM and SALM terminals for operational and non-operational systems using the Persian Gulf Sea, by combining the techniques in the WEC model by Pecher et al. (2014) and CALM buoy model by Amaechi et al. (2019a, 2019b). Hasanvand et al. (2021, 2020) observed that the tensions generated at the PLEM of the SALM were less than the tension for the CALM terminal, and that for both cases, the connection point should be one critical consideration. Stability and wave forces are also important as they could also direct some bending forces on hoses, and deformations on these offshore structures. As such, the need to investigate the motion characteristics of the floating structure, the hydrodynamic performance, and the structural component comes up based on earlier studies (Lighthill 1979, Isaacson 1977, 1979, MacCamy & Fuchs 1954, Molin 1979, Garrison 1984, 1975, 1974, Rahman 1997, 1984). There are recent investigations on the hydrodynamic performance and wave-structure interaction (WSI) of offshore structures (Poguluri & Cho 2020, Jiang et al. 2020, Gao et al. 2015, Konovessis et al. 2013, Nallayarasu & Kumar 2017, Kannah & Natarajan 2006). Poguluri & Cho (2020) presented a numerical and analytical investigation on wave interaction for a vertical slotted barrier based on computational fluid dynamics (CFD) using turbulent Reynolds-averaged Navier-Stokes (RANS) model, as a complementary approach to compute the hydrodynamic performance. Konovessis D. et al. (2013) presented an investigation on the stability of offshore floating offshore structure generally while Esmailzadeh et al. (2001) focused on CALM systems by presenting an analytical investigation on the stability of CALM floating offshore structures. The latter considered the governing equations for the motion of floating structures based on nonlinear parametric ordinary differential equations of second-order and obtained conditions by applying Schauder’s fixed-point theorem. Huseby et al. (2000) conducted an experiment on higher-harmonic wave forces acting on a vertical cylinder for periodic Stokes waves on wave slope up to 0.24. Wang et al. (2014) presented an analytical investigation on the wave exciting forces acting on CALM buoy having skirts with experimental validation and found that the skirts affect it, particularly the exciting wave forces (Mavrakos et al. 1994, Vugts 1968, Newman 1966, 1996, Milgram et al. 1971). The model was developed using earlier experiments on truncated cylinders (Zhao et al. 2003, Zhang et al. 2016, ~~Liu et al. 2020~~, Li et al. 2019, Faltisen et al. 1995) and vertical cylinders (Feng X. et al. 2020, Chau et al. 1992, Raman et al. 1976, Chakrabarti 1972, Jacobsen 1949), similar to other studies on hydrodynamic loadings (Venugopal V. et al. 2008, Bhatta et al. 1995, 2003, 2007, Yeung R.W. 1981, Sabuncu & Calisal 1981, Zhou et al. 2014) and wave diffraction (Bhatta 2007, Wu 1991, Liu J. et al. 2016, Mei 1978). Bhatta and Rahman (1995) studied the wave diffraction and radiation by a floating vertical truncated cylinder and investigated the wave forces and moment. Malenica et al. (1995) presented on third-harmonic wave diffraction acting on a vertical cylinder, by using Green’s function. Huang et al. (1996) presented some analytical modelling on second-order wave diffraction acting on a truncated cylinder that is circular and under monochromatic waves and predicted locations for maximum elevation from the free surface based on linear wave theory and the nonlinear theories. Newman (1963, 1967) presented the wave forces on large structures, drift force and moments on ships in waves, before later presenting an investigation on the second-order wave forces acting on a vertical cylinder (Newman, 1996) and considered the finite depth formulation of MacCamy & Fuchs (1954) by using Bessel and Hankel functions. Different forces and loads act on offshore buoys. Zhou et al. (2014) investigated on wave and current induced seabed response on submarine pipelines. Sagrilo et al. (2002) presented a coupled dynamic technique on CALM systems based on diffraction equation and diffraction/radiation theory, and the study presented some profiles on assessment of the tension for the connections. Culla et al. (2007) presented a statistical moment prediction for a moored floating body that oscillated under irregular waves as a reference on CALM systems, using CPSP and SLSP perturbation methods. Generally, these studies are needed for accessing the strength and stability of various offshore structures, hull designs and components. Slender body connections mostly consider Morison’s theory, such as composite marine risers (Amaechi et al. 2017, 2019c, Wang et al. 2015, Pham et al. 2016, Toh et al. 2018), bundled hybrid offset riser (BHOR) systems (Webster et al. 2011, Bai & Bai 2005, Sparks 2018, Dareing 2019, 2012) and marine bonded hoses (Gao et al. 2021, 2018, 2017, 2016; Amaechi et al. 2019a, 2019b, 2019c, 2017). Generally, marine hoses are also layered structures, that are well bonded and have a helix reinforcement which is usually made of steel. Different types of marine bonded hoses include floating hoses, submarine hoses, reeling hoses and water hoses. These marine hoses are dependent on the support of an existing marine structure, such as the Single Anchor Leg Mooring (SALM) buoy, Catenary Anchor Leg Mooring (CALM) buoy, Floating Production Storage and Offloading (FPSO) or FSO tanker. However, these marine hose structures are connected using different configurations on single point moorings (SPM) terminals. Currently, there are different configurations, such as the Lazy-S, Steep-S, Chinese lantern, Conventional Multi-Buoy Mooring (CMBM) and the tandem mooring. Due to these different configurations and applications of these marine hoses, there are usually different operations and factors that result in hose failures and thus reduces the service life of the marine hoses. These include the impact of harsh waves and weather (environmental conditions), the hose-line clashing with another hose, the impact from an FPSO or a tug boat, the fail-safe failure during hose disconnection, the impact of marine hose on the mooring lines, the damage on the liner of the marine hoses, the disconnection-induced load creating large hose pressure, failure of the hose end valve (HEV), and failure of the marine breakaway coupling (MBC). There is a gap in the effect of disconnection on marine bonded hoses but this has also been an issue, as reported in the CALM buoy incidents (Jean et al. 2005, ABCNews, 2005). An example is the Girassol buoy whereby there was premature rupture of Girassol buoy’s mooring chains encountered an early fatal fracture despite being in operation for about 6 months which was attributed to the first free link of the mooring chain been out of plane thereby resulting to bending fatigue while still positioned in the fairlead of the chain support (Jean et al. 2005, Edwards et al. 2021), and this affected the system as an integrity check had to be carried out on the entire CALM buoy hoses. In another study by O’Sullivan (2003, 2002), some challenges on the prediction of different loads and responses that can interact thereby influencing the motion of offloading systems and particularly deep water CALM buoys were presented but the hose disconnection was not studied. Several researchers have investigated on the mathematical, numerical and experimental model tests on marine bonded hoses. Some studies on the performance behaviour of marine bonded hoses conducted theoretically show that hoses respond to different loadings such as vertical bending forces (Gao et al. 2021; Zhou et al. 2018; Quash & Burgess 1979; Brown 1984; Brown & Elliott 1988; O’Donoghue 1988; O’Donoghue & Halliwell 1990). Some earlier investigations include small-scale model tests (Pinkster & Remery 1975; Quash & Burgess 1979) and large scale tests (Brady et al 1974; Tschoepe & Wolfe 1981; Saito et al. 1980; Young et al. 1980; Brady et al. 1974; Lebon & Remery 2002). More recent investigations have involved more numerically investigations (Amaechi C.V. 2019a; Roveri et al. 2002; Edward C. et al. 2021; Lassen et al. 2014) and experimental validations (Duggal & Ryu 2005, Cozijn, et al. 2004, 2005, Cunff et al., 2007a, 2007b, 2008). Gao et al. (2021) and Zhou et al. (2018) presented theoretical analysis on the reinforcement layers of marine bonded hoses with spiral stiffeners subjected to internal pressure. Gao et al. (2018) presented an experimental and numerical analysis on marine composite rubber hoses that are ring-stiffened under internal pressure. Some other works include parametric studies on marine bonded hoses under internal pressure, multiscale modelling, progressive damage and compressive-tensile fatigue of the cords (Tonatto et al. 2020, 2019, 2017, 2016a, 2016b). Based on the load response, Lassen et al. (2014) presented a numerical modelling of marine bonded hoses with experimental tests on the helix and load-induced response. Amaechi et al. (2019) presented a submarine hose model using finite element model in Orcaflex and hydrodynamic model in ANSYS AQWA and validated the model analytically. However, these studies did not also consider any accidental operation. Thus, this present study contributes to the knowledge by investigating the disconnection of these marine hoses and their load response effect under different wave loadings, configurations, and environmental conditions.

In this article, numerical and analytical solutions to wave diffraction forces on CALM buoy hose system with disconnection-induced load response during different operations have been conducted. Hydrodynamic analysis is carried out on the disconnection-induced load response of marine bonded hoses during normal operation and accidental operation under irregular waves. The marine hoses investigation is conducted on CALM buoy system carried out on Chinese Lantern and Lazy-S configurations. In Section 2, some mathematical theories and governing equations including wave theory, boundary element method (BEM) and catenary equations. In Section 3, numerical modelling carried out is presented including the materials and methodology applied. In Section 4, the results and discussion are presented on this study. This study also investigates the loads response on marine bonded hoses attached to a CALM buoy, under disconnection-induced loads. A comparative study on normal operation and accidental operation is also presented, with details on the hose performance, and some statistical analysis on hose parameters for the CALM buoy hose system.



Figure An operational floating CALM Buoy showing attached hawsers and floating hoses (Courtesy: CultofSea)

2.0 Theoretical Modelling

In this section, some theory and the governing equations on this study are presented.

**2.1 Theory & Governing Equations**

### 2.1.1 Wave Theory

The governing equations used in the Orcaflex algorithm are based on applying Newton’s 2nd law of motion, Morison’s equation, JONSWAP spectrum equation, hydrodynamic equations, Navier-Stokes, and buoy stability equations. For irregular waves, the flow considered is turbulent, therefore neglect the forces due to elasticity and the surface tension.

JONSWAP wave spectrum accounts for any imbalance in the energy flow within the wave system. Equations (50) is from Pierson-Moskowitz spectrum (Pierson & Moskowitz 1964), which is then applied as the JONSWAP spectrum (Hasselmann et al. 1973). It was modified to take care of regions with geographical boundaries to limit the fetch regarding wave generation. The JONSWAP relationship is given as Equation (1);

(1)

Where denotes the angular frequency, denotes the peak angular frequency, η denotes the incident wave amplitude, g denotes gravitational constant, γ denotes the peak enhancement factor, while the other parameters σ, σ1, σ2 are data items used by the solver. These are also dependent on the significant wave height, Hs and the period at zero-crossing, Tz.

Based on the forces on the risers, the Morison’s equation was used, as it considers the wave forces moving onto a cylinder due to the body’s relative motion when immersed in the fluid (Morison et al. 1950). This is represented as the summation of the Froude-Kyrov force FFK, the hydrodynamic force of the fluid, FH, and the drag force, FD. Morison’s equation is expressed in Equation (2);

(2)

where V is the volume of the body, *Vr* is the relative velocity of fluid particles, A is the area of the body, *C*a is the added mass coefficient, Cd is the drag coefficient, Cm is the inertial force coefficient and D is the diameter of the body. The equation can be simplified, as the fluid force is equal to the sum of the drag force and the force of inertia, thus Equation (3);

(3)

The global design conducted in this investigation was carried out under irregular wave, and the damping was calculated as presented in the revised Morison Equation (Morison et al. 1950).

*(4*)

### 2.1.2 Boundary Element Method (BEM)

Two sets of numerical models were utilized in the present research; a Finite Element Model (FEM) cum a hydrodynamic model based on Boundary Element Method (BEM) which was formulated using potential flow theory, developed in ANSYS AQWA (ANSYS 2017a, 2017b). While the FEM uses differential equations in its solutions, BEM uses integral equations in its solutions. BEM is used because of the integral functions and source potentials, thus it reduces the integral equations. Secondly, the BEM considers only the surface of the body during meshing, and reduces the dimensions by first-order. This reduces the size of the problem and is convenient for solving finite elements occupied within infinite space, as such far distances are not considered. The motion responses and force parameters for this CALM buoy were calculated using this model. The body’s motion is relative to the submerged volume of the CALM buoy, which is the wetted surface, *sw*. As the CALM buoy hull oscillates, there are changes in the surface area, and it experiences some deformation (Odijie 2016, Amaechi C.V. et al. 2019a, 2021c; Odijie and Ye 2015). However, to explain the dynamic effect of fluid structure interactions on the stability (balance) and strength (deformation) of floating bodies like CALM buoys, a complete overview of diffracted and radiation wave conditions is needed. In this analysis, hydrodynamic relationships were used to evaluate flow pressure and force quantities and to correlate different variables and correlations. These are founded on the fluid’s source potential resolution of a free-floating body having 6DoF. When considering an impermeable CALM buoy hull having an incompressible, irrotational and inviscid fluid, the velocity field of the fluid flow domain satisfies the Laplace definition expressed in Equation (5); where denotes the velocity potential and demotes the Laplace operator.

(5)

Considering the rectangular coordinate system (x.y,z), the Laplace identity in Equation (5) becomes:

(6)

While, in a cylindrical or polar coordinate system (r,ϴ,z), the Laplace identity in Equation (5) becomes:

(7)

Based on the application of the boundary conditions at the seafloor, at any submerged surface of the buoy’s hull, and the free surface, then Equation (8) can be obtained as computed (for instance, choosing the seafloor).

(8)

The Bernoulli’s equation correlates the fluid’s velocity potential of a flow stream to the hydrodynamic pressure (*Phyd*) given in the relationship in Equation (9);

(9)

where h denotes the draft height (that is the height of the buoy’s hull from its submerged area), t denotes time and denotes the seawater density.

Wave propagating direction (θ)

Wave elevation. (

**X**

**Z**

|  |
| --- |
| **Wave surface view**  **Y** |
| **Underwater view**  Figure 2 Wave definition on a floating CALM buoy |

The complexities associated with resolving velocity potential around the boundaries described in the equations above can be resolved using various wave theories. The total wave potential is expressed as a sum of the incident, diffraction, and radiation wave potentials in linear normal wave theory (Airy wave), as given in Equation (10);

φ= φI φS + φR (10)

Where φR denotes the radiation potential, φS denotes the scattered wave potential and φI denotes the incident wave potential.

On the XY plane, both the regular wave and the irregular wave have an elevation that forms an angle. The ‘wave direction' is the term used to describe this angle, as illustrated in Figure 2.

### 2.1.3 Hydrodynamic Equations

Along the horizontal plane, the hydrodynamic force that acts on a body is represented in Equation (11), can be mathematically written as;

{Fhyd} =} +} + [K]{*x*} (11)

Where {x} denotes the motion vector, [K] denotes the stiffness matrix, [C] denotes the structural damping matrix, [M] denotes mass matrix of the hull while {Fhyd} denotes the hydrodynamic force vector (Odijie 2016, Odijie & Ye 2015a, Amaechi et al. 2019a).

Since the hydrodynamic exciting forces are a product of the wave potential, which is a function of incident waves for each unit amplitude, they were derived from the wave exciting force.

= -ρ (ni *ds,*  (12)

The expression for the wave exciting forces is represented in Equation (12), where{W} denotes the velocity field vector of the steady flow; *fw* denotes the wave oscillating frequency, *ui*denotes the incident diffraction wave potentials per unit amplitude; *ui*denotes the diffraction wave potentials per unit amplitude; *ρ* denotes the density of sea water; and *i* denotes DoF.

### 2.1.4 CALM Catenary Equations

The governing equations used in the calculation of the statics for the mooring lines is the Catenary equation. It is also applied in other applications like Steel Catenary Risers (SCR) and cable structures (H. Max Irvine 1981, Bai & Bai 2005, Amaechi et al. 2019a). In the case of mooring lines, which suspends from the PC Semi to the anchor on the seabed, and thus take up a catenary shape that is approximate, and is defined by the following equation (13), where w denotes weight per unit length and H denotes the tension along the horizontal component.

13)

)

)

)

The catenary equations for CALM systems is presented in Equations (13)-(19), where h (or z) denotes the height above seabed, s denotes the arc length, x denotes the section length of the mooring cable, ws denotes the submerged weight, TH denotes the tension along the horizontal component, Tv denotes the tension along the vertical component, T denotes the tension component along the plane, V denotes the body’s volume and W denotes the body’s weight. The schematic of catenary mooring system of CALM Buoy is illustrated in Figure 3.

)

)

)

**h**

**θ**

**s**

**TH**

**TV**

**T**

**ws**

**X**

**Z**

**TH**

Figure Schematic of Catenary Mooring system of CALM Buoy under static state

### 2.1.5 Marine Hose & Riser Equations

Considering the motion of the hose to be in the direction perpendicular to the Mean Water Level (MWL), then the equation of motion in Equation (20) exists, as presented by Bishop & Johnson (2011); (1960), where the load, Q depends on the weight of the hose, w and the radius of the hose, r located on the sea of sea depth, h and EIz is the bending stiffness of a general section of hose.

*(20)*

**Vo**

**Ho**

**B**

**Fo**

**To**

**Mo**

**A**

**θ**

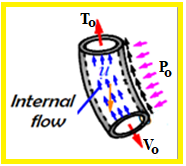


Figure Schematic of short segment of riser hose string

Considering a short segment of the hose-string, as given in Figure 4, it can be easily deduced from the governing differential equations (Sparks 2007;0 Dareing 2012). The resultant force, T0 is located at point A on the arc length, s. The horizontal force, H0 is from the origin, O of the Cartesian Coordinate system and the vertical force is V0. The external pressure Po, acts on the body of the hose whilst the external force, Fo acts at the top section of the hose string. Due to the motion of the hose string different for each time duration, thus it will make different angles between the axis of the hose string and horizon, ϴ(i=1,2,3,..n). The amount of times it uses for a full wave cycle is given by n. Betwixt the horizontal and the resultant force’s direction makes an angle given by ϴ0. The submarine hose being modelled is considered as a beam under tension, as shown Figure 5.

Z

X

Y

Z

Y

X

Line Nodes

Contact Surface

Submarine Hose

Splined Line Segment

Spline

Line End Axes

Figure Submarine hose segment showing spline line and nodes

Hose curvature is given by the inverse of the minimum bending radius (MBR), as:

(21)

The limit of permission for the bending radius is subject to the stiffness, EI, becomes:

(22)

Based on the hose content or marine riser content, the pressure field acting on the internal fluid column is closed and in equilibrium with the weight of the internal fluid. The lateral pressures acting on the pipe wall are equal and opposite to those acting on the internal fluid. Hence, by superposition and *addition* of the two force systems, those lateral pressures are eliminated. However, the supposedly axial tension in the fluid column denoted as -*p*i*A*i remains; where *p*i is the internal pressure and *A*i is the internal cross-sectional area of the pipe (Sparks 2018, 2007). This leads to the equations for the effective tension *T*e and apparent weight *w*a of the equivalent system.

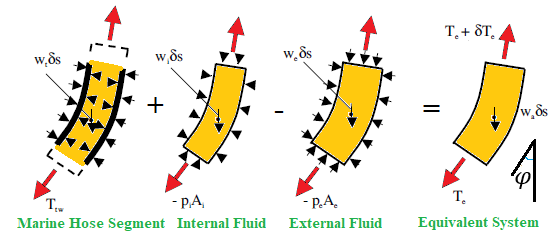


Figure The equivalent force system of Marine Risers/Hoses for internal fluid and external fluid flows

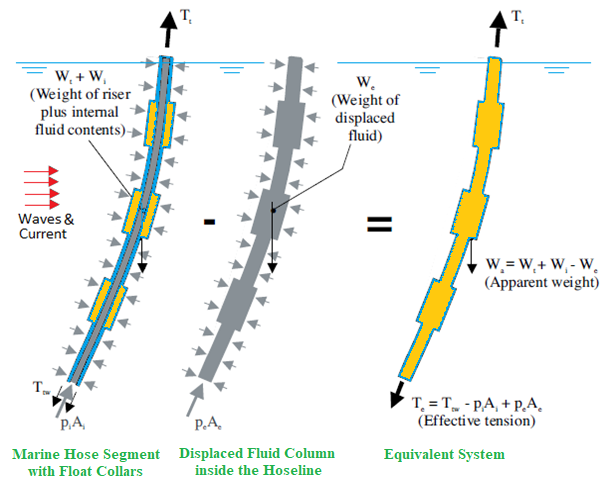


Figure Schematic of force loads and pressures acting along a hose-string segment or a long riser segment

When external pressure *p*e is also present, it can be approached in a similar fashion. Both lateral pressure effects are removed by adding the force systems acting on the pipe section and the internal fluid, then subtracting the force system operating on the displaced fluid. When external pressure *p*e is also present, it is approached similarly, as depicted in Figures 6-7.

The force systems operating on the pipe section and the internal fluid are added together, and then the force systems are subtracted. In Figures 6-7, and *w*t denotes the equivalent system’s weight, *w*e denotes the weight of the displaced fluid column, *w*a denotes the weight of the internal fluid column while *w*i denotes the weight per unit length of the tube.

The effective tension, denotes the axial tension calculated at any point of the riser by considering only the top tension and the apparent weight of the intervening riser segment (Sparks 2018, 2007, Dareing 2012, 2019; Amaechi et al. 2019). The equations for the effective tension *T*e can be expressed as in Equation (23)-(24).

(23)

(24)

For the apparent weight *w*a, that can then be represented by Equation (74)

(25)

The resolution of forces along the axial direction of an element of length *ds,* can be represented as:

(26)

Considering the resolution of forces along the vertical plane of an element of length *ds* at small angles to the vertical, yields:

(27)

### 2.1.6 Orcaflex Line Theory

The Line theory as depicted in the line theory model in Figure 8 was applied for the Finite Element Model (FEM) in Orcaflex 11.0f. It was modelled by utilising the nodes on the hoses and mooring lines, as shown in Figure 11. It applies some discretization for the CALM buoy, to ensure less computational time and resources (Orcina 2014, 2020, 2021, Amaechi et al. 2019a, 2019b).

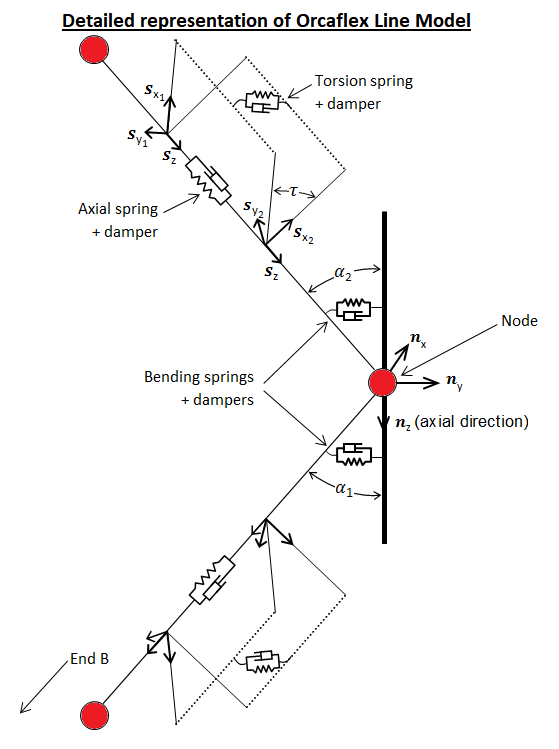
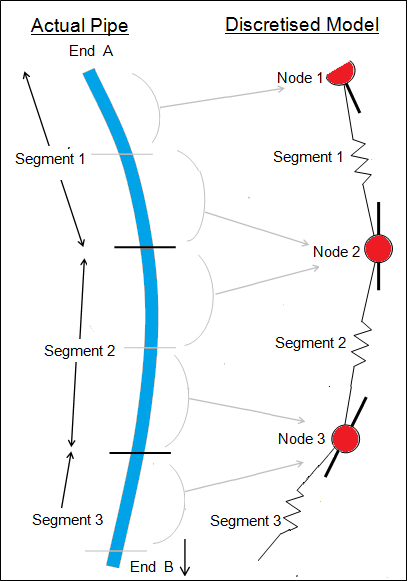


Figure 8 Orcaflex line model (Adapted with permission, Courtesy: Orcina, 2014, 2020)

**2.2 Analytical Model**

The analytical model for the CALM buoy having skirt is depicted in Figure 9. Based on the problem formulation, the floating buoy of mass m is considered having a draft denoted as T, radius of the buoy denoted as a1 and radius of the buoy’s skirt is a2. The water depth is denoted as d, and is assumed to be constant. The skirt has a thickness that is equal to S2-S1, where S2 denotes the distance between the top of the skirt and the seabed, while S1 denotes the distance between the bottom of the skirt and the seabed.

Some assumptions that were considered include that the fluid is inviscid, incompressible and irrotational flow. For the model, two reference frames acting from the origin locus at the seabed, were considered. These are the cylindrical polar coordinates (r,θ,x) and the cylindrical cartesian coordinates (x,y,z), acting along the vertical axis in z-direction and the horizontal axis in x-direction. To appreciate the force field induced on the buoy by considering a regular wave having a wave height H, and propagates along the horizontal plane in x-axis with wave frequency ω. Thus, the total velocity potential can be represented using cylindrical polar coordinates (r,θ,x), for the diffracted waves and the incident waves, as:

28)

However, the wave frequency is related by dispersion with the wave number k as in:

29)

Where the value of , k denotes the wave number and g denotes the acceleration due to gravity.

θ

O

r=a1

r=a2

Ω3

S2

O

T

d

Mean Sea Level (MSL)

**(a) Buoy Top Cross-section**

**(b) Buoy Side Plan Cross-section**

Ω1

Ω2

S1

z

x

x

y

Figure 9 Illustration of CALM buoy with skirt and wave diffraction

The velocity potential can be represented from solving the Laplace equation and obtaining the solution for the entire fluid domain which will satisfy the following boundary domains:

30)

31)

32)

33)

An additional boundary condition considered is the radiation condition for the outgoing waves on the CALM buoy system, thus:

34)

To linearize the problem, the fluid pressure *p(r,θ,z,t)* can be obtained by applying the unsteady linearized Bernoulli’s Equation, where ρ denotes the seawater density and t is the time for the wave oscillation in the polar coordinate.

35)

The resultant wave excitation moment and the resultant wave excitation forces that acts upon the floating CALM buoy can be written as

36)

37)

38)

Herewith, the CALM buoy’s mean wetted surface denoted by *SB*, the vertical position of the Centre of Gravity (CoG) is denoted by zg, the x- component of the outward unit normal vector is denoted by nx while the z-component of the outward unit normal vector is denoted by nz*.*

As depicted in Figure 9, the fluid domain has been subdivided into three fluid regions represented by Ω1, l=1, 2, 3, as depicted in Figure 9. The relationship for the velocity potential φ1, that satisfies the Laplace Equation and Equations (30), (31), and (34) can be written to be:

39)

Within the exterior fluid region Ω1 , the velocity potential around can be written as:

40)

whereby, represents the Bessel function of first kind and order m; represents the modified Bessel function of second kind of order m, while represents its first derivative; represents the Hankel function of first kind of order m, while represents its first derivative.

It is noteworthy to state that = -ik, whereby satisfies the expression in Equation (41):

41)

Within the interior fluid region Ω2, the solution for the velocity potential can be written as:

42)

43)

where denotes the modified Bessel function of first kind and order *m*.

Thus, within the fluid region Ω3, the velocity potential can be written as:

44)

45)

Whereby, represents the Hankel function of second kind of order m, and represents its derivative.

The boundary conditions for continuity of the potential function at , are given as:

46)

47)

Considering the both the conditions that are needed for the continuity of the velocity in addition to the kinematical boundary conditions at , these boundary conditions can be written as:

48)

The body boundary conditions at , can be expressed as:

49)

Using the method by Wang D. et al. (2014), both sides of Equation (46) are multiplied by cos(, Equation (47) and Equation (49) by and Equation (48) by , and next integrating the resultant equations all through each of the regions of validity. Based on logistics on the numerical implementation of the method, some truncation of series to limit it is necessary. The infinite series are truncated after N1+1 terms within region Ω1, N2+1 terms within region Ω2, N3+1 terms within region Ω3, respectively. By utilising the trigonometric functions’ orthogonal characteristics, the solution can be obtained for the unknown coefficients of *Amn,Bmn, Cmn, Dmn*.

3.0 Numerical Modelling

**3.1 Model Description**

CALM buoys are offshore structures that display 6DoF, as depicted in Figures 12-13. CALM buoys are designed as an application of single point mooring (SPM), by considering industry specifications. For mooring of the floating structures, the design considerations used are from industry specifications API RP 2SK (API 2005), ABS (ABS 2021) and DNVGL-OS-E301 (DNV 2015a, 2015b, 2016). They are also used in ocean environments and their motions could be induced by water waves. The global loads are based on DNVGL (2017). Wave forces on marine structures are computed by considering both the inertial component and the drag component of the body as represented in Morison’s equation. This is detailed in subsequent sections herein.

**3.2 Methodology**

The methodology applied is a coupled dynamic modelling of ANSYS AQWA and Orcaflex, as presented. A schematic sketch of this numerical procedure is depicted in Figure 10. The methodology for the analysis was performing the hydrodynamic analysis of the floating buoy using ANSYS AQWA R2 2020. The amplitude values for the motion called RAOs are then loaded into Orcaflex 11.0f. The method of analysis is based on the effect of disconnection-induced loads on the marine hoses, as such the motion of the buoy was also investigated. The numerical procedure was conducted in two stages. The first stage was the hydrodynamic analysis or diffraction analysis, and the second stage was the finite element analysis (FEA), as shown in Figure 10. The model involves the generation of the RAOs and then using the fluid hydrodynamic pressure to input the RAOs. These RAOs are computed at a variation of phase angles and can be exported in two ways: either by using ANSYS AQWA beta mode or loading the generated RAOs in a text file that is scripted using FOTRAN language in ANSYS APDL. This is then loaded into the finite element analysis as a load mapping processing.

**RAO plots**

**Pressure and motions**

**and motions**

**Diffraction Analysis**

**Finite element analysis**

**Tensions**

**Stress**

**Bending & Curvature**

**Deformations**

**Forces**

Figure Schematic chart for the numerical analysis

Load transfer in ANSYS beta mode or using FORTRAN

**3.3 Panel Hydrodynamic Model**

The modelling of hydrodynamic aspects includes the development of the panel hydrodynamic model for the CALM buoy. This has been presented in sea environment as in Figure 11. It was utilised in the hydrodynamic investigation in ANSYS AQWA R2 2020. The RAO values obtained were from a free-floating CALM buoy without any mooring lines or marine bonded hoses attached to the CALM buoy.

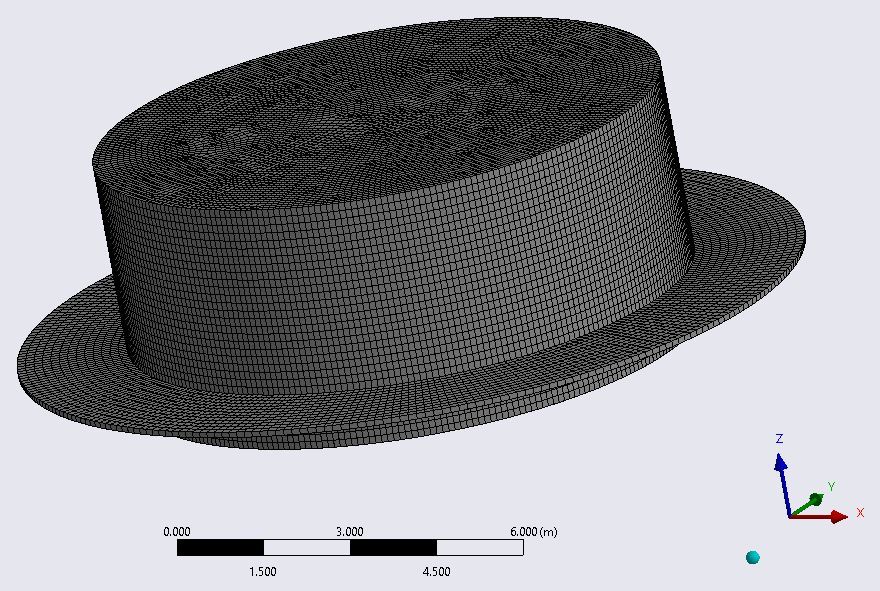


Figure Hydrodynamic Panel Model of CALM buoy (in ANSYS AQWA R2 2020)

**3.4 Finite Element Model**

As illustrated in the line theory model in Figure 8, the Line theory was applied for the Finite Element Model (FEM) in Orcaflex 11.0f. It was modelled by utilising the nodes on the hoses and mooring lines, as shown in Figure 12. It applies some discretization for the CALM buoy, to ensure less computational time and resources (Orcina 2014, 2020, 2021). The submarine hose model was configured as Lazy-S. The statics calculation for the submarine hose was done by B-splines as presented in Figure 5. The model setup for a similar study has been given in the literature (Amaechi et al. 2019a, 2019b).

******

Figure 12 FEM of CALM Buoy system in Lazy-S showing nodal axes in Orcaflex

**3.5 Materials**

The materials applied in this numerical model are presented in this sub-section.

### 3.5.1 Buoy

The cartesian coordinate system of the floating buoy is presented in Figure 13. The buoy's body was 10m in diameter, and a draft line was considered in the modelling. The model was developed by fitting the floating characteristics of the buoy in the FEM, as shown in Figure 14. The details on the buoy parameters are presented in Table 1.

Table Parameters for the Buoy

|  |  |  |
| --- | --- | --- |
| **Particulars** | **Value** | **Unit** |
| Height | 4.40 | m |
| Draft size | 2.40 | m |
| Main body diameter | 10.00 | m |
| Skirt diameter | 13.87 | m |
| Buoy Mass | 198,762.00 | kg |
| Water Depth: Lazy-S | 100.00 | m |
| Water Depth: Chinese-Lantern | 26.00 | m |

Roll

Yaw

Z

X

Y

Pitch

Sway

Surge

Heave

Flow Direction

Figure Motion components showing coordinates and six degrees of freedom of a floating buoy

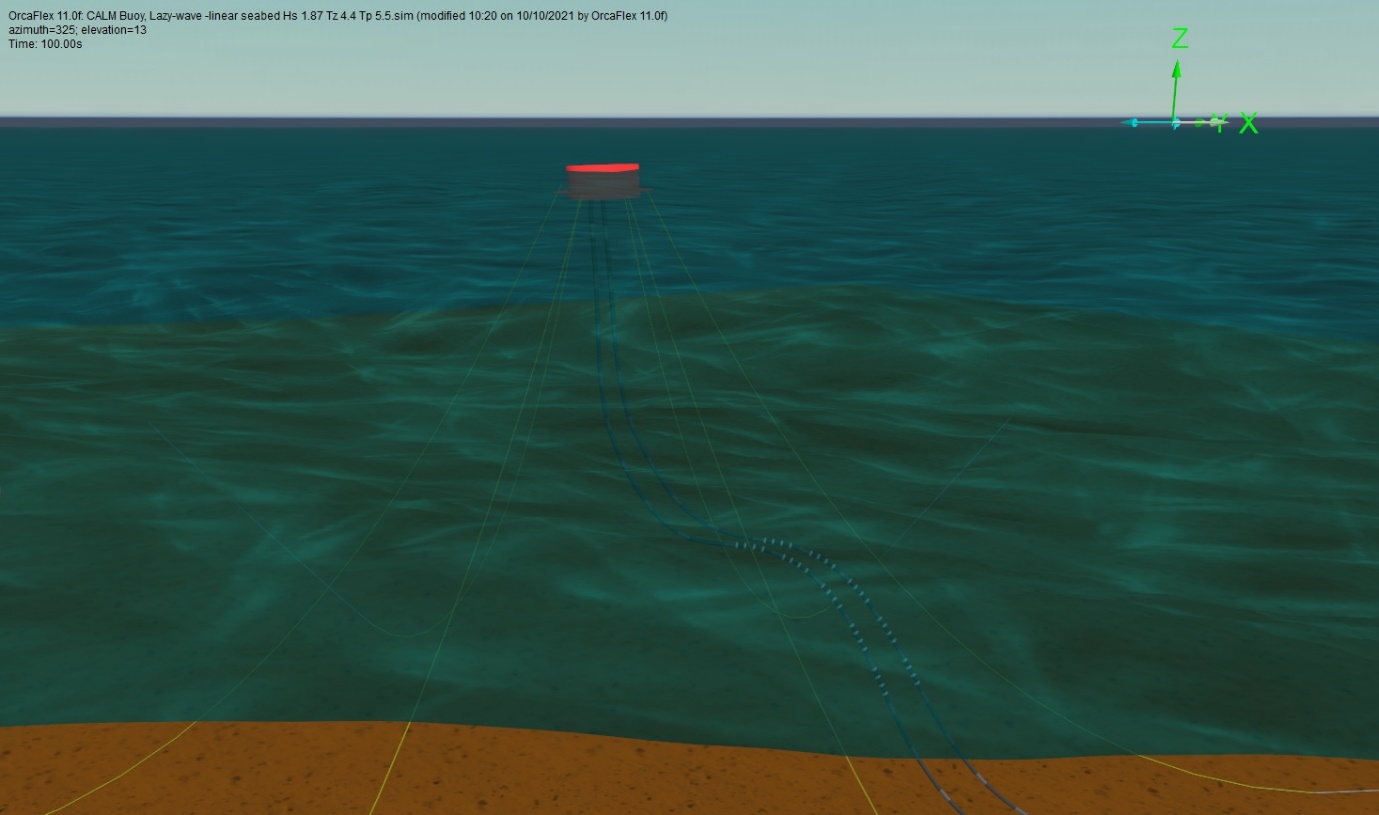


Figure 14 FEM in Orcaflex showing floating buoy model with details on moorings and marine bonded submarine hoses

### 3.5.2 FPSO Tanker

The FPSO applied in this model is an FPSO tanker that can be used for offloading and discharging operations, as presented in the Orcaflex model shown in Figure 15. The length of the FPSO is 103 m, and it is designed with attachments couplings for the floating hose and hawsers. Details of the FPSO parameters are presented in Table 2. The calculations on the FPSO are the primary motion for the 6DoFs, wind load, current load, 1st order wave loads, 2nd order wave drift load, wave drift damping, damping, and added mass. The hydrodynamics of the floating FPSO was designed using vessel theory (Orcina, 2020). The ship-shaped FPSO has six degrees of freedom (6DOFs), as presented in Figure 13.

Table Parameters for the FPSO

|  |  |  |
| --- | --- | --- |
| **Parameters** | **Value** | **Unit** |
| Length | 103.00 | m |
| Draft | 6.70 | m |
| Height | 13.40 | m |
| Width | 16 | m |

**Heave**

**Yaw**

**Surge**

**Roll**

**Sway**

**Pitch**

Figure The 6DoF motions for the FPSO

### 3.5.3 Floats

The floats are made from materials that can help them to float and ensure good buoyancy. The floats were designed differently depending on the application. The float on the submarine hoses and the floating hoses were slightly different sizes but the same materials, as given in Table 3. An illustration of buoyancy floats is shown in Figure 16.

*Table 3 Parameters for the Float*

|  |  |  |
| --- | --- | --- |
| **Particulars** | **Value** | **Unit** |
| Inner Diameter | 0.799 | m |
| Outer Diameter | 1.23 | m |
| Metal Part Material | Stainless Steel | --- |
| Net Buoyancy | 280 | kg |
| Type of Float | Standard bolted-type float | --- |
| Weight in Air | 102 | kg |
| Shell Material | Polyethylene | --- |
| Pitch of Float | 2.00 (depends on section) | m |
| Filling Material | Polyurethane foam | --- |
| Number of Floats | Depends on configuration | --- |
| Length of Float | 0.60 | m |

Hose Diameter

Marine Bonded Hose

Float Length

Float

Float’s Pitch centre-to-centre

Float Diameter

figure illustration of floats on a marine bonded hose

### 3.5.4 Marine Breakaway Coupling (MBC)

The MBC was modelled to have 3 sections and was attached to the floating hose. The outer diameter (OD) of the MBC is 0.735m while the inner diameter (ID) of the MBC is 0.5m. It was made of steel material with a material density of 7,850kg/m3. MBC can be connected between two hose sections at strategic locations close to the hose end nearer to the service tanker or where needed on the marine hose, such as on reeling hoses and floating hoses (EMSTEC 2016, Yokohama 2016, MarineBreakawayCouplings 2018, TechFlowMarine 2021, GallThomson 2018). Typical MBC is shown in Figure 17.



**(a)**

**(b)**

Figure Typical: (a) Marine Breakaway Coupling on a floating hose and (b) a Petal Valve MBC (Courtesy: Gall Thomson)

### 3.5.5 Floating Hose

The floating hose modelled in this investigation is connected to a manifold, as illustrated in Figure 18. The hose has an outer diameter of 0.64m and an inner diameter of 0.5m, and a mass per unit length of 182.1 kg/m. It was designed using GMPHOM OCIMF (OCIMF 2009) and API 17K (API 2017) industry standards with a limit consideration on the minimum bending radius of 2.0m. A typical floating hose is shown in Figure 17(a).

Hose Length, L

Manifold Angle

Submarine Hose

MSL

Hose Axis

Floating Hose

Buoy

Figure Illustration showing loadings on the floating hose and submarine hose attached to the floating buoy

### 3.5.6 Submarine Hose

The submarine hoses were designed using Lazy-S configuration as depicted in Figures 19. The submarine hose's inner diameter (or bore) is 0.49m, while the outer diameter is 0.65m, as detailed in Table 4. The length of the submarine hose was 162.63m, and connected from the Pipeline End Manifold (PLEM) to the underneath manifold of the CALM buoy, as illustrated in Figures 18. The hoses were designed for fully filled conditions and tested with both seawater and oil. The seawater and the oil densities are 1,025 kg/m3 and 825 kg/m3, respectively.

Table Array of the submarine hose-string for 3 divisions (or sections)

|  |  |  |
| --- | --- | --- |
| **Parameters** | **Arrangement** | **Value** |
| **Hose Division 1** | | |
| **Item Detail** | First-off Buoy with Float collars | |
| **Bending Stiffness (kNm2)** | S1 (fitting) | 10,000 |
| S1 (reinforce end) | 120 |
| S1 (body) | 78 |
| S1 (fitting) | 10,000 |
| **Hose Inner Diameter (m)** |  | 0.490 |
| **Mass (kg/m)** |  | 239 |
| **Length (m)** |  | 8.49 |
| **Hose Division 2** | | |
| **Item Detail** | Mainline without Float collars | |
| **Bending Stiffness (kNm2)** | S2 (fitting) | 10,000 |
| S2 (end) | 98 |
| S2 (body) | 78 |
| S2 (end) | 98 |
| S2 (fitting) | 10,000 |
| **Hose Inner Diameter (m)** |  | 0.490 |
| **Mass (kg/m)** |  | 495 |
| **Length (m)** |  | 9.02 |
| **Hose Division 3** | | |
| **Item Detail** | First-off PLEM with Float collars | |
| **Bending Stiffness (kNm2)** | S3 (fitting) | 10,000 |
| S3 (end) | 98 |
| S3 (body) | 78 |
| S3 (reinforce end) | 120 |
| S3 (fitting) | 10,000 |
| **Hose Inner Diameter (m)** |  | 0.490 |
| **Mass (kg/m)** |  | 239 |
| **Length (m)** |  | 8.49 |

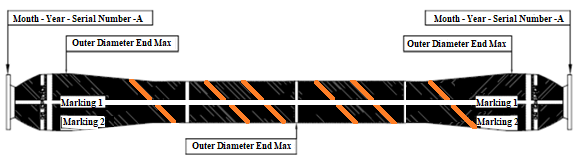


Figure Hose segment of 12m in length, showing descriptions with markings

### 3.5.7 Hawser

Two hawser cables were designed that connect the floating buoy to the FPSO tanker, shown in Figure 20. The outer diameter 0.0765m, with mass per unit length of 5.25kg/m. The hawser is a thick cable, because the principle behind its manufacture is with three-rope strands twisted together left-handed in three ways to have nine strands. The hawser is designed with polyamide materials. It is a thick rope with flexible properties. The weight was considered in setting up the model for the single point mooring (SPM).

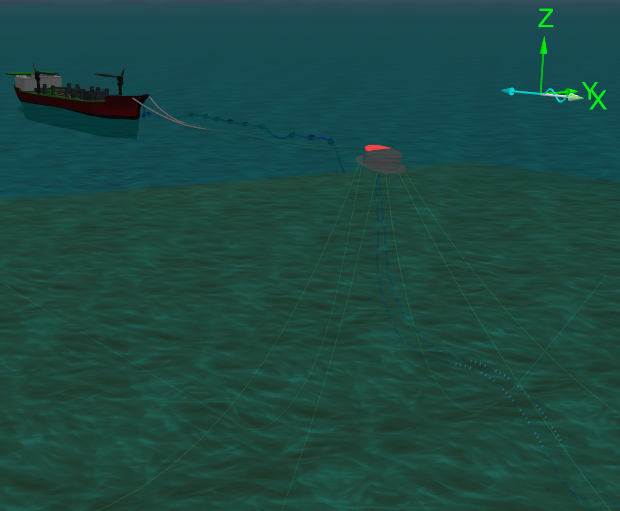


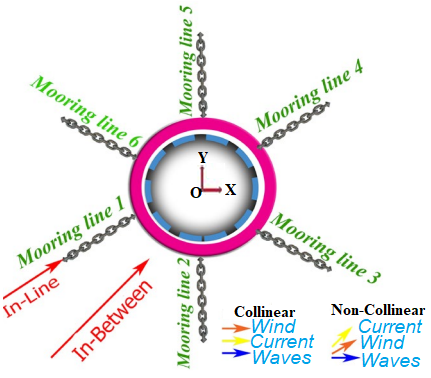
Figure The FPSO tanker attached to the CALM buoy offloading system showing hose disconnect (in Orcaflex 11.0f)

### 3.5.8 Mooring lines

The CALM buoy model was moored using six (6) mooring lines, arranged as shown in Figures 20-21. The materials for the mooring lines were a composite arrangement of steel chain and polyester rope, as detailed in Table 5.

*Table 5 Parameters for the Moorings*

|  |  |  |
| --- | --- | --- |
| **Particulars** | **Value** | **Unit** |
| Type of Mooring Configuration | Catenary Mooring | --- |
| Contact Diameter | 0.229 | m |
| Nominal Diameter | 0.120 | m |
| Drag coefficient, Cd | 1.00 | --- |
| Mass coefficient, Cm | 1.00 | --- |
| Axial Stiffness, EA | 407,257.00 | kN |
| Bending Stiffness | 0.00 | kN |
| Mass per unit length | 0.088 | kN/m |
| Ratio of Section Lengths | 150:195 | --- |
| Poisson Ratio | 0.50 | --- |
| Angles apart for each moorings | 60 | ° |



60 ̊

Figure The arrangement of the mooring chains around the CALM buoy showing Top Plan View with global load linearity

**3.6 Design Parameters**

The design parameters applied in this investigation are presented in this sub-section.

### 3.6.1 Ocean and Seabed

The numerical model was designed using some ocean and seabed considerations for the model. The seabed profile is modelled as 3D flat seabed, and it is determined by using the top surface of the seabed in regards to its position with the surface of the sea called the Mean Sea Level (MSL), as shown in Figures 11, 13 and 20. The seabed is a function of hydraulic pressure that influences its stability, such as pore water pressure, as detailed in literature (Li et al. 2016, Odijie 2016, Eshiet 2012). The parameters for the seabed and the ocean in the study are given in Table 6. This method of wave computation coupled with oceanic and seabed parameters has been validated in some technical studies on different offshore structures (Amaechi 2021, Amaechi et al. 2019a, 2021a; Odijie 2016; Odijie & Ye 2015a, 2015b).

**Table 6 Parameters for the Ocean and Seabed**

|  |  |  |
| --- | --- | --- |
| **Particulars** | **Value** | **Unit** |
| Seabed Shape Direction | 0 | ° |
| Seabed Shape Type | 3D Profile | --- |
| Seabed Model Type | Nonlinear Soil Model | --- |
| Temperature of Ocean | 10 | °C |
| Kinematic Viscosity of Ocean | 1.35 X 10-6 | m2s-1 |
| Seabed Critical Damping | 0 | % |
| Seabed Friction Coefficient | 0.5 | --- |
| Seabed Stiffness | 7.5 | kNm-1m2 |
| Amplitude of Wave | 0.145 | m |
| Density of Water | 1,025 | kgm-3 |

### 3.6.2 Waves and Wave spectrum

The numerical model was designed using some environmental considerations for the weather. The wave angles considered in this investigation were at an interval of 0°, and are as follows: 0°, 30°, 60°, 90°, 120°, 150°, 180°, as detailed in the wave parameters given in Table 7. An illustration showing the direction of waves and FPSO across the sea is presented in Figure 22. The lowest frequency applied for the hydrodynamic design analysis in ANSYS AQWA was 0.06048 Hz. For the waves, the value for the peak factor was 3.3, and the wave spectrum considered was JONSWAP spectrum, as plotted in Figure 23.

*Table 7 Wave Parameters*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Cases** | ***H*S** | ***T*Z** | ***T*P** | ***Wave Angle*** |
| 1st Case | 1.87m | 4.10s | 5.27s | 0°, 30°, 60°, …,180° |
| 2nd Case | 2.20m | 5.60s | 7.20s | 0°, 30°, 60°, …,180° |
| 3rd Case | 4.10m | 7.00s | 9.00s | 0°, 30°, 60°, …,180° |

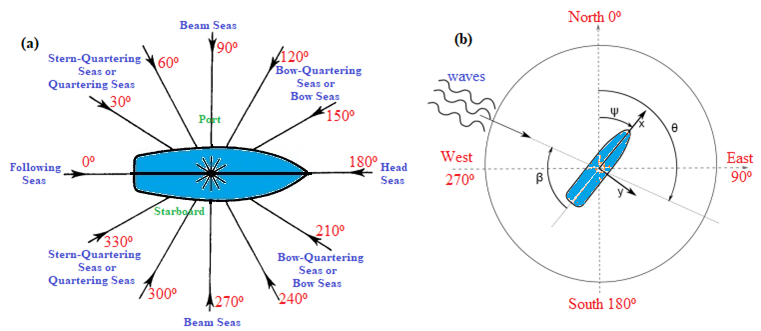


Figure Illustration showing the direction of waves and FPSO with respect to the sea, showing (a) the wave heading with various types of seas defined, and (b) waves on ship-shaped FPSO.

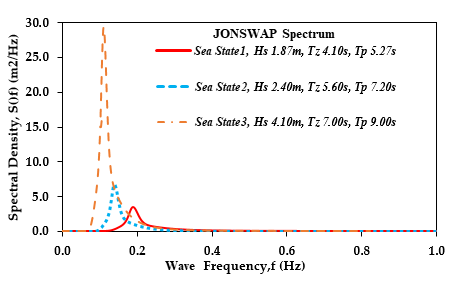


Figure The sea states for the JONSWAP wave spectrum

### 3.6.3 Wind and Current

The present researched models were setup using some parameters in the modelling. For the wind and current, the speed of the wind was 22 m/s, while the speed of the surface current was 0.5 m/s. For the air, an air kinematic viscosity of 15.0X10-6 m2s-1 under an air density of 1.225 kgm3 (0.00123gcm-3), as detailed in Table 8. A uniform profile for the current as presented in Figure 24 is utilised on the marine hose models on each of the cases investigated. Figure 25(a) presents the wind load coefficient, while the current load coefficient is presented in Figure 25(b).

**Table 8 Wind and Current Parameters**

|  |  |
| --- | --- |
| **Particulars** | **Value** |
| Wind Type | Constant |
| Density of Air (gcm-3) | 0.00123 |
| Kinematic Viscosity of Air (m2s-1) | 0.000015 |
| Power Law Exponent | 7.0 |
| Current Method | Power Law |
| Current Direction(°) | 180 |
| Surface Current (ms-1) | 0.50 |
| Seabed Current (ms-1) | 0.45 |
| Speed of Wind (ms-1) | 22.0 |

Figure The vertical profile of the Current at seabed origin

|  |  |
| --- | --- |
|  |  |

Figure 25 CALM buoy system loads showing (a) Wind load coefficient and (b) current load coefficients

**3.7 Validation**

The validation of the theory applied on this study is based on existing validated studies by the author (Amaechi C.V. et al. 2019a, 2019b, 2021a). The dynamic models from Orcaflex are expected to be able to perform dynamic analysis on the hose in centennial configuration. The dynamic effects offered by Orcina’s Orcaflex were examined on catenary S-lay pipeline through recently completed sea testing in field trials (Wang et al., 2017) and experimentally in Lancaster University wave tank (Amaechi et al. 2021e, 2021f, 2021n). It was also validated numerically using confirmed static models on Lazy-S configuration (Amaechi C.V. et al. 2021a), as well as on Chinese-lantern Configuration, (Amaechi C.V. et al. 2019a). To evaluate the numerical model, a comparative analysis of a load case from the experimental test was used to validate the model and analytical model (Amaechi et al. 2021e, 2021f).

The second validation was carried out by comparing result of experiment against the analytical model in Section 2.2. To achieve this, values for N1,N2 and N3 were assumed for a finite depth d1 of 1.0m, deeper depth of 100m, and cylinder draft D of 0.3m, and the same radius of cylinder a1 of 0.13m. Figure 26(a) is for the wave exciting force, while Figure 26(b) is for the wave exciting moment. The analytical solution was obtain using the analytical solutions presented in Section 2. Comparing the results against experimental results (Hintao et al. 2003), the analytical results (Wang D. et al. 2014) and the numerical results (present study) shows good agreement as observed in Figures 26(a-b). Other validation methods considered are using coupled models and the parameters like effective tension and bending moment in other related studies.

|  |  |
| --- | --- |
|  |  |

*Figure 26 Validation of wave diffraction on buoy showing (a) wave exciting force and (b) wave exciting moment*

4.0 Results and Discussion

The results of this investigation and the discussion are put forward in this part of the article.

## 4.1 Buoy motion study

### **4.1.1 Statistical analysis on buoy motion response**

The result of the environmental conditions given in Table 7 were applied to investigate the buoy motion responses. It was conducted using the hydrodynamic RAOs generated from ANSYS AQWA, then inputed into the Orcaflex model by coupling. It can be observed that the buoy motion is dependent on the environmental conditions, as the three cases had different motion behaviour. It can be observed that the CALM buoy motion increased more in the surge motion than in the heave. Therefore, the tension magnitude of the mooring cables attached to the CALM buoy needs to be improved. However, the *case3* values were generally the highest, followed by the *case2* values and then the *case1* values. Thus, this shows that some pertubations from the buoy motion can induce some response on the hoses, as will be shown in results in subsequent sections.

For the statistical method, two methods were applied to validate the model. They are the Pearson Correlation Coefficient and the Weibull statistical method. The application of the Pearson Correlation Coefficient to study the data from the buoy responses was possible when loaded with wave RAO loads. Pearson Correlation Coefficient is an important technique used in data mining in Ocean Engineering analysis (Ali et al. 2019; Wang et al. 2016f; Moon et al. 2008; Gao et al. 2010; Mahjoobi et al. 2008). Correlation analysis is a technique used to investigate and analyse for some relativity correlation of data variables, their dependence on the other, and the correlation of the direction of one variable with respect to others. Pearson correlation coefficient helps to obtain the strength, magnitude and direction correlation between the variables. This coefficient varies from -1 to 1, and values that approach close to 1 are positive correlation while the values close to -1 are the negative correlation.

The Correlation Coefficient of the buoy motions for surge, heave, roll and pitch motions are obtained for the three (3) environmental conditions being investigated win the forty-two (42) cases. It was used to obtain the relationship when the buoy is loaded with wave load RAOs and when it is without wave load RAOs. Pearson Correlation Coefficient was obtained for each of the environmental conditions as presented in literature (Amaechi et al. 2019a, 2019b). These coefficients are obtained by using the equation for Pearson Correlation Coefficient, given in Equation (50).

)

*Table 9 Pearson Correlation Coefficients for the Buoy Motions*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Environmental Conditions** | **Pearson Correlation Coefficients for the Buoy Motions** | | | |
| **Surge, X** | **Heave, Z** | **Roll, RX** | **Pitch, RY** |
| Case 1 | 0.985649 | -0.30552 | 0.451008 | 0.764914 |
| Case 2 | 0.981876 | -0.21852 | 0.51911 | 0.938082 |
| Case 3 | 0.924578 | -0.36845 | 0.906697 | 0.920569 |

Where n denotes the sample size, denotes the average of the buoy motion without wave load RAOs, denotes the average of the buoy motion with wave load RAOs, and r denotes the Pearson Correlation Coefficient. From Table 9, it shows that there is positive correlation between the buoy motions for the surge, roll and pitch while a negative correlation exists for the heave motion. This means that the motion of the buoy being predicted by the analysis will affect the hoses, despite the shallow water depth. However, the hoses need to be redesigned to cushion the heave effect from the heave motion of the buoy.

For the Weibull statistical method, 95% confidence values of 21.8825 and 26.4572 were obtained. The 3-hour return level for the upper tail of the pitch motion (RY) is 23.4187° from the Weibull Distribution. A threshold of 41 data points above the threshold of 17° with decluttering based on mean up-crossings is used. The fitted Weibull parameters obtained are presented in Table 10. Weibull Distribution tool has been used to validate the reliability of these motion results. The expression for the Weibull Distribution is given by Equation (51):

51)

Where x, α and β are numeric values; x is the value that is required to evaluate the function. From the results, it shows that the roll had highest data points, followed by the surge motion. It was least in the heave, which means it had good stability in the heave motion.

*Table 10 Weibull Analysis Distribution of the CALM buoy motions*

|  |  |  |
| --- | --- | --- |
| **Parameters** | **Data Points** | **Threshold** |
| **Surge** | 59 | 3.22m |
| **Heave** | 16 | -1.083m |
| **Roll** | 89 | 0.00037° |
| **Pitch** | 41 | 17° |

### **4.1.2 Surge RAO & Radiation damping on buoy**

An investigation on the surge RAO and radiation damping has been carried out on three buoy models of varying skirt geometries. The skirts on the buoy presented in Table 11 and Figure 27 were investigated for effect on the hydrodynamic behaviour using surge RAO. As shown in Figure 28(a), *BuoySkirt1*(13.90m diameter) had the least surge RAO while *BuoySkirt3* (11.90m diameter) had the highest surge RAO. Thus, the higher the skirt diameter, the lesser the surge RAO. Figure 28(b) shows that *BuoySkirt1*was maximum at 215,191 N/(m/s). Thus, the diameter of the buoy skirt affects the surge RAO and the radiation damping. However, a detailed study on the motion response is recommended.

*Table 11 Table showing CALM buoy skirt diameters considered*

|  |  |  |  |
| --- | --- | --- | --- |
| CALM buoy Skirt Cases | Skirt Diameter, Ds (m) | Buoy Diameter, Db (m) | Diameter Ratio, D = Ds/Db |
| Skirt 1 | 13.90 | 10.0 | 1.39 |
| Skirt 2 | 12.90 | 10.0 | 1.29 |
| Skirt 3 | 11.90 | 10.0 | 1.19 |

|  |  |  |
| --- | --- | --- |
|  |  |  |

*Figure 27 CALM buoy of skirt diameter (a) Ds1=13.90m (b) Ds2=12.90m and (c) Ds3=11.90m*

|  |  |
| --- | --- |
|  |  |
| (a) Effect of buoy skirt diameters on Surge RAO | (b) Effect of buoy skirt diameters on Radiation Damping |

*Figure 28 Influence of buoy skirt diameters*

## 4.2 Load response study

### **4.2.1 Floating hose load response in normal configuration**

The investigation on the disconnection-induced load on the floating hose was investigated and the results presented in Figures 29-31. The hose bending moment in normal operation shown in Figure 29(a-b) shows lower profile than the hose bending moment in accidental operation in Figure 29(c-d). It was recorded that the Case3 has higher bending moment profile than that of Case2, and the least bending moment is the Case1. The hose curvature in normal operation shown in Figure 30 (a-b) shows lower profile than the hose curvature in accidental operation in Figure 30(c-d). It was recorded that the Case3 has higher curvature profile than that of Case2, and the least curvature is the Case1. However, the curvatures obtained are still within safe limit of less than 2.0m as recommended in OCIMF (2009) industry standard. In similar manner, the hose effective tension in normal operation shown in Figure 31(a-b) shows lower profile than the hose effective tension in accidental operation in Figure 31(c-d). It was recorded that the Case3 has higher effective tension profile than that of Case2, and the least effective tension is the Case1. Thus, it can be deduced that the hose performance is affected by disconnection-induced loads, however a fatigue study and local design are recommended on this to evaluate the extent of damage on the hose. It can be also be observed that the effective tension profiles at the ends are higher than at midpoints of the floating hoses, and at disconnection, the profile increases and has a transfer of tension in the opposite direction, which is typically represented as given in Section 2.5. Thus, it would be necessary to ensure that reliable and well-tested marine breakaway couplings are used during disconnection.

### **4.2.2 Submarine hose load response in Chinese-lantern configuration**

The investigation on the disconnection-induced load on the submarine hoses in Chinese lantern configuration was investigated and the results presented in Figure 32. This was also investigated by considering the *DAFhose*, as proposed by Amaechi et al. (2019a). The hose curvature for the accidental operation has higher curvature than the normal operation in Figure 32(a). It was also observed in Figure 32(b) that the curvature *DAFhose* for the normal operation is also lower than that of the accidental operation. In similar manner, the hose effective tension for the accidental operation has higher effective tension than the normal operation in Figure 32(c). It was also observed in Figure 32(d) that the effective tension *DAFhose* for the normal operation is also lower than that of the accidental operation. Also, the hose bending moment for the accidental operation has higher bending moment than the normal operation in Figure 32(c). It was also observed in Figure 32(d) that the bending moment *DAFhose* for the accidental operation is also higher than that of the normal operation. As such, it is necessary that a good integrity check is carried out on the submarine hoses after any accidental operation, no matter how minimal it may appear, unless it is assessed to be within safe limits. In the profiles, the Chinese-lantern configuration for the bending moment and the curvature have slightly similar profile but different magnitudes. However, this does not ascertain the configuration that is more affected by the disconnection-induced load effect, but it indicates the presence of some load response from the marine bonded hoses. This requires further investigation on fatigue study which is recommended and investigated in another study.

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Figure Result of the hose bending moment during (a-b) normal operation and (c-d) accidental operation

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Figure Result of the hose curvature during (a-b) normal operation and (c-d) accidental operation

|  |  |
| --- | --- |
|  |  |
|  |  |

Figure Result of the hose effective tension during (a-b) normal operation and (c-d) accidental operation

|  |  |
| --- | --- |
|  |  |
| 1. Curvature for Hose in Lazy-S config. | (b) Curvature *DAFHose* for Hose in Lazy-S config. |
|  |  |
| (c) Effective Tension for Hose in Lazy-S config. | (d) Effective Tension *DAFHose* for Hose in Lazy-S config. |
|  |  |
| (e) Bending moment for Hose in Lazy-S config. | (f) Bending Moment *DAFHose* for Hose in Lazy-S config. |

*Figure 32* Effect of hydrodynamic loads on the submarine hose in Lazy-S config.

|  |  |
| --- | --- |
|  |  |
| 1. Curvature for Hose in Chinese-lantern config. | (b) Curvature *DAFHose* for Hose in Chinese-lantern config. |
|  |  |
| (c) Effective Tension for Hose in Chinese-lantern config. | (d) Effective Tension *DAFHose* for Hose in Chinese-lantern config. |
|  |  |
| (e) Bending moment for Hose in Chinese-lantern config. | (f) Bending Moment *DAFHose* for Hose in Chinese-lantern config. |

*Figure 33* Effect of hydrodynamic loads on the submarine hose in Chinese-lantern config.

### **4.2.3 Submarine hose load response in Lazy-S configuration**

The investigation on the disconnection-induced load on the submarine hoses in lazy-S configuration was investigated and the results presented in Figure 33. This was also investigated by considering the *DAFhose*, as proposed by Amaechi et al. (2019a). The hose curvature for the accidental operation has higher curvature than the normal operation in Figure 33(a). It was also observed in Figure 30(b) that the curvature *DAFhose* for the normal operation is also lower than that of the accidental operation. In similar manner, the hose effective tension for the accidental operation has higher effective tension than the normal operation in Figure 33(c). It was also observed in Figure 33(d) that the effective tension *DAFhose* for the normal operation is also lower than that of the accidental operation. Also, the hose bending moment for the accidental operation has higher bending moment than the normal operation in Figure 33(c). It was also observed in Figure 33(d) that the bending moment *DAFhose* for the accidental operation is also higher than that of the normal operation. As such, it is necessary that a good integrity check is carried out on the submarine hoses after any accidental operation, no matter the magnitude, unless it is assessed to be within safe limits. In the profiles, the bending moment and the curvature have similar profile under the lazy-S configuration but have different magnitudes (and units). However, this is different with the Chinese-lantern configuration in Section 4.2.2, where the bending moment and the curvature have inversely similar profiles and with different magnitudes and units. Although, it does not ascertain the configuration that is more affected by the disconnection-induced load effect, but it indicates the presence of load response on the marine bonded hoses.

### **4.2.4 Wave load and flow angle analysis on bending moment**

The effect of hydrodynamic loads was investigated for the submarine hoses under a water depth of 26m, under Chinese-lantern configuration as it does not require much length in the investigation. The results presented in Figure 35(a-d) show the details on the configuration, and the profiles for the bending moment at two ends – End A and End B. The maximum bending moment were recorded at the hose ends. Also, the curvature is within the limit as recommended in the industry standard by OCIMF (2009). Thus, it shows that the designed submarine hose is fit for the designed application. As can be observed in Figure 34, the curvature of the hose from the bending moment is within the design limit as specified in OCIMF (2009). The hose curvature has been induced by the wave and current loads as well as other hydrodynamic loads. As recorded in Figure 35, it can be observed that the *SeaState3* reflected the highest bending moment magnitudes over the *SeaState2* and *SeaState1*. This is due to the higher frequency of the *SeaState3* and the significant wave height being of higher value than the others. A comparative study on the model by including RAOs as given in Figure 35 shows that the hydrodynamic load affects the performance of the marine bonded hoses. In addition, it was recorded that across the varying flow angles investigated, that the case of flow angle **180°** was the highest. However, it is also relatively dependent on the RAO loads as seen too. Thus, the RAO loads and the wave angles are key parameters that influence the load response of the marine bonded hoses. As observed in the tabulated hose bending characteristics, it can be observed that the bending moment profiles shows that the hydrodynamic loads influence the motion behaviour of the submarine hoses. It is evidently clear too that the *SeaState3* reflected the highest bending moment magnitudes over the *SeaState2* and *SeaState1*. This is due to the higher frequency of the *SeaState3* and the significant wave height being of higher value than the others. Based on the statistical analysis, the 9**0°** flow angle gave the least deviation in bending moment in all the three sea states. This is due to the flow being in line with the wave direction. But for perpendicular flows in **0°** and **180°**, the bending moments have higher deviations. Thus, the study is highly indicative of high bending moment across the different flow angles investigated, especially along the hose arc lengths that have maximum curvatures. Thus, it is recommended to dampens the hose sections around those regions that recorded high bending moments, such as increasing the damping coefficients.



Curvature due to Sensitivity to the significant wave height on the submarine hose

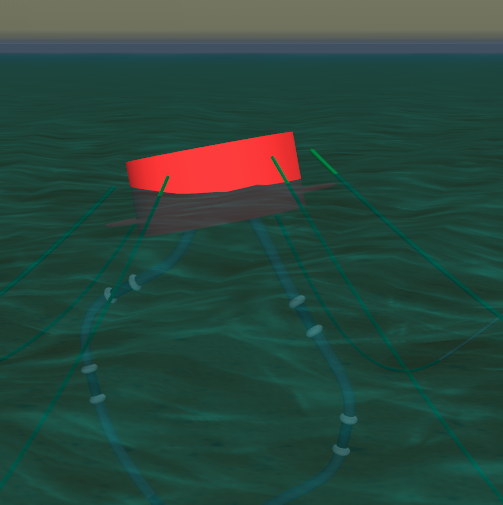
Figure Curvature of submarine hose in Chinese-lantern configuration

|  |  |
| --- | --- |
|  |  |
| (a) Hose1 Bending Moment With RAO load | (b) Hose1 Bending Moment Without RAO load |
|  |  |
| (c) Hose2 Bending Moment With RAO load | (d) Hose2 Bending Moment Without RAO load |

Figure Influence of RAO load on bending moment of submarine hose in Chinese-lantern configuration

### **4.2.5 Wave load and flow angle analysis on effective tension**

The effect of hydrodynamic loads was investigated for the submarine hoses under a water depth of 26m, under Chinese-lantern configuration as it does not require much length in the investigation. The results presented in Figure 37(a-d) show the details on the configuration, and the profiles for the effective tension at two ends – End A and End B. The maximum effective tensions were recorded at the hose ends. Also, the tension recorded is within the limit as recommended in the industry standard by OCIMF (2009). Thus, it shows that the designed submarine hose is fit for the designed application. As can be observed in Figure 36, the region of the hose-string that is most susceptible to high tension is close to the manifolds, as depicted. As recorded in Figure 37, it was recorded that the *SeaState3* reflected the highest bending moment magnitudes over the *SeaState2* and *SeaState1*. This is due to the higher frequency of the *SeaState3* and the significant wave height being of higher value than the others. Furthermore, it was recorded that across the varying flow angles investigated, that the case of flow angle **180°** was the highest. However, it is also relatively dependent on the RAO loads as seen too. Thus, the RAO loads and the wave angles are key parameters that influence the load response of the marine bonded hoses. In conclusion, the effective tension plots in Figure 37 shows that the tension profiles reflect that the hydrodynamic loads have an effect on the submarine hoses. It is evidently clear too that the *SeaState3* reflected the highest bending moment magnitudes over the *SeaState2* and *SeaState1*. This is due to the higher frequency of the *SeaState3* and the significant wave height being of higher value than the others. The hose tension has been induced by the wave and current loads as well as other hydrodynamic loads. In addition, when such happens, the hoses twist or experience some torsion which in turn induces high tension. In that light, the hoses begin to experience high fatigue from the induced loadings. Another scenario for the induced loadings is during the disconnection, where the disconnection-induced loads induce some fatigue on the marine hoses. In summary, the study is highly indicative of high tensions across the different flow angles investigated. Thus, it is recommended to reinforce those regions with reinforced ends to offset the high tensions recorded.



Region of high tension close to the manifold connection due to wave loads on the submarine hose, the wave height, and the wave amplitudes

Figure Tension region of submarine hose in Chines-lantern configuration

|  |  |
| --- | --- |
|  |  |
| (a) Hose1 Effective Tension With RAO load | (b) Hose1 Effective Tension Without RAO load |
|  |  |
| (c) Hose2 Effective Tension With RAO load | (d) Hose2 Effective Tension Without RAO load |

Figure Influence of RAO load on effective tension of submarine hose in Chinese-lantern configuration

## 4.3 Discussion

The investigation on the hydrodynamic analysis has shown the existence of disconnection-induced load response on the CALM buoy hose system and presented some comparative profiles for two different hoses- the floating hoses and the submarine hoses. It was observed that there is the presence of disconnection-induced loading from the comparative study between normal operation and accidental operation. There was also a comparison in the influence of the designs using Lazy-S and Chinese-lantern configurations on submarine hoses. It was also observed that there had different profiles that were inversely similar. Also, the magnitudes of the bending moment, curvature, and effective tensions were not the same. On the aspect of investigating the most affected configuration, it was concluded that further research on the fatigue study of the marine hoses is conducted. On the part of the statistical analysis on the submarine hoses and the buoy motion, there were good findings that suggest that the hoses were fit for use as they passed the recommendations of the industry standard (OCIMF 2009). In addition, the profiles presented on the wave loads and the flow angles showed that the hydrodynamic analysis on the marine bonded hoses had good correlations for the parameters investigated.

5.0 Conclusion

The hydrodynamic analysis on disconnection-induced load response of marine bonded hoses during normal operation and accidental operation under irregular waves has been presented in this paper. The study involves numerical investigation on CALM buoy and the marine bonded hoses attached to it. Two hoses were applied in the model: the floating hoses and the submarine hoses. Some presentations made on the mathematical formulations include the wave theory, boundary element method (BEM), hydrodynamics equations, catenary equations, and the equations on marine hoses and marine risers. Detailed numerical investigation on CALM buoys with submarine hoses in two configurations: Lazy-S and Chinese-lantern, were conducted. The hydrodynamic panel was developed in ANSYS AQWA and computed using diffraction theory and JONSWAP Wave Spectrum for the three (3) environmental conditions used (). The boundary conditions considered for the submarine hoses were attached on the PLEM and hose manifold underneath the CALM buoy. The RAOs calculated were then coupled into the Orcaflex FEM model developed based on Orcaflex Line theory. This proposed line theory uses the nodes on the hoses and mooring lines, but applies some discretization for the CALM buoy, to ensure less computational time and resources, and has been validated in an earlier study (Amaechi C.V. et al. 2019a).

The model highlights the following: firstly, novelty in disconnection-induced load response on marine bonded hoses under different ocean conditions and normal and accidental operations. Secondly, wave load and flow angle analysis on bending moment and effective tensions under irregular waves. Thirdly, a novelty in hydrodynamic studies on the hose disconnection studies for Lazy-S and Chinese-lantern configurations using water waves. Fourthly, the effect of different hose parameters hydrodynamic loads on hose profiles for bending moment, curvature, deflection, and effective tension on hose behaviour. Lastly, the effect of wave loads on buoy motion response from the diffraction analysis, and validation using statistical analysis. This study is important in enabling designers to design appropriately based on the hose behaviour, buoy geometry and environmental data.

The study presented a detailed investigation on the effect of disconnection-induced loads on the marine bonded hoses, and presented profiles for the normal operation and accidental operation for floating hoses and submarine hoses in Lazy-S, and for submarine hoses in Chinese-lantern configurations. It was observed that the accidental operation which was the case during disconnection of hose from the CALM buoy and the FPSO tanker showed good results as predicted. Thus, extra checks must be taken to ensure that the hoses have reliable marine breakaway couplings (MBCs) and hose end valves (HEVs). Also, it is recommended to reinforce the hoses towards ends that recorded very high tensions. On the buoy study, the motion was a function of the wave loads, such as in the surge RAO magnitudes. It would be recommended to have some floats around the buoy to reduce the vortex effect around it, and to reduce it damping or using strakes, and pneumatic fenders. However, further investigation using CFD is recommended. On the aspect of investigating the most affected configuration, it was concluded that further research on the fatigue study of the marine hoses be conducted. On the aspect of the statistical analysis on the submarine hoses and the buoy motion, the findings suggest that the hoses were fit for use as they passed the recommendations of the industry standard (OCIMF 2009). In addition, the profiles presented on the wave loads and the flow angles showed that the hydrodynamic analysis on the marine bonded hoses had good correlations for the parameters investigated. Further investigation on model tests in large scale can be conducted for the disconnection-induced load effect on a CALM buoy hose system. In addition, a detailed study on the motion response of the CALM buoy is recommended.

# Conflict of Interest

The author declares no conflict of interest in this research. The funders had no hand in the determination of the results. The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper. The outcome was also not influenced by or funded by any buoy or hose manufacturer. The findings of this research were part of a PhD research in Lancaster University on marine bonded hoses and composite marine risers.

# Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

# Authorship CRediT Contribution Statement

Conceptualization, C.V.A, J.Y; methodology, C.V.A., F.W., J.Y; software, C.V.A., F.W., J.Y; validation, C.V.A., F.W., J.Y; formal analysis, C.V.A., F.W., J.Y; investigation, C.V.A., F.W., J.Y; resources, C.V.A., J.Y; data curation, C.V.A., F.W., J.Y; writing—original draft preparation, C.V.A.; writing—review and editing, C.V.A., F.W., J.Y; visualization, C.V.A., F.W., J.Y; supervision, C.V.A., F.W., J.Y; project administration, C.V.A., F.W., J.Y; funding acquisition, C.V.A., F.W., J.Y.

# Funding

The Department of Engineering, Lancaster University, UK and EPSRC Doctoral Training Centre (DTC) are highly appreciated. In addition, the funding of Overseas Scholarships by Nigeria’s NDDC (Niger Delta Development Commission) is also appreciated, as well as the support of Standards Organisation of Nigeria (SON), F.C.T Abuja, Nigeria. The research reported in this paper is part of the Project 51922064 supported by the Natural Science Foundation of China (NSFC).

# Acknowledgement

The author acknowledges the technical support from Lancaster University Engineering Department staff. Also, grateful to Dr. Abiodun K. Oyetunji of Lancaster University, Lancaster Environment Centre (LEC), UK, Dr. Ebube Charles Amaechi of University of Ilorin, Kwara State, Nigeria and Dr. Charles A. Odijie of MSCM Limited UK for reviewing an earlier version of this manuscript. The support team of the ANSYS and Orcaflex’s Orcina are appreciated for technical support. Lastly, the peer-review by the journal editor and the reviewers on this manuscript are immensely appreciated.

# References

ABCNews, 2005. Accident prompts Navy to replace submarine hoses. *Australian Broadcasting Corporation*, p.1. Available at: http://www.abc.net.au/news/2005-08-03/accident-prompts-navy-to-replace-submarine-hoses/2072338.

ABS, 2021. *Rules For Building And Classing - Single Point Moorings*, New York, USA: American Bureau of Shipping. Available at: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/offshore/8\_rules-forbuildingandclassingsinglepointmoorings\_2021/spm-rules-jan21.pdf (Accessed on: 21st September, 2021).

Ali M. & Prasad R. (2019). Significant wave height forecasting via an extreme learning machine model integrated with improved complete ensemble empirical mode decomposition. Renewable and Sustainable Energy Reviews, Volume 104, April 2019, Pages 281-295 https://doi.org/10.1016/j.rser.2019.01.014

Amaechi, C.V., Wang F., Hou X., and Ye J. (2019a). “Strength of submarine hoses in Chinese-lantern configuration from hydrodynamic loads on CALM buoy,” *Ocean Engineering*, vol. 171, no. 2019, pp. 429–442, 2019. https://doi.org/10.1016/j.oceaneng.2018.11.010

Amaechi, C.V., Ye J., Hou X., and Wang F.-C. (2019b). Sensitivity Studies on Offshore Submarine Hoses on CALM Buoy with Comparisons for Chinese-Lantern and Lazy-S Configuration OMAE2019-96755,” in *38th International Conference on Ocean, Offshore and Arctic Engineering, Glasgow, Scotland, June 9–14, 2019*.

Amaechi, C.V., Gillet N., Hou X., and Ye J. (2019c). Composite Risers for Deep Waters Using a Numerical Modelling Approach,” *Compos. Struct.*, vol. 210, no. 2019, pp. 486–499, 2019. https://doi.org/10.1016/j.compstruct.2018.11.057.

Amaechi, C.V.; Gillett, N.; Odijie, A.C.; Wang, F.; Hou, X.; Ye, J. (2019d). Local and Global Design of Composite Risers on Truss SPAR Platform in Deep Waters. In Proceedings of 5th International Conference on Mechanics of Composites. Instituto Superior de Tecnico, Lisbon, Portugal, 1–4 July 2019; no. 20005, pp. 1–3.

Amaechi, C.V.; Odijie, C.; Sotayo, A.; Wang, F.; Hou, X.; Ye, J. (2019e). Recycling of Renewable Composite Materials in the Offshore Industry. *Encycl. Renew. Sustain. Mater.* **2019**, *2*, 583–613, doi:doi:10.1016/B978-0-12-803581-8.11445-6.

Amaechi, C.V.; Odijie, C.; Etim, O.; Ye, J. (2019f). Economic Aspects of Fiber Reinforced Polymer Composite Recycling. *Encycl. Renew. Sustain. Mater.* **2019**, *2*, 377–397, doi: 10.1016/B978-0-12-803581-8.10738-6.

Amaechi, C.V. & Ye, J., 2017. A numerical modeling approach to composite risers for deep waters. In *International Conference on Composite Structures (ICCS20) Proceedings*. Paris, France: Societa Editrice Esculapo.

Amaechi, C.V., Wang F., Ye J. (2021a). Numerical Assessment on the Dynamic Behaviour of Submarine Hoses Attached to CALM Buoy Configured as Lazy-S under Water Waves. *J. Mar. Sci. Eng.****2021****, 9(10), 1130;* <https://doi.org/10.3390/jmse9101130>.

Amaechi, C.V., Wang F., Ye J. (2021b). Numerical studies on CALM buoy motion responses, and the effect of buoy geometry cum skirt dimensions with its hydrodynamic waves-current interactions. Ocean Eng. 2021, under review.

Amaechi, C.V. (2021c). Investigation on hydrodynamic characteristics, wave-current interaction, and sensitivity analysis of submarine hoses attached to a CALM buoy. *J. Mar. Sci. Eng*. 2021, under review.

Amaechi, C.V. (2021d). Analytical cum numerical solutions on added mass and damping of a CALM buoy towards understanding the fluid-structure interaction of marine bonded hose under random waves. Mar. Struct. 2021, under review.

Amaechi, C.V. (2021e). Experimental study on motion characterization of CALM buoy hose system with CFD investigation on vortex effect. *J. Mar. Sci. Eng.*, 2021, under review.

Amaechi, C.V. (2021f). Experimental and analytical study on CALM buoy hydrodynamic motion response and the hose-snaking phenomenon under water waves. *J. Mar. Sci. Eng.*, 2021, under review.

Amaechi, C.V, Wang F., Ye J. (2021g). Mathematical Modelling of Bonded Marine Hoses for Single Point Mooring (SPM) Systems, with Catenary Anchor Leg Mooring (CALM) Buoy application: A Review. *J. Mar. Sci. Eng*. **2021**, 9(11): 1179. <https://doi.org/10.3390/jmse9111179>.

Amaechi, C.V. (2021h). Development of bonded marine hoses or sustainable loading or unloading operation in the offshore industry. *Ships and Offshore Structures.* 2021, under review.

Amaechi, C.V., ChestertonC., Butler H.O., Wang F., Ye J. (2021i). An Overview on Bonded Marine Hoses for sustainable fluid transfer and (un)loading operations via Floating Offshore Structures (FOS). *J. Mar. Sci. Eng.* 2021, 9(11):1236. <https://doi.org/10.3390/jmse9111236>.

Amaechi, C.V., ChestertonC., Butler H.O., Wang F., Ye J. (2021j). Review on the design and mechanics of bonded marine hoses for Catenary Anchor Leg Mooring (CALM) buoys. *Ocean Engineering Journal*. 2021, **242,** <https://doi.org/10.1016/j.oceaneng.2021.110062>

Amaechi, C.V., Ye J. (2021k). Local tailored design of deep water composite risers subjected to burst, collapse and tension loads. *Ocean Engineering* 2021, https://doi.org/10.1016/j.oceaneng.2021.110196.

Amaechi, C.V. (2021l). A review of state-of-the-art and meta-science analysis on composite risers for deep seas. *Ocean Engineering* 2021, under review.

Amaechi, C.V. (2021m). Development of composite risers for offshore applications with review on design and mechanics. *Ships and Offshore Structures.* 2021, under review.

Amaechi, C.V. (2021n). Novel design, hydrodynamics and mechanics of marine hoses in oil/gas applications. PhD Thesis. Lancaster University, Engineering Department, Lancaster, UK, 2021, in view.

Amaechi, C.V. (2021o) Single Point Mooring (SPM) hoses and Catenary Anchor Leg Mooring (CALM) buoys. LinkedIn Pulse. Published on 26 July 2021. Available online: https://www.linkedin.com/pulse/single-point-mooring-spm-hoses-catenary-anchor-leg-calm-amaechi (Accessed on 1 September 2021).

Amaechi, C.V. (2021p). Experiment and finite element modelling on the load response of offshore bonded loading hoses during reeling operation, normal operation and non-operation conditions. *Ocean Engineering,* under review.

Amaechi, C.V. (2021q). Liner Wrinkling, Helix Spring Deformation and mechanical behaviour of Marine Bonded Composite Hoses (MBCH) using local design pressure under burst and collapse*.* *J. Mar. Sci. Eng.,* under review.

Amaechi, C.V., Odijie C.A., Wang F., Ye J. (2021r). Numerical investigation on mooring line configurations of a Paired Column Semisubmersible for its global performance in deep water condition. *Ocean Eng.* **2021**, under review.

Amaechi, C.V., Wang F., Ye J. (2021s). Parametric investigation on tensioner stroke analysis, recoil analysis and disconnect for the marine drilling riser of a Paired Column Semisubmersible under deep water waves. *Ocean Eng.* **2021**, under review.

Amaechi, C.V., Wang F., Ye J. (2021t). Dynamic analysis of tensioner model applied on global response of marine riser recoil and disconnect. *Ocean Eng.* **2021**, under review.

Amaechi, C.V., Wang F., Ye J. (2021u). Effect of marine riser integration for characteristic motion response studies on a Paired Column Semisubmersible in deep waters. *Mar. Struct.* **2021,** under review.

ANSYS, 2017a. *ANSYS Aqwa Theory Manual, Release 18.2*, Canonsburg, USA: ANSYS Inc.

ANSYS, 2017b. *ANSYS Aqwa User’s Manual, Release 18.2*, Canonsburg, USA: ANSYS Inc.

ANSYS, 2017c. *ANSYS Meshing User’s Guide, Release 18.2*, Canonsburg, USA: ANSYS Inc.

API. (2005). API RP 2SK- Design and analysis of stationkeeping systems for floating structures. 3rd Edition, American Petroleum Institute (API), Washington, USA.

API. (2006). Specification for Bonded Flexible Pipe . ISO 13628-10 (Identical), Petroleum and natural gas industries-Design and operation of subsea production systems-Part 10: Specification for bonded flexible pipe. American Petroleum Institute (API), Washington, USA.

API. (2017). API 17K- Specification for Bonded Flexible Pipe, 3rd Edition. American Petroleum Institute (API), Washington, USA.

Bai, Y. & Bai, Q., 2005. *Subsea Pipelines and Risers* 1st ed., Oxford, UK: Elsevier.

Barltrop, N.D.P., 1998. *Floating Structures: A guide for design and analysis- Volume 2*, Herefordshire, UK: Oilfield Publications Limited (OPL).

Barltrop, N.D.P. & Adams, A.J., 1991. *Dynamics of fixed marine structures* 3rd Ed., Oxford, UK: Butterworth Heinemann.

Berhault, C., Guérin, P., Le Buhan, P., and J.M. Heurtier (2004). "Investigations On Hydrodynamic And Mechanical Coupling Effects For Deepwater Offloading Buoy." Paper presented at the The Fourteenth International Offshore and Polar Engineering Conference, Toulon, France, May 23-28, 2004. Toulon, France: ISOPE, pp. 374–379. Available at: http://legacy.isope.org/publications/proceedings/ISOPE/ISOPE%202004/volume3/2004-pf-03.pdf (Accessed on: 12th July, 2021).

Berteaux, H.O., 1976. *Buoy engineering* 1st Ed., New York, USA: John Wiley and Sons.

Bhatta D. D., Rahman M. Wave loadings on a vertical cylinder due to heave motion. International Journal of Mathematics and Mathematical Sciences, 1995, 18(1): 151~170.

Bhatta D. D., Rahman M. On scattering and radiation problem for a cylinder in water of finite depth. International Journal of Engineering Science, 2003, 41: 931~967

Bhatta D. D. (2007). Computation of added mass and damping coefficients due to a heaving cylinder. Journal of Appl. Math. & Computing, Vol. 23, No. 1-2, pp. 127-140.

Bhosale D. (2017). Mooring analysis of a Paired Column Semisubmersible. BEng Dissertation. Lancaster University, Engineering Department, Lancaster, UK.

Bishop, R.E.D. & Price, W.G., 2005. *Hydroelasticity of ships*, New York, USA: Cambridge University Press.

Bishop R.E.D & Johnson D.C. (2011). *The Mechanics of Vibration*. 1960 Reprint.Cambridge University Press, London, UK.

Bluewater, 2011. *Bluewater Turret Buoy- Technical Description*, Amsterdam, The Netherlands: Bluewater Energy Services. Available at: https://www.bluewater.com/wp-content/uploads/2013/04/digitale-brochure-TurretBouy-Tech-description.pdf. (Accessed on: 12th July, 2021).

Bluewater, 2009. *Buoyed Up: The future of tanker loading/offloading operations*, Amsterdam, The Netherlands: Bluewater Energy Services. Available at: https://www.bluewater.com/wp-content/uploads/2013/04/CALM-Buoy-brochure-English.pdf. (Accessed on: 12th July, 2021).

Brady, I., Williams, S. & Golby, P., 1974. A study of the Forces Acting on Hoses at a Monobuoy Due to Environmental Conditions. In *Offshore Technology Conference Proceeding -OTC 2136*. Dallas, Texas, USA: OnePetro, pp. 1–10.

Brebbia, C.A. & Walker, S., 1979. *Dynamic Analysis of Offshore Structures* 1st Ed., London, UK: Newnes-Butterworth & Co. Publishers Ltd.

Bree, J., Halliwell, A.R. & Tom O’Donoghue, 1989. Snaking of floating marine oil hose attached to SPM buoy. *Journal of Engineering Mechanics*, 115(2), pp.265–284.

Brown, M.J.; Elliott, L. Two-dimensional dynamic analysis of a floating hose string. *Appl. Ocean Res.* **1988**, *10*, 20–34. <https://doi.org/10.1016/S0141-1187(88)80021-X>

Brown, M.J.; Elliott, L. A design tool for static underbuoy hose-systems. *Appl. Ocean Res.* **1987**, 9*(3)*, 171–180. https://doi.org/10.1016/0141-1187(87)90021-6

Brown, M.J. Mathematical Model of a Marine Hose-String at a Buoy—Part 1—Static Problem. In *Offshore and Coastal Modelling*; Dyke, P., Moscardini, A.O., Robson, E.H., Eds.; Springer: London, UK, 1985; pp. 251–277. <https://doi.org/10.1007/978-1-4684-8001-6_14>

Brown, M.J. Mathematical Model of a Marine Hose-String at a Buoy—Part 2—Dynamic Problem. In *Offshore and Coastal Modelling*; Dyke, P., Moscardini, A.O., Robson, E.H., Eds.; Springer: London, UK, 1985; pp. 279–301. <https://doi.org/10.1007/978-1-4684-8001-6_13>

Chakrabarti, S.K., 2005. *Handbook of Offshore Engineering - Volume 1*, Oxford, UK: Elsevier.

Chakrabarti, S.K., 2001. *Hydrodynamics of offshore structures* Reprint., Southampton, UK: WIT Press.

Chandrasekaran, S., 2015. *Dynamic Analysis and Design of Offshore Structures* 1st Ed., New Delhi, India: Springer. https://doi.org/10.1007/978-81-322-2277-4

Chakrabarti, S.K., 1975. Second-order wave loads on large vertical cylinders. Journal of waterways, harbors and coastal engineering division, ASCE, Vol. 101, No. WW3, Proc. Paper 11476, Aug. 1975, pp. 311-317.

Chakrabarti, S.K. 1972. Nonlinear wave forces on vertical cylinder. Journal of the Hydraulics Division. Proccedings of the American Society of Civil Engineers.Vol.98, No. HY11, Nov. 1972, pp. 18951909

Chau F.P., Eatock R.T. (1992). Second-order wave diffraction by a vertical cylinder. Journal of Fluid Mechnaics, Vol. 240, pp. 571-599.

Continental (2020). *Continental Marine Hose Brochure*; Dunlop Oil & Marine, Continental Contitech Oil & Gas: Grimsby, UK, 2020; Available online: https://aosoffshore.com/wp-content/uploads/2020/02/ContiTech\_Marine-Brochure.pdf (Accessed on 17 November 2021).

Cozijn, H., Uittenbogaard, R. & Brake, E. Ter, 2005. Heave , Roll and Pitch Damping of a Deepwater CALM Buoy with a Skirt. In *International Society of Offshore and Polar Engineering Conference Proceedings*. Seoul, Korea: ISOPE, pp. 388–395.

Cozijn, J.L. & Bunnik, T.H.J., 2004. Coupled Mooring Analysis for a Deep water CALM Buoy; OMAE2004-51370. In *International Conference on Offshore Mechanics and Arctic Engineering (OMAE) Proceedings*. Vancouver, British Columbia, Canada: ASME, pp. 1–11.

Culla, A. and Carcaterra, A., 2007. Statistical moments predictions for a moored floating body oscillating in random waves. *Journal of Sound and Vibration*, 308(1-2), pp.44-66. DOI: 10.1016/j.jsv.2007.07.018

DNVGL, (2016). *DNVGL-OS-E403 Offshore loading units*, Oslo, Norway: Det Norske Veritas & Germanischer Lloyd. Available at: https://rules.dnv.com/docs/pdf/DNV/OS/2016-04/DNVGL-OS-E403.pdf (Accessed on 12th October, 2021).

DNVGL, (2015a). *DNVGL-OS-E403 Offshore loading buoys*, Oslo, Norway: Det Norske Veritas & Germanischer Lloyd. Available at: https://rules.dnv.com/docs/pdf/DNV/os/2015-07/DNVGL-OS-E403.pdf (Accessed on 12th October, 2021).

DNVGL (2015b) *DNVGL-OS-E403 Position Mooring*, Oslo, Norway: Det Norske Veritas & Germanischer Lloyd. Available at: https://rules.dnv.com/docs/pdf/DNV/os/2015-07/DNVGL-OS-E301.pdf (Accessed on 12th October, 2021).

DNVGL, 2017. *DNVGL-RP-F205 Global performance analysis of deepwater floating structures*, Oslo, Norway: Det Norske Veritas & Germanischer Lloyd.

Dareing, D.W., 2012. *Mechanics of Drillstrings and Marine Risers*, New York, USA: ASME Press. <https://doi.org/10.1115/1.859995>

Dareing, D.W., 2019. *Oilwell Drilling Engineering*, New York, USA: ASME Press. <https://doi.org/10.1115/1.861875>

Doyle, S. & Aggidis, G. (2019). Development of multi-oscillating water columns as wave energy converters. *Renewable and Sustainable Energy Reviews,* 107, 75-86. https://doi.org/10.1016/j.rser.2019.02.021

Doyle, S. & Aggidis, G. A. (2021). Experimental investigation and performance comparison of a 1 single OWC, array and M-OWC. *Renewable Energy,* 168, 365-374. https://doi.org/10.1016/j.renene.2020.12.032

Duggal, A. & Ryu, S., 2005. The dynamics of deepwater offloading buoys. In *WIT Transactions on The Built Environment*. Singapore: WIT Press.

Edward C., Kr. Dev D.A. (2021) Assessment of CALM Buoys Motion Response and Dominant OPB/IPB Inducing Parameters on Fatigue Failure of Offshore Mooring Chains. In: Okada T., Suzuki K., Kawamura Y. (eds) Practical Design of Ships and Other Floating Structures. PRADS 2019. Lecture Notes in Civil Engineering, vol 64. Springer, Singapore. <https://doi.org/10.1007/978-981-15-4672-3_35>

EMSTEC, 2016. *EMSTEC Loading & Discharge Hoses for Offshore Moorings*, Rosengarten: EMSTEC. Available at: <https://denialink.eu/pdf/emstec.pdf> (Accessed on: 29th September, 2021).

Eshiet K.I.I. (2012). Modelling of hydraulic fracturing and its engineering application. PhD Thesis. School of Civil Engineering, University of Leeds, Leeds, UK.

Esmailzadeh E., Goodarzi A. (2001). Stability analysis of a CALM floating offshore structure. International Journal of Non-Linear Mechanics. Volume 36, Issue 6, September 2001, Pages 917-926 . https://doi.org/10.1016/S0020-7462(00)00055-X

Faltisen O.M., Newman J.N, Vinje T. (1995). Nonlinear wave loads on a slender vertical cylinder, Journal of Fluid Mechanics, Vol. 289, pp. 179-98. https://doi.org/10.1017/S0022112095001297

Feng X. et al. (2020). Experimental investigation of higher harmonic wave loads and moments on a vertical cylinder by a phase-manipulation method. Coastal Engineering, Vol. 160, Issue 103747, pp. https://doi.org/10.1016/j.coastaleng.2020.103747

GallThomson (2018). Petal Valve Marine Breakaway Couplings. Available at: https://www.yumpu.com/en/document/read/51474544/gall-thomson-petal-valve-sunflex (Assessed on: 16th May, 2021).

Gao N., Yang J., Zhao W., Li X. (2015). Numerical simulation of deterministic freak wave sequences and wave-structure interaction. Ships and Offshore Structures. Volume 11, 2016 - Issue 8, Pages 802-817. <https://doi.org/10.1080/17445302.2015.1073864>

Gao P, Gao Q, An C, Zeng J. (2021). Analytical modeling for offshore composite rubber hose with spiral stiffeners under internal pressure. *Journal of Reinforced Plastics and Composites*. 2021;40(9-10):352-364. doi:[10.1177/0731684420962577](https://doi.org/10.1177/0731684420962577)

Gao Q., Zhang P., Duan M., Yang X., Shi W., An C., Li Z. (2018). Investigation on structural behavior of ring-stiffened composite offshore T rubber hose under internal pressure. Applied Ocean Research. 79 (1), 7-19. <https://doi.org/10.1016/j.apor.2018.07.007>

Gao Q., Li Z.L., Zhao D.W., Duan M. (2016). Structural behavior of offshore bonded rubber hose under torsion, in: Menglan Duan, Youngsoon Yang (Eds.), Proceedings of SUTTC 2016 on Subsea Engineering, Beijing, 2016, pp. 246–257.

Gao Q., Duan M., Yang X., Shi W., Zhao D., An C., Li Z. 2017. Analysis of multi-layered fiber-wound offshore rubber hose under internal pressure. In *Proceedings of International Conference on Composite Structures*, ICCS20 Conference, Paris, France.

Gao, Y. Y., Yu, D. Y., Li, C. L. and Xu, D. L., 2010. Calculation of significant wave height using the linear mean square estimation method, Journal of Ocean University of China, 9(4): 327–332. https://doi.org/10.1007/s11802-010-1753-6

Garrison, C..J., Hydrodynamics of Large Objects in the Sen; Part I: Hydrodynamic Analysis, Journal of Hydronautics, 8, (1974), pp. 5-12. https://doi.org/10.2514/3.62970

Garrison, C. J., Hydrodynamics of Large Objects in the Sea; Part II: Motion of FreeFloating Bodies, Journal of Hydronautics, 9, 2 (1975), pp. 58-63. https://doi.org/10.2514/3.63020

Garrison, C. J., Nonlinear wave loads on Large structures, In Proc. Third Int. Offshore Mechanics and Arctic Engineering Symposium, ASME, Volume 1, pp. 128-135, (1984).

Garrison, C. J. 1979. The consistent second-order theory of wave / structure interaction. Report Number FEDDOCS D 208.14/2: NPS-69-79-010. Naval Postgraduate School, Research Reports Division, Monterey, California, USA. Pages 1-42. Available at: https://core.ac.uk/download/pdf/36722593.pdf (Assessed on: 16th May, 2021).

Gu H., Stansby P., Stallard T., Moreno E.C., (2018). Drag, added mass and radiation damping of oscillating vertical cylindrical bodies in heave and surge in still water. Journal of Fluids and Structures. Volume 82, October 2018, Pages 343-356 https://doi.org/10.1016/j.jfluidstructs.2018.06.012

Guo B., Song S., Chacko J., Ghalambor A. (2005). *Offshore Pipelines.* 1st Ed., Elsevier Publishers (*Gulf Professional Publishing Imprint*), Oxford, UK. https://doi.org/10.1016/B978-0-7506-7847-6.X5052-5

Gong, S., Xu P., Bao S., Zhong W., He N., Yan H., 2014. Numerical modelling on dynamic behaviour of deepwater S-lay pipeline. *Ocean Engineering*, 88, pp.393–408. https://doi.org/10.1016/j.oceaneng.2014.07.016

Haitao, Z.H.A.O., Bin, T., Guangwei, L.I., & Yi-zhu, L. (2003). An experimental study of first-harmonic wave force on vertical truncated cylinder. *China Offshore Platform,* 2003,18(4):12-17, in Chinese.

Hasanvand E., Edalat P. (2021). A Comparison of the Dynamic Response of a Product Transfer System in CALM and SALM Oil Terminals in Operational and Non-Operational Modes in the Persian Gulf region. International Journal of Coastal and Offshore Engineering, Volume 5, Issue 1 (Winter 2021) ijcoe. 2021; 5 (1) :1-14. URL: http://ijcoe.org/article-1-232-en.html (Assessed on: 16th May, 2021).

Hasanvand E., Edalat P. (2020). Sensitivity Analysis of the Dynamic Response of CALM Oil Terminal, in The Persian Gulf Region Under Different Operation Parameters. International Journal of Marine Engineering. Volume 16, Issue 32 (11-2020) (in Persian language). DOI: 10.29252/marineeng.16.32.73. URL: https://marine-eng.ir/article-1-794-en.pdf (Assessed on: 16th May, 2021).

Hasselmann, K., Barnett, T.P., Bouws, E., Carlson, H., Cartwright, D.E., Enke, K., Ewing, J.A., Gienapp, H., Hasselmann, D.E., Kruseman, P., Meerburg, A., Müller, P., Olbers, D.J., Richter, K., Sell, W., Walden, H., 1973. Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). *Ergänzungsheft zur Deutsche Hydrographische Zeitschrift; Ergänzungsheft; Reihe A*, 12(8 0). Available at: http://resolver.tudelft.nl/uuid:f204e188-13b9-49d8-a6dc-4fb7c20562fc (Assessed on: 16th May, 2021).

Hirdaris, S.E., Bai, W., Dessì, D., Ergin, A., Gu, X., Hermundstad, O.A., Huijsmans, R.H., Iijima, K., Nielsen, U.D., Parunov, J., Fonseca, N., Papanikolaou, A.D., Argyriadis, K., & Incecik, A. (2014). Loads for use in the design of ships and offshore structures. Ocean Engineering, 78, 131-174. DOI: 10.1016/j.oceaneng.2013.09.012.

Huang J.B, Eatock R.T. (1996). Semi-analytical solution for second-order wave diffraction by a truncated circular cylinder in monochromatic waves. Journal of Fluid Mechanics, Vol. 319, pp. 171-196. https://doi.org/10.1017/S0022112096007306

Huseby M., Grue J. (2000). An experimental investigation of higher-harmonic wave forces on a vertical cylinder. Journal of Fluid Mechanics, Vol. 414, pp. 75-103 https://doi.org/10.1017/S0022112000008533

Irvine, H.M., 1981. *Cable structures*, USA: MIT Press.

Isaacson M. (1979). Wave forces on compound cylinders. Proc. Civil Engineering in the Oceans IV, ASCE, San Francisco, (1979), 518-530

Isaacson M. (1977). Nonlinear wave forces on large offshore structures. Journal of waterways, harbors and coastal engineering division, ASCE, Vol. 103, No. WW1, Feb. 1977, Technical Notes, pp. 166-170. Available at: https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0005068 (Accessed on: 12th July, 2021).

Isaacson M. (1979). Nonlinear inertia forces on bodies. Journal of the waterway port coastal and ocean division. Vol. 105, No. WW3, pp. 213-227. Available at: https://cedb.asce.org/CEDBsearch/record.jsp?dockey= 0008910 (Accessed on: 12th July, 2021).

Isaacson M., Cheung K.F. (1979) Second order wave diffraction around two-dimensional bodies by time-domain method. Applied Ocean Research Volume 13, Issue 4, August 1991, Pages 175-186 https://doi.org/10.1016/S0141-1187(05)80073-2

Jacobsen L.S. (1949). Impulsive hydrodynamics of fluid inside a cylindrical tank and of fluid surrounding a cylindrical pier. Bulletin of the Seismological Society of America 1949;; 39 (3): 189–204. doi: https://doi.org/10.1785/BSSA0390030189

Jean P., Goessens K., LHostis D. (2005). Failure of Chains by Bending on Deepwater Mooring Systems. OTC-17238-MS. Paper presented at the Offshore Technology Conference, Houston, Texas, USA. May 2–5, 2005. https://doi.org/10.4043/17238-MS

Jiang C., Moctar O., Schellin T.E. & Paredes G.M. (2020). Comparative study of mathematical models for mooring systems coupled with CFD. Ships and Offshore Structures. Volume 16, 2021 - Issue 9, Pages 942-954. <https://doi.org/10.1080/17445302.2020.1790294>

Kang, Y, Sun, L, Kang, Z, & Chai, S. 2014. Coupled analysis of FPSO and CALM buoy offloading system in West Africa. In *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE2014-23118*. California, USA. olume 8A: Ocean Engineering. San Francisco, California, USA. June 8–13, 2014. V08AT06A010. ASME. https://doi.org/10.1115/OMAE2014-23118

Kannah & Natarajan (2006). Experimental investigation of an external turret-moored FPSO system by VALM arrangement. Ships and Offshore Structures. Volume 1, 2006 - Issue 3, Pages 199-212. <https://doi.org/10.1533/saos.2006.0128>

Konovessis D., Chua K.H., Vassalos D. (2013). Stability of floating offshore structures. Ships and Offshore Structures. Volume 9, 2014 - Issue 2, Pages 125-133. <https://doi.org/10.1080/17445302.2012.747270>

Lassen T., Lem A.I., Imingen G. (2014). Load response and finite element modelling of bonded offshore loading hoses. Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE2014, June 8-13, 2014, San Francisco, California, USA, Paper OMAE2014-23545. V06AT04A034. ASME. https://doi.org/10.1115/OMAE2014-23545

Le Cunff, C., Ryu, S., Duggal, A., Ricbourg, C., Heurtier, J-M, Heyl, C., Liu, Y., and Beauclair O. (2007). "Derivation of CALM Buoy Coupled Motion RAOs In Frequency Domain And Experimental Validation." Paper presented at *The Seventeenth International Offshore and Polar Engineering Conference*, Lisbon, Portugal, July 2007. Pages 1-8. Available at: https://www.sofec.com/wp-content/uploads/white\_papers/2007-ISOPE-Derivation-of-CALM-Buoy-Coupled-Motion-RAOs-in-Frequency-Domain.pdf (Accessed on 12th October, 2021).

Le Cunff, C., Ryu, S., Heurtier, J., & Duggal, A.S. (2008). "Frequency-Domain Calculations of Moored Vessel Motion Including Low Frequency Effect." *Proceedings of the ASME 2008 27th International Conference on Offshore Mechanics and Arctic Engineering*. *Volume 1: Offshore Technology*. Estoril, Portugal. June 15–20, 2008. pp. 689-696. ASME. <https://doi.org/10.1115/OMAE2008-57632> Available at: https://www.sofec.com/wp-content/uploads/white\_papers/2008-OMAE-57632-Low-Frequency-Domain-Calculations-of-Moored-Vessel-Motion-including-LF-Effect.pdf (Accessed on 12th October, 2021).

Lebon, L., and J. Remery (2002). "Bonga: Oil Off-loading System using Flexible Pipe." Paper presented at the Offshore Technology Conference, Houston, Texas, May 6-9, 2002. doi: <https://doi.org/10.4043/14307-MS>

Lenci, S. & Callegari, M., 2005. Simple analytical models for the J-lay problem. *Acta Mechanica*, 39, pp.23–39. https://doi.org/10.1007/s00707-005-0239-x

Li A.J., Liu Y. (2019). New analytical solutions to water wave diffraction by vertical truncated cylinders. International Journal of Naval Architecture and Ocean Engineering. Volume 11, 2019, Pages 952-969. <https://doi.org/10.1016/j.ijnaoe.2019.04.006>

Li S.C. et al. (2016). Large scale three-dimensional seepage analysis model test and numerical simulation research on undersea tunnel. Applied Ocean Research, Volume 59, September 2016, Pages 510-520 https://doi.org/10.1016/j.apor.2016.07.013

Lighthill J. (1979). Waves and hydrodynamic loading, In Proc. Second Int. Conference on Behaviour of Offshore Structures, Volume 1, pp. 1-40.

Liu B. Fu D., Zhang Y., CHen X. (2015). Experimental and numerical study on the wave force calculation of a partially immersed horizontal cylindrical float. International Journal of Naval Architecture and Ocean Engineering. Volume 12, 2020, Pages 733-742. https://doi.org/10.1016/j.ijnaoe.2020.08.002

Liu J. Guo A., Li H. (2016). Analytical solution for the linear wave diffraction by a uniform vertical cylinder with an arbitrary smooth cross-section. Ocean Engineering, Volume 126, 1 November 2016, Pages 163-175 https://doi.org/10.1016/j.oceaneng.2016.09.010

MacCarny R.C. and Fuchs R.A., Wave forces on piles: A diffraction theory. U.S. Army Corps of Engineers, Beach Erosion Board, Technical Memo, No. 69 (1954). Available at: https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/3444/1/BEB-TM-69.pdf (Retrieved on 16th May, 2021).

Mahjoobi, J., Etemad-Shahidi, A., and Kazeminezhad, M. H., 2008. Hindcasting of wave parameters using different soft computing methods. Appl. Ocean Res., 30(1): 28–36. https://doi.org/10.1016/j.apor.2008.03.002

MarineBreakawayCouplings (2018). The effectiveness of Marine Breakaway Couplings in minimising risk to FPSO transfer operations: from the perspective of reeled or in-air catenary reeled configurations. Marine Breakaway Couplings White Paper. Available at: https://www.marinebreakawaycouplings.com/wp-content/uploads/2019/01/FPSO-MBC-on-reel-whitepaper-marinebreakawaycouplings-August-2018.pdf (Retrieved on 16th May, 2021).

Mavrakos S.A, Grigoropoulos G.J. (1994). Numerical and experimental investigation of the exciting wave loads on a vertical truncated cylinder. Transactions on Ecology and the Environment vol 8, WIT Press. Available at: https://www.witpress.com/Secure/elibrary/papers/HY94/HY94014FU2.pdf (Accessed on: 12th July, 2021).

Mei, C.C., Numerical methods in water wave diffraction and radiation. Ann. Rev. Fluid Mech., 1978, 10:393-416. https://doi.org/10.1146/annurev.fl.10.010178.002141

Milgram J.H., Halkyard J.E. (1971). Wave forces on large objects in the sea. Journal of Ship Research Vol 15(02), SNAME, June 1971, pp.115-124. https://doi.org/10.5957/jsr.1971.15.2.115

Molin B., Second order diffraction loads upon three dimensional bodies, *Applied Ocean Research* 1, 197-202 (1979). https://doi.org/10.1016/0141-1187(79)90027-0

Moon B.Y., Kim S.Y., Kang G.J. (2008). Initial ship design using a Pearson correlation coefficient and artificial intelligence techniques. International Journal of Modern Physics B, Vol. 22, No. 09n11, pp. 1801-1806 (2008). <https://doi.org/10.1142/S0217979208047444>

Morison, J.R., Johnson, J.W., and S.A. Schaaf., 1950. The Force Exerted by Surface Waves on Piles. *J Petroleum Transactions, AIME*, 2 (1950) 189, pp.149–154. https://doi.org/10.2118/950149-G

MSF, 2013. *Guidelines for offshore marine operations (GOMO)*, London, UK: Marine Safety Forum (MSF). Available at: http://www.g-omo.info/wp-content/uploads/2016/06/201311-GOMOfinal.pdf. (Accessed on: 12th July, 2021).

Nallayarasu S., Kumar N.S. (2017). Experimental and numerical investigation on hydrodynamic response of buoy form Spar under random waves. Ships and Offshore Structures. Volume 12, 2017 - Issue 5, Pages 734-746. <https://doi.org/10.1080/17445302.2016.1218600>

Newman J.N. (1996). The second-order wave force on a vertical cylinder. Journal of Fluid Mechanics, Vol. 320, pp. 417-443. https://doi.org/10.1017/S0022112096007598

Newman J.N. (1967). The drift force and moment of ships in waves. Journal of ship research., VOl. 11(01), SNAME, March 1967. pp. 51-60 https://doi.org/10.5957/jsr.1967.11.1.51

Newman J.N. (1963). The exciting forces on fixed bodies in waves. Report No 171, David Taylor Model A Basin, Hydrodynamics Laboratory, Washington D.C.

Malenica S., Molin B. (1995). Third-harmonic wave diffraction by a vertical cylinder. Journal of Fluid Mechanics, Vol. 320, pp. 203-229. https://doi.org/10.1017/S0022112095004071

O’Donoghue, T. & Halliwell, A.R., 1990. Vertical bending moments and axial forces in a floating marine hose-string. *Engineering Structures*, 12(4), pp.124–133. https://doi.org/10.1016/0141-0296(90)90018-N

O’Sullivan, M., 2003. Predicting interactive effects of CALM buoys with deepwater offloading systems. *Offshore Magazine*, 63(1). Available on: https://www.offshore-mag.com/production/article/16755731/predicting-interactive-effects-of-calm-buoys-with-deepwater-offloading-systems (Retrieved on: 16th May, 2021).

O’Sullivan, M., 2002. West of Africa CALM Buoy Offloading Systems. *MCS Kenny Offshore Article*. Available at: http://www.mcskenny.com/downloads/Software - Offshore Article.pdf. (Retrieved on: 16th June, 2019).

OCIMF, 2009. *Guide to Manufacturing and Purchasing Hoses for Offshore Moorings (GMPHOM)*, Livingstone, UK: Witherby Seamanship International Ltd.

Odijie, A.C., Quayle, S. & Ye, J., (2017a). Wave induced stress profile on a paired column semisubmersible hull formation for column reinforcement. *Engineering Structures*, 143, pp.77–90. Available at: http://dx.doi.org/10.1016/j.engstruct.2017.04.013.

Odijie, A.C., Wang, F. & Ye, J., (2017b). A review of floating semisubmersible hull systems: Column stabilized unit. *Ocean Engineering*, 144, pp. 191–202. Available at: https://doi.org/10.1016/j.oceaneng.2017.08.020.

Odijie, A.C.; Ye, J. (2015a). Effect of Vortex Induced Vibration on a Paired-Column SemiSubmersible Platform. *Int. J. Struct. Stab. Dyn.* **2015**, *15*, 8. <https://doi.org/10.1142/S0219455415400192>

Odijie, A.C.; Ye, J. (2015b). Understanding Fluid-Structure Interaction for high amplitude wave loadings on a deep-draft paired column semi-submersible platform: A finite element approach. In Proceedings of the 4th International Conference on Light Weight Design of Marine Structures, Glasgow, UK, 09–11 November 2015.

Odijie, A.C. (2016). Design of Paired Column Semisubmersible Hull. Ph.D. Thesis. Lancaster University, Engineering Department, Lancaster, UK, 2016. Available at: <https://eprints.lancs.ac.uk/id/eprint/86961/1/2016AgbomeriePhD.pdf> (Accessed on 14 June 2021).

Oil&GasUK, 2014. *Tandem Loading Guidelines, Issue 3*, London, UK: Oil & Gas UK. Available at: http://www.marinesafetyforum.org/images/Tandem\_Loading\_Guidelines\_Issue 3 Nov 14.pdf. (Retrieved on: 16th May, 2021).

Orcina, 2014. *OrcaFlex Manual, Version 9.8a*, Ulverton, Cumbria, UK: Orcina Ltd. Available at: https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/index.php. (Retrieved on: 16th May, 2021).

Orcina, 2021. *Orcaflex Documentation, Version 11.0f.* Available at: <https://www.orcina.com/webhelp/OrcaFlex/Default.htm> . (Accessed on 4th May, 2021).

Orcina 2020. Vessel theory: RAOs and phases. Available: <https://www.orcina.com/webhelp/OrcaFlex10.3d/Content/html/VesseltheoryRAOsandphases.htm> (Accessed 15th Dec. 2020).

Palmer A.C., King R.A. (2008). Subsea Pipeline Engineering. 2nd Edition. PennWell Corporation, Oklahoma, USA.

Pecher A., Foglia A., Kofoed J.P. (2014). Comparison and Sensitivity Investigations of a CALM and SALM Type Mooring System for Wave Energy Converters. Journal of Marine Science and Engineering 2(1):93-122. DOI: 10.3390/jmse2010093

Petrone, C., Oliveto, N.D. & Sivaselvan, M. V., 2015. Dynamic Analysis of Mooring Cables with Application to Floating Offshore Wind Turbines. *Journal of Engineering Mechanics*, 142(3), pp.1–12. http://dx.doi.org/10.1061/(ASCE)EM.1943-7889.0000999

Pham, D., Sridhar, N., Qian, X., Sobey, A., Achintha, M. and Shenoi, A. (2016). A review on design, manufacture and mechanics of composite risers. Ocean Engineering, Volume 112, 15 January 2016, Pages 82-96 <https://doi.org/10.1016/j.oceaneng.2015.12.004>

Pierson, Willard J., Jr. and Moskowitz, Lionel A. Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S. A. Kitaigorodskii, *Journal of Geophysical Research*, Vol. 69, p.5181-5190, 1964. https://doi.org/10.1029/JZ069i024p05181

Pinkster, J.A., and G.F.M. Remery, 1975. "The Role of Model Tests in the Design of Single Point Mooring Terminals." Paper presented at the Offshore Technology Conference, Houston, Texas, May 4–7, 1975. doi: <https://doi.org/10.4043/2212-MS>

Poguluri S.K. & Cho I.H. (2020). Analytical and numerical study of wave interaction with a vertical slotted barrier. Ships and Offshore Structures. Volume 16, 2021 - Issue 9, Pages 1012-1024. https://doi.org/10.1080/17445302.2020.1790299

Quash, J.E., & Burgess, S. (1979). Improving underbuoy hose system design using relaxed storm design criteria. Paper presented at the Offshore Technology Conference, Houston, Texas, April 30–May 3, 1979. doi: https://doi.org/10.4043/3565-MS

Quéau, L.M., Kimiaei, M. & Randolph, M.F., 2015. Approximation of the maximum dynamic stress range in steel catenary risers using artificial neural networks. *Engineering Structures*, 92, pp.172–185. https://doi.org/10.1016/j.engstruct.2015.02.025

Quéau, L.M., Kimiaei, M. & Randolph, M.F., 2011. Dynamic Amplification Factors for Response Analysis of Steel Catenary Risers at Touch Down Areas. In *International Conference on Offshore and Polar Engineering (ISOPE) Proceedings*. Maui, Hawaii, USA: ISOPE, pp. 1–5. Available at: https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE11/All-ISOPE11/ISOPE-I-11-233/13224 (Retrieved on: 16th May, 2021).

Rahman M., Nonlinear hydrodynamic loading on offshore structures, Journal of Theoretical and Computational Fluid Dynamics, (Special issue in tribute to Sir James Lighthill, FRS) 9, 25 pages (1997)

Rahman M., Wave diffraction by large offshore structures: An exact second-order theory, Applied Ocean Research 6, 90-100 (1984) https://doi.org/10.1016/0141-1187(84)90046-4

Raman, H. and Venkatanarasaiah, P., 1976. Forces due to nonlinear waves on vertical cylinders. Journal of the Waterways, Harbors and Coastal Engineering Division , Proc. ASCE, Vol. 102, No. WW3.

Raman, H., Jothishankar, N. and Venkatanarasaiah, P. 1977 Nonlinear wave interaction with vertical cylinder of large diameter. Journal of Ship Research , SNAME Vol. 21, No. 2, 120-124.

Randolph, M. & Quiggin, P., 2009. Non-linear hysteretic seabed model for catenary pipeline contact. OMAE2009-79259. In *28th International Conference on Ocean, Offshore and Arctic Engineering Proceedings*. Honolulu, Hawaii, USA: ASME, pp. 1–10. https://doi.org/10.1115/OMAE2009-79259

Ricbourg, C., Berhault, C., Camhi, A., Lécuyer, B., and R. Marcer.  2006. Numerical and Experimental Investigations on Deepwater CALM Buoys Hydrodynamics Loads. Paper Number OTC 18254-MS. In *Offshore Technology Conference Proceeding,* Houston, Texas, USA, May 1-4, 2006. Publisher: OnePetro, pp. 1–8. https://doi.org/10.4043/18254-MS

Roveri, F.E., Volnei, Luís Sagrilo, S. & Cicilia, F.B., 2002. A Case Study on the Evaluation of Floating Hose Forces in a C.A.L.M. System. In *Internation Offshore and Polar Engineering Conference*. Kitakyushu, Japan, May 2002: ISOPE, Paper Number: ISOPE-I-02-030, pp. 190–197. Available at: https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE02/All-ISOPE02/ISOPE-I-02-030/8329 (Retrieved on: 16th May, 2021).

Ryu, S., Duggal, A.S., Heyl, C.N., and Yonghui Liu, 2006. Prediction of Deepwater Oil Offloading Buoy Response and Experimental Validation. *International Journal of Offshore and Polar Engineering*, 16(3), pp.1–7. Available at: https://www.sofec.com/wp-content/uploads/white\_papers/2006-ISOPE-Prediction-of-DW-Oil-Offloading-Buoy-Response.pdf (Retrieved on: 16th May, 2021).

Sabuncu T, Calisal S. (1981). Hydrodynamic coefficients for vertical circular cylinders at finite depth. Ocean Engineering, Vol. 8, pp. 25-63. https://doi.org/10.1016/0029-8018(81)90004-4

Sagrilo, L.V.S. et al., 2002. A coupled approach for dynamic analysis of CALM systems. *Applied Ocean Research*, Vol. 24 (1), pp. 47–58. https://doi.org/10.1016/S0141-1187(02)00008-1

Saito, Hideaki, Mochizuki, Takao, Fukai, Toshio, and Kenzo Okui (1980). "Actual Measurement Of External Forces On Marine Hoses For SPM." Paper presented at the Offshore Technology Conference, Houston, Texas, May 5-8, 1980. doi: <https://doi.org/10.4043/3803-MS>

Salem, A.G. et al., 2012. Linearization of Quadratic Drag to Estimate CALM Buoy Pitch Motion in Frequency-Domain and Experimental validation. *Journal of Offshore Mechanics and Arctic Engineering*, 134(11305–1), pp.3–8. Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering. Volume 1: Offshore Technology. Honolulu, Hawaii, USA. May 31–June 5, 2009 https://doi.org/10.1115/OMAE2009-80212

Santala, M.J. & Wang, H., 2016. Component Approach for Confident Predications of Deepwater CALM Buoy Coupled Motions - Part 2: Analytical Implementation -OMAE2005-67140. ASME 2005 24th International Conference on Offshore Mechanics and Arctic Engineering, (Omae 2005), pp.1–9. DOI:10.1115/OMAE2005-67140

Sarpkaya, T., 2014. *Wave forces on offshore structures* 1st ed., New York, USA: Cambridge University Press.

Sparks C.P. 2007. *Fundamentals of Marine Riser Mechanics: Basic Principles and Simplified Analyses*, 1st Ed., PennWell Books, Oklahoma, USA.

Sparks C.P. 2018. *Fundamentals of Marine Riser Mechanics: Basic Principles and Simplified Analyses*. 2nd Ed., PennWell Books, Oklahoma, USA.

Sun, L, Zhang, X, Kang, Y, & Chai, S. (2015). "Motion Response Analysis of FPSO’s CALM Buoy Offloading System." Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering. Volume 11: Prof. Robert F. Beck Honoring Symposium on Marine Hydrodynamics. St. John’s, Newfoundland, Canada. May 31–June 5, 2015. V011T12A008. ASME, pp. 1–7. https://doi.org/10.1115/OMAE2015-41725

TechFlowMarine 2021. Marine Coupling Systems. Available at: <http://www.techflowmarine.com/products/marine-coupling-system/> Retrieved on: 16th May, 2021

Toh W., Tan L.B., Jaiman R.K., Tay T.E., Tan V.B.C. (2018). A comprehensive study on composite risers: material solution, local end fitting design and local design. Marine Structures 61 (2018), 155-169. <https://doi.org/10.1016/j.marstruc.2018.05.005>

Tonatto, M. L., Forte M. M. C. & Amico, S. C. (2016). Compressive-tensile fatigue behavior of cords/rubber composites. Polymer Testing, Volume 61, August 2017, Pages 185-190 <https://doi.org/10.1016/j.polymertesting.2017.05.024>

Tonatto, M. L., Forte M. M. C., Tita, V., & Amico, S. C. (2016). Progressive damage modeling of spiral and ring composite structures for offloading hoses. Materials & Design, Volume 108, Issue 2016, Pages 374-382. <https://doi.org/10.1016/j.matdes.2016.06.124>

Tonatto, M. L., Tita, V., & Amico, S. C. (2020). Composite spirals and rings under flexural loading: Experimental and numerical analysis. *Journal of Composite Materials*, *54*(20), 2697–2705. [https://doi.org/10.1177/0021998320902504](https://doi.org/10.1177%2F0021998320902504)

Tonatto, M. L., Tita, V., Araujo R. T., Forte M. M. C., & Amico, S. C. (2017). Parametric analysis of an offloading hose under internal pressure via computational modelling. Marine Structures, Volume 51, Issue 2017, Pages 174-187 <https://doi.org/10.1016/j.marstruc.2016.10.008>

Tonatto, M. L., Tita, V., Forte M. M. C. & Amico, S. C. (2018). Multi-scale analyses of a floating marine hose with hybrid polyaramid/polyamide reinforcement cords. Marine Structures, Volume 60,  Pages 279-292 <https://doi.org/10.1016/j.marstruc.2018.04.005>

Tonatto, MLP, Roese, PB, Tita, V, et al. (2019). Offloading marine hoses: computational and experimental analyses. In book: *Marine Composites: Design and Performance*, (Editors: Pemberton R., Summerscales J., Graham-Jones J.). Elsevier Publisher (Woodhead Publishing imprint), Cambridge, UK. pp. 389–416. DOI: [10.1016/B978-0-08-102264-1.00014-5](https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1016%2FB978-0-08-102264-1.00014-5?_sg%5B0%5D=LtE46mE3bZTY07p4sBFRxO_8hKt4lLOQ0_oQt7KSVA1vbQi_lGtpA5ol04LB4hN6WBpBmylnl0e9n2mpMj-cCH7qoQ.lF03PCDAYSrEaHb0QDSDJzrofQDPZDaN31cp8baOtenyDfVEWiD1eyc1dW4_sOEOdLSagH-kWVDbLo_vhj8F-Q)

Trelleborg, 2018. *Oil & Gas Solutions: Oil & Gas Hoses for Enhanced Fluid Transfer Solutions*; *Vol. 1, page 1-30*. Trelleborg Fluid Handling Solutions. Oil & Marine Hoses: Innovation and Safety for Oil & Gas Transfer Systems. Trelleborg: Clemont-Ferrand, France.

Trelleborg (2016). *Hose assembly Handling guide*, page 1-5. Trelleborg Fluid Handling Solutions. Clemont-Ferrand, France: Trelleborg. Available at: https://www.trelleborg.com/fluidhandling/-/media/fluid-handling-solutions/guidelines/gb/gb\_guide\_handling\_trelleborg.pdf (Accessed on 23rd November, 2021).

Tschoepe, Emil C., and George K. Wolfe (1981). "SPM Hose Test Program." Paper presented at the Offshore Technology Conference, Houston, Texas, May 4-7, 1981. doi: <https://doi.org/10.4043/4015-MS>

Venugopal V., Varyani K.S., Westlake P.C. (2008). Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment. 2009;223(1):121-136. doi:10.1243/14750902JEME124

Vugts, J.H. (1968). ‘The Hydrodynamic Coefficients for Swaying, Heaving and Rolling Cylinders in a Free Surface’. Report 112 S; 194-P/TNO, Netherlands Ship Research Centre TNO, Shipbuilding Laboratory, Delft Technological University, Netherlands. Available at: http://resolver.tudelft.nl/uuid:5c647df4-3f70-4451-8895-13d1f08bf769 (Accessed on 23rd November, 2021).

Wall, M., Pugh H.R., Reay A. & Krol J. 2001. *Failure Modes, Reliability and Integrity of Floating Storage Unit (FPSO, FSU) Turret and Swivel Systems*, Abingdon, UK: HSE Books. Available at: http://www.hse.gov.uk/research/otohtm/2001/oto01073.htm. (Retrieved on: 16th May, 2021).

Wang, D. & Sun, S., 2015. Study of the Radiation Problem for a CALM Buoy with Skirt. *Ship Building of China*, Vol. 56(1), pp. 95–101.

Wang, D. & Sun, S., 2013. An analytical solution of wave exciting loads on CALM Buoy with Skirt. Applied Mechanics and Materials, Vol. 477-478, pp. 254-258 DOI:10.4028/www.scientific.net/AMM.477-478.254

Wang, F., Chen J., Gao S., Tang K., Meng X. (2017). Development and sea trial of real-time offshore pipeline installation monitoring system. *Ocean Engineering*, Volume 146, Pages 468-476. Available at: https://doi.org/10.1016/j.oceaneng.2017.09.016.

Wang, F., 2018. Effective design of submarine pipe-in-pipe using Finite Element Analysis. *Ocean Engineering*, 153, pp.23–32. https://doi.org/10.1016/j.oceaneng.2018.01.095

Wang, F. & Han, L., 2019. Analytical behaviour of carbon steel-concrete-stainless steel double skin tube (DST) used in submarine pipeline structure. *Marine Structures*, 63, pp.99–116. https://doi.org/10.1016/j.marstruc.2018.09.001

Wang L.P. et al. 2016. Application of linear mean-square estimation in ocean engineering. China Ocean Eng 30, 149–160 (2016). https://doi.org/10.1007/s13344-016-0007-9

Webster W., Kang Z., Liang W., Kang Y., Sun L., 2011. Bundled hybrid offset riser global strength analysis. *Journal of Marine Science and Application* 10(4): 465–470. https://doi.org/10.1007/s11804-011-1092-z

Wichers, I.J., 2013. *Guide to Single Point Moorings*, Houston, USA: WMooring Inc. Available at: [wmooring.com/files/Guide\_to\_Single\_Point\_Moorings.pdf](http://wmooring.com/files/Guide_to_Single_Point_Moorings.pdf) (Accessed on: 12th August, 2021).

Williams, N.A. & McDougal, W.G., 2013. Experimental Validation Of A New Shallow Water Calm Buoy Design - OMAE2013-11392. In *International Conference on Ocean, Offshore and Arctic Engineering*. Nantes, France: ASME, pp. 1–6.

Wilson, J.F., 2003. *Dynamics of offshore structures* 2nd ed., New Jersey, USA: John Wiley and Sons.

Wu G.X. (1991). Hydrodynamic forces on a submerged cylinder advancing in water waves of finite depth. Journal of Fluid Mechnaics, Vol. 224, pp. 645-659. doi:10.1017/S002211209100191X

Ye J., Cai H., Liu L., Zhai Z., Amaechi C. V., Wang Y., Wan L., Yang D., Chen X., Ye J. (2021). Microscale intrinsic properties of hybrid unidirectional/woven composite laminates: Part Ⅰ: experimental tests. Composite Structures, Vol. 262, Issue 113369. <https://doi.org/10.1016/j.compstruct.2020.113369>

Ye, J., 2016. *Structural and Stress Analysis: Theories, tutorials and examples* Second., New York, USA: CRC Press.

Yeung, R.W., 1981. Added mass and damping of a vertical cylinder in finite-depth waters, Applied Ocean Research 3(3):119-133. https://doi.org/10.1016/0141-1187(81)90101-2

Yokohama, 2016. *Seaflex Yokohama Offshore loading & discharge hose*, Hiratsuka City, Japan: The Yokohama Rubber Co. Ltd. Available at: https://www.y-yokohama.com/global/product/mb/pdf/resource/seaflex.pdf (Accessed on: 17th May 2021).

Young, Raymond A., Brogren, Erik E., and Subrata K. Chakrabarti. "Behavior Of Loading Hose Models In Laboratory Waves And Currents." Paper presented at the Offshore Technology Conference, Houston, Texas, May 5-8, 1980. doi: <https://doi.org/10.4043/3842-MS>

Yu H., Zheng S., Zhang Y., Iglesias G. (2019). Wave radiation from a truncated cylinder of arbitrary cross section. Ocean Engineering, Volume 173, 1 February 2019, Pages 519-530 https://doi.org/10.1016/j.oceaneng.2019.01.013

Yuan Z., Huang Z. (2015). Morison coefficients for a circular cylinder oscillating with dual frequency in still water: an analysis using independent-flow form of Morison’s equation. J. Ocean Eng. Mar. Energy (2015) 1:435–444. DOI 10.1007/s40722-015-0030-6

Zhang D., Paterson E. (2015). A study of wave forces on an offshore platform by direct CFD and Morison equation. E3S Web of Conferences 5:04002. DOI:10.1051/e3sconf/20150504002

Zhang S.F., Chen C., Zhang Q.X., Zhang D.M., Zhang F. (2015). Wave Loads Computation for Offshore Floating Hose Based on Partially Immersed Cylinder Model of Improved Morison Formula. The Open Petroleum Engineering Journal, Vol 8, pp. 130-137. Publisher Id: TOPEJ-8-130. DOI: 10.2174/1874834101508010130

Zheng S., Zhang Y. (2016). Wave radiation from a truncated cylinder in front of a vertical wall. Ocean Engineering, Volume 111, 1 January 2016, Pages 602-614https://doi.org/10.1016/j.oceaneng.2015.11.024

Zhou X.L. et al. (2014). Wave and current induced seabed response around a submarine pipeline in an anisotropic seabed. Ocean Engineering, Vol 75, pp. 112-27. https://doi.org/10.1016/j.oceaneng.2013.11.016

Zhou Y., Duan M.L., Ma J.M., Sun G.M. (2018). Theoretical analysis of reinforcement layers in bonded flexible marine hose under internal pressure, Eng. Struct. 168 (2018) 384–398. <https://doi.org/10.1016/j.engstruct.2018.04.061>

Ziccardi, J.J. & Robbins, H.J., 1970. Selection of Hose Systems for SPM Tanker Terminals. In *Offshore Technology Conference Proceeding -OTC 1152*. Dallas, Texas, USA: OnePetro, pp. 83–94. https://doi.org/10.4043/1152-MS

Zou, J. (2008). "Dynamic Responses of a Dry Tree Semi-submersible Platform with Ram Style Tensioners in the Post-Katrina Irregular Seas." In *The Eighteenth International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers, Vancouver, Canada, July 2008. Available at: https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE08/All-ISOPE08/ISOPE-I-08-031/10683 (Retrieved on: 16th May, 2021).

Zou J., Poll P., Roddier D., Tom N., Peiffer N. (2013). "VIM Testing of a Paired Column Semi Submersible." In *ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, pp. V007T08A001-V007T08A001. American Society of Mechanical Engineers, 2013. https://doi.org/10.1115/OMAE2013-10001

Zou J., Poll P., Antony A., Das S., Padmanabhan R., Vinayan V., Parambath A. (2014). "VIM Model Testing and VIM Induced Mooring Fatigue of a Dry Tree Paired-Column Semisubmersible Platform." In*Offshore Technology Conference*. Offshore Technology Conference, 2014. https://doi.org/10.4043/25427-MS