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VERTICAL CONNECTION OF AN UNDERWATER FLEXIBLE PIPE IN A SUBSEA EQUIPMENT

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Abstract. *The present study describes the numerical analysis of the Subsea Flexible Pipe installation method named as "Direct Vertical Connection". This type of operation is widely employed in offshore deep water petroleum fields in Brazil, and the main concept is to connect the flexible pipe in the subsea equipment by using a Vertical Connection Module. The commercial software OrcaFlex is used to perform the numerical analysis of the operation. For this purpose, an external function is implemented to represent the reaction of the subsea equipment to the Vertical Connection Module, i.e., the elastic stiffness of the subsea equipment is represented by a Euler–Bernoulli beam. Lumped mass method is used to represent the flexible pipe through the numerical tool, in which the physical properties and loads such as mass, weight, buoyancy, drag forces are discretely distributed at the nodes. The hydrodynamic forces are considered according to Morison formulation. A sensitivity study is proposed by varying the inertia and drag coefficients in the Morison formulation, in order to verify their influence in the system response through the bending moments, wall tensions and shear forces.*

Keywords: *Vertical Connection Module, Production Riser, Riser installation method, Direct Vertical Connection*

1. INTRODUCTION

The discoveries of offshore petroleum fields in the last decade have led to technological challenges regarding the development of production systems. In offshore Brazil, most of the attractive reservoirs are located in deep water depth in which a subsea equipment should be operated without the assistance of a diver. In this scenario, one critical operation is the connection of a flexible pipe to the subsea equipment (Moreira *et al.*, 1996).

In deepwater, floating platforms and ships are used as a base for operations to install or to retrieve field development equipment. Offshore operations are usually exposed to static and dynamic loads coming from the environment, caused by wind, waves and sea current.

Many research projects have been conducted with respect to installation of flexible pipes. Bai and Bai (2014) provided a general introduction to flexible pipe installation, and classified the pipe laying operation using a reel ship as the best method in consideration of economic issues. For pipes installed by reel ships, the main factor that affects the loads during lay down and pull in operations are the pipe axial and bending stiffness (Johnston, 1992). Regarding the loads induced by the flexible pipe in the structure during the installation, De Souza *et al.* (2001) used a finite element analysis program to evaluate the installation loads due to pipe self-weight, crush forces applied by the tensioning system, and compared the results with experimental tests. Liu and Ding (2012) studied the stress distribution in the flexible pipe in the touchdown point and in the pipe laying vessel during the installation phase. Sevillano *et al.* (2013) presented a study of a riser behavior during a subsea equipment installation, and performed an evaluation of loads acting in the structure for several environmental conditions. Gay Neto and Martins (2013) presented a numerical methodology to analyze structural instabilities due to residual torsion in the flexible pipe during lay operation. Sun and Kang (2015) investigated the structural behavior of a Flowline Jumper installation under a range of environmental conditions. Ting *et al.* (2017) reported the details of an installation of a flexible pipe connected to a Pipeline End Termination. Ribeiro and Vaz (2017) derived analytical equations to study the physical phenomenon of pipeline installation in flooding condition.

With reference to Direct Vertical Connection, Lopes (2005) performed an investigation regarding the influence of flexible pipe bending stiffness on loads induced in the subsea equipment, Bicudo (2009) detailed the procedure of flexible pipe installation by using Vertical Connection Module, and also the global and local analyses by the Finite Element Method. A recent work by Santos *et al.* (2015) reported that excessive loads may occur in the gooseneck due to the load transfer from the flexible pipe to the Vertical Connection Module. The curvature of the flexible pipe and the bend restrictor limits were observed during the connection operation. Later on, inclination of the Vertical Connection Module was addressed, and the influence of entrance angle during the connection was investigated (Freitas *et al.*, 2017).

During an operation for the installation of a subsea equipment in offshore deepwater, the floating vessel and subsea equipment have effects of the hydrodynamic loads from the environment. Hydrodynamic loads can be estimated from one of the following approaches: the Diffraction theory, the Froude–Krylov theory or the Morison equation assumptions (Chakrabarti, 1987). In the case of the Diffraction theory, it is considered that the structure modifies the characteristics of the wave field in the vicinities of the floating vessel or subsea equipment. The Keulegan – Carpenter parameter (KC) determine the importance of diffraction effects, and it is expected when dimensions of the floating or underwater body are in the same magnitude of the wave length. In the case of the structure size is relatively small compared with the wave length, the force induced by the fluid in the structure can be represented as the sum of a term proportional to the structure inertia and another term proportional to the drag force. The Froude Krylov theory can be applied for the case in which the inertia force is predominant. On the other hand, Morison equation (Morison *et al.*, 1950) is applicable in the case when the drag force prevails compared to the inertia force component. In the present study, the modified Morison equation is used to represent the fluid-structure interaction as detailed in Sumer and Fredsøe (2006), in which there are three components, the inertia, the Froude Krylov and the drag force. The principle of inertia component is that the fluid particle carries momentum with it, and when it passes through the cylinder boundary, it accelerates and decelerates, for this reason, it is required work to be done by the cylinder to increase its momentum. The concept related to the drag force is the presence of a differential pressure in the upstream of the cylinder compared to the downstream. The third term in Morison equation is the Froud Krylov, which represents the inertia carried by the fluid.

The main aim of the present study is to investigate the influence of hydrodynamic coefficients in the behavior of the system during the Direct Vertical Connection operation. Several inertia and drag coefficients are used in order to obtain a range of results and study its influence.

2. METHODOLOGY

Numerical simulations are performed to analyze the Direct Vertical Connection operation in an offshore deepwater operation. A numerical model was developed and the computational tool OrcaFlex has been used. Structural behavior of a flexible pipe is simulated for an operation to realize a Direct Vertical Connection.

2.1 The Direct Vertical Connection

Brandao and Couto (1992) present the concept of the Vertical Connection Module (VCM) to connect a flexible pipe to a subsea equipment. The main issue of this operation was the remotely operated connection system as an alternative to the diver assisted pull-in. The VCM is composed by a mechanical connector hydraulically actuated, a gooseneck and a metal to metal seal. The subsea equipment has a receptacle and an orientation system to receive the VCM in the correct position. Figure 1 shows a schematic representation of the operation.

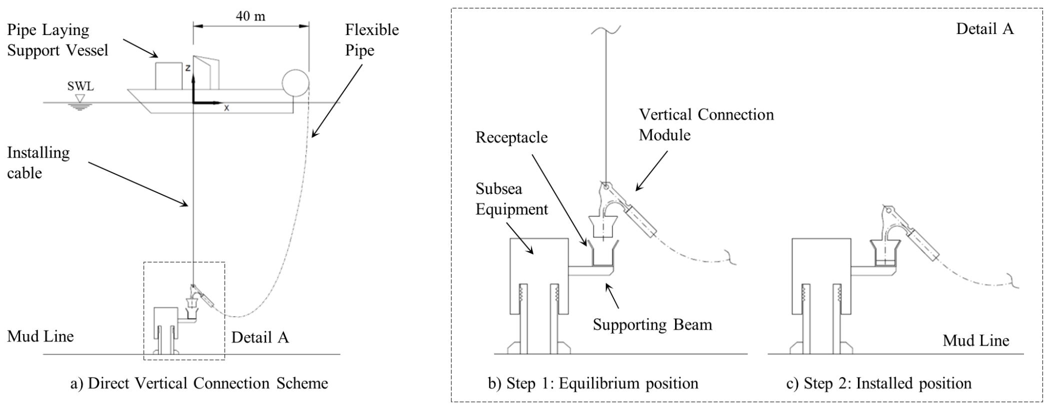


Figure 1. Direct Vertical Connection

The operation may be described in two steps. In the first step, Fig. 1b the VCM is positioned near the receptacle with assistance of an installing cable. After the equilibrium position is achieved, the VCM is released to reach the receptacle.

During this stage, the flexible pipe induces loads in the Vertical Connection Module, which is the major interest of the present work. Figure 1c shows the Vertical Connection Module installed in its final position (step 2).

2.2 Environmental Loads

During the installation process, the flexible pipe is subjected to loads due to action of its self weight, waves, sea current, buoyancy and the movements of the Pipe Laying Support Vessel (PLSV). In order to estimate wave forces, the Linear Airy wave theory is commonly used to approach the design of offshore structures (Chakrabarti, 1987), in general. In this approach, a two-dimensional regular progressive wave is adopted, and the wave height is considered small when compared with the water depth. The flow is taken irrotational and the fluid is ideal, and the wave profile is described by its wave period and wave height. A flat, rigid and uniform sea bottom with constant water depth is also assumed in this modeling.

2.3 Pipe Laying Support Vessel

In offshore operations, attention is given to the determination of the behavior of ships due to wave and current in the open ocean environment. Pipe Laying Vessel is designed aiming to minimize vessel vertical motions for the flexible pipe installation. In this scenario, direction of incident waves and the ship hull design play an important role in the vessel motions. Figure 2 shows the orientation of incident wave and the rigid body motion directions in a PLSV.

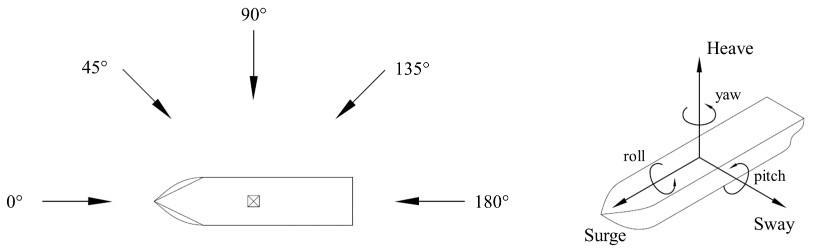


Figure 2. Vessel motions and incident wave directions

To investigate the behavior of the vessel in different sea states, the transfer function known as Response Amplitude Operator (RAO) are applied. The RAO are usually needed in the design phase of the vessel, and they can be obtained by reduced scale model experiments or through numerical simulations. In the present study, RAOs of a PLSV operated in the Bicudo (2009) were used. Figure 3 shows the RAO, amplitude and phase of motions for the incident wave from 0°.

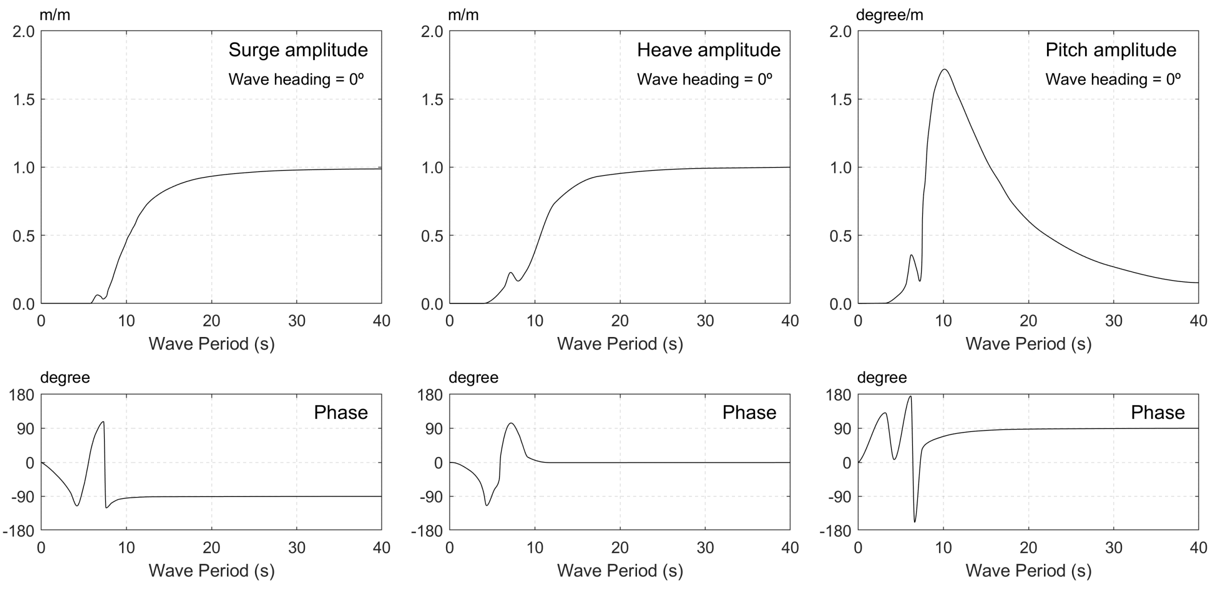


Figure 3. Response Amplitude Operator – Incident Wave from 0°

The RAO of the PLSV is used in the numerical simulations carried out for the operation of the Direct Vertical Connection.

2.4 Numerical model

A numerical model was developed for simulations by using the OrcaFlex, a fully 3D non-linear time domain commercial software. Line structures are divided into segments and the Lumped Mass method is adopted, which means that all the physical properties and loads, namely mass, weight, buoyancy, drag forces are "lumped" discretely at the nodes of each segment. The first step of the evaluation is to perform a static analysis, in which an iterative numerical process is applied for finding the equilibrium position of the flexible pipes and other bodies in the simulation. The second step is called build up step, when the environmental loads are gradually applied at the bodies in the simulation. And, finally, the third step is the dynamic analysis, in which the bodies are subjected to the wave loads, current and external forces. A two-dimensional approach is considered to evaluate the Direct Vertical Connection installation process. The dynamic equation for the VCM and flexible pipe can be written, as follows:

$$[M]\left\{\ddot{d}\right\} + [C]\left\{\dot{d}\right\} + [K]\left\{d\right\} = \left\{f\right\} \tag{1}$$

where $[M]$ is the lumped mass matrix, $[C]$ is the damping matrix and $[K]$ is the element stiffness matrix, and $\{f\}$ is the external load vector. Vector $\{d\}$ is the displacement of the structure, and its first and second time derivatives represent the velocity and acceleration respectively. The hydrodynamic forces in the VCM and flexible line are computed as shown in Eq. (2). The modified Morison equation for a moving body in an oscillatory flow was considered (Chakrabarti, 1987; Orcina, 2018):

$$F = \rho A\dot{U} + \rho C_a A\left(\dot{U} - \ddot{d}\right) + \frac{1}{2}\rho C_D D\left(U - \dot{d}\right)\left|U - \dot{d}\right| \tag{2}$$

where, F represents the total inline force acting in the flexible pipe, ρ is the mass density of water, C_a is the added mass coefficient, C_D is the drag coefficient, U is the local water particle velocity at the centerline of the cylinder, D is the cylinder external dimeter, A is the external diameter cross-section area, dots stands for time derivatives, and the inertia coefficient is defined as $C_M(= 1 + C_a)$. The first term of Eq. (2) is known as Froude-Krylov force, which represents the absolute motion of the fluid, the second term is the added mass component and the third term is the drag force which is proportional to the relative velocity between the fluid and the structure.

2.5 External Function

OrcaFlex accepts data given by an user-defined external function for simulations. A Python script was implemented to represent a cantilever beam structure which models stiffness for the quasi-static reaction behavior of the Subsea Equipment when the VCM touches during the operation of connection. The dynamic equation of a uniform beam structure with uniform cross–section is as follows:

$$EI\frac{\partial^4 w}{\partial x^4}(x,t) + \rho_b A_b \frac{\partial^2 w}{\partial t^2}(x,t) = f(x,t) \tag{3}$$

where, E is the Young's Modulus, I is the moment of inertia of plane area , w is the vertical deflection of the beam, x is the spatial position, ρ_b is the mass density of the beam, A_b is the cross-section area of the beam. For the sake of simplicity, the inertial term is neglected and only the stiffness effect is accounted. The boundary conditions for the cantilever beam with a concentrated vertical load in the free tip are listed in the following Equations (4).

$$w(0) = 0 \qquad \frac{\partial w}{\partial x}(0) = 0 \qquad \frac{\partial^2 w}{\partial x^2}(L) = 0 \qquad \frac{\partial^3 w}{\partial x^3}(L) = -P \tag{4}$$

Then, Equations (3) and (4) gives the vertical deflection of the cantilever beam structure given the concentrated load at the beam tip, as follows:

$$w(L) = \frac{PL^3}{3EI} \tag{5}$$

Calculating the bending stiffness of the access receptacle for the VCM at the Subsea Equipment, and replacing by an equivalent cantilever beam, then the dynamic simulation of connecting process can be made.

2.6 Subsea Equipment

Flexible pipes may be connected to a production or injection subsea equipment such as, Manifolds, Terminals, Wet christmas tree, or Hybrid risers systems. The subsea equipment studied herein is a Production Adapter Base (PAB), also known as tubing spool. Its main function is to provide a housing for the tubing hanger, to serve as a structure base to install the wet christmas tree, and to connect the flowlines through the VCM (Prado *et al.*, 1999).

The PAB primary structure described here is composed by three structural members. The first one is the receptacles, with the shape of a funnel, aiming to support and orient the VCM in the correct position when connecting the flexible pipes. There is one receptacle for the VCM of production line, a second receptacle for VCM of annulus access line, and a third receptacle to connect umbilical line. The second structural member is the PAB block, which has an internal profile and mechanisms to install and lock the tubing hanger internally. The third member is the frame structure, which is responsible to support the receptacles and transfer the loads due to VCM installation to the PAB block. A hydraulic connector is used to attach the PAB structure to the subsea wellhead.

In order to obtain an estimative of the bending stiffness of the subsea equipment, a Finite Element Model were made in ANSYS software. Despite the simplicity of the model adopted here, the aim is to obtain the bending stiffness of the load path of the primary structure of the PAB, from the receptacle to the base of the wellhead. The dimensions were approximated based on a work reported by Prado *et al.* (1999). Figure 4 show the PAB structural model.

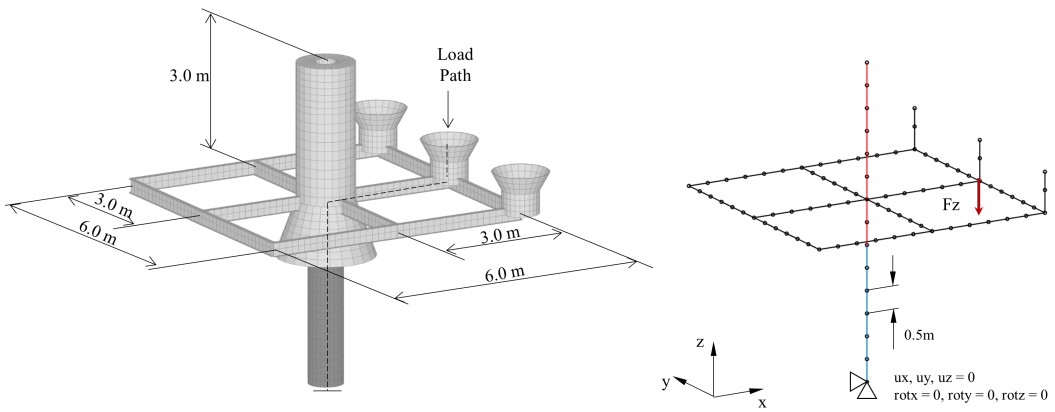


Figure 4. Production Adapter Base structure model

A two-node frame beam element was considered to evaluate the flexural stiffness of subsea equipment described above. Material property was considered as linear elastic theory. The element is uniaxial and oriented by nodes in the three-dimensional space, physical and geometrical properties of structural members used to perform this study are summarized in Tab. 1. The sea bottom (soil) is considered as rigid, the PAB block is rigidly attached to the subsea wellhead, and in the calculations, a vertical force was applied in Z direction downwards in the middle receptacle as represented by the "Fz" in the Fig. 4.

Table 1. Subsea equipment structural members properties

Properties	PAB block	Frame Structure	Receptacle	Wellhead
Young's Modulus (MPa)	210000	210000	210000	210000
Moment of inertia of plane area (m^4)	0.125	3.598×10^{-5}	3.811×10^{-3}	0.014
Cross section area (m^2)	1.088	2.639×10^{-3}	3.110×10^{-2}	0.278
Element length (m)	0.5	0.5	0.5	0.5

This calculation was performed in order to estimate the bending stiffness of the subsea equipment in the arm of the receptacle. Figure 5 shows the magnitude of vertical force as a function of vertical deflection of the structure in the receptacle.

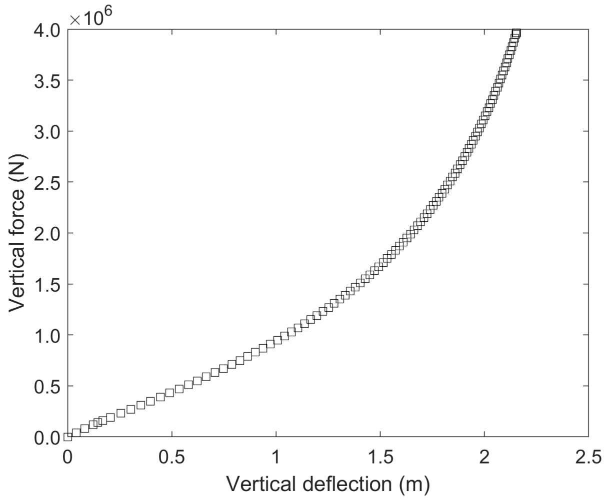


Figure 5. Vertical deflection of PAB

In the Figure 5, initial linear relationship between force and deflection in the curve is used to represent the stiffness of the subsea equipment load path. This result is considered in Eq. (5) to compose the necessary data to build the external function in the simulations.

2.7 VCM Model

In order to verify the position of the VCM (OrcaFlex model) relative to the supporting beam (external function) representing the quasi-static reaction force of the receptacle to the VCM, a GAP function based on the beam equation was defined, as already presented. The Figure 6 shows a scheme indicating the vertical gap and connecting process. The initial gap considered is equal to 1m. The supporting beam is expressed by the external function Eq. (5), while the VCM, flexible pipe and installing cable are modeled directly in OrcaFlex main program. The flexible pipe is considered free flooding with sea water, three different properties are used to describe the lines according to Fig. 6.

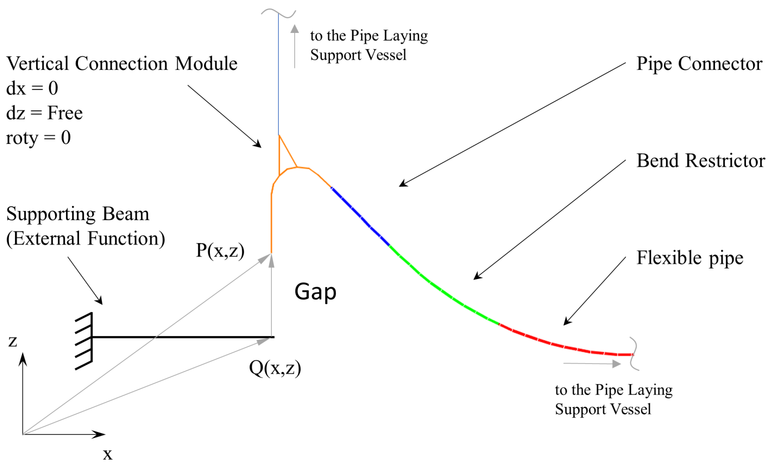


Figure 6. Numerical Model Description

P(x,z) and Q(x,z) are defined as the position vectors of the VCM and the supporting beam, respectively. The VCM is lowered at 4 seconds of analysis. The position vectors keep tracking of the positions from both bodies at each time step. When the GAP becomes zero, the external function acts and it starts giving back information of the values of force at each vertical deflection of the beam according to Eq. (5). And once the GAP is closed, the contact remains closed during the whole analysis.

The methodology adopted in the present work is implemented internally to the commercial software OrcaFlex, and it was run through the time domain analysis. The external function acts at each time step and the GAP function is as defined previously. This procedure is illustrated in Fig 7.

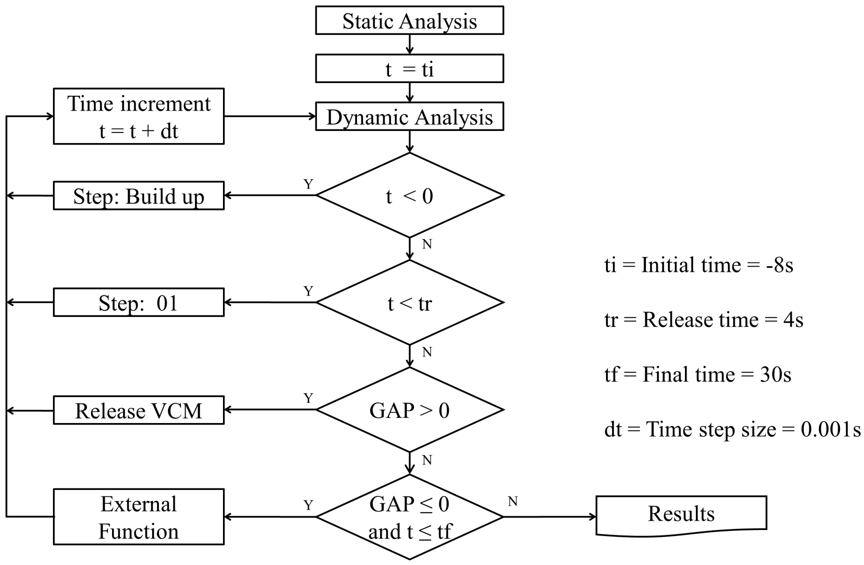


Figure 7. Procedure Flowchart

For the sake of simplicity, the build up step was omitted in the results reported in this work.

3. RESULTS

The Table 2 summarizes the mechanical properties of each component in the VCM system, namely, pipe connector, bending restrictor and flexible pipe, used in the numerical simulations.

Table 2. Mechanical properties of flexible pipes

Properties	Pipe Connector	Bend Restrictor	Flexible Pipe
Outer diameter (m)	0.235	0.235	0.235
Inner diameter (m)	0.152	0.152	0.152
Dry specific mass (kg/m)	200	100	100
Axial Stiffness (kN)	5298800	700000	700000
Bending stiffness (kN $\times$ m^2)	25900	120	120
Minimum Bending Radius (m)	-	3.0	-
Undeformed length (m)	2.0	8.0	502.1

The structural damping is represented by Rayleigh damping theory, and a damping ratio of 5% in the first two modes of flexible pipes was considered for all the analyses carried out in the present work. The Direct Vertical Connection in the numerical simulations is done in water depth of 500m, with the landing beam positioned in 4.0m above the mudline at the seabed. The mechanical properties of supporting beam which represent the VCM receptacle are shown in Tab. 3.

Table 3. Mechanical properties for the supporting beam

Properties	Supporting beam
Young's Modulus (MPa)	210000
Moment of inertia of plane area (m^4)	4.180×10^{-5}
Length (m)	3.0

The hydrodynamic coefficients are governed by physical properties of the studied body and flow parameters, such as geometry, roughness, Reynolds number, Kaulegan-Carpenter number and reduced velocity. Inertia and drag coefficients are empirical data, and show large scatter values for different experiments methodologies and setup. Moreover, an extensive literature provides a discussion on the dependency of hydrodynamic coefficients on several of these parameters

(Sarpkaya, 2010). A typical value for inertia and drag coefficients considered in the present work were 2.0 and 1.2 respectively. The effect of the hydrodynamic forces was verified for the system response. The inertia coefficient (C_M) was varied from 1.5 to 2.5, at steps of 0.25, while the hydrodynamic drag coefficient (C_D) was changed ranging from 0.4 to 2.6, at steps of 0.20.

Surface waves were considered with the wave period of 8.0s and 0.25m of amplitude, waves incoming from the stern to the bow of PLSV. Since the Direct Vertical Connection is an operation that happens only under moderate environmental conditions, the current velocity is taken equals to zero, and sea water mass density is taken as 1025 kg/m^3 in the present analysis. The mass of Vertical Connection Module is 4000kg, the drag area normal to vertical direction is 1.3m^2, submerged volume is 0.509m^3, and its initial position was taken at 5.0m above the mudline at the seabed.

Operation for the Direct Vertical Connection is evaluated for different inertia and drag coefficients in the numerical simulations and results are shown. The flexible pipe is connected to the VCM through a bolted flanged API connection. Since the VCM is modeled as a rigid body in the present analysis, results obtained from the lower extremity of the flexible pipe are considered as reactions that act into the flanged connection. Figure 8 schematically shows the directions of the analyzed reactions. In the Figure 8, Tw is the wall tension, Vs is the shear force and My is the bending moment.

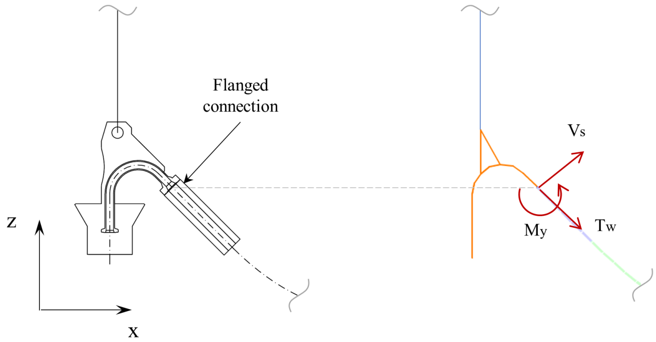


Figure 8. Loads induced by flexible pipe

The time history from simulations for the vertical position of the VCM is shown in Fig. 9. The VCM is released at 4s in the simulation, and the landing beam is positioned at -496.0m water depth. After the first contact, the landing beam oscillates until it reaches its final equilibrium position.

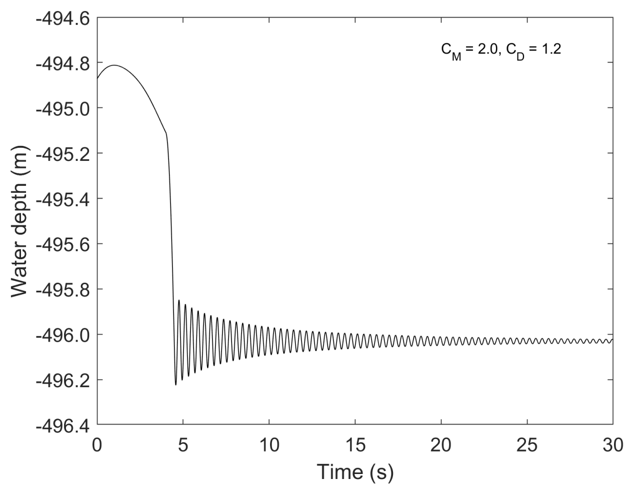
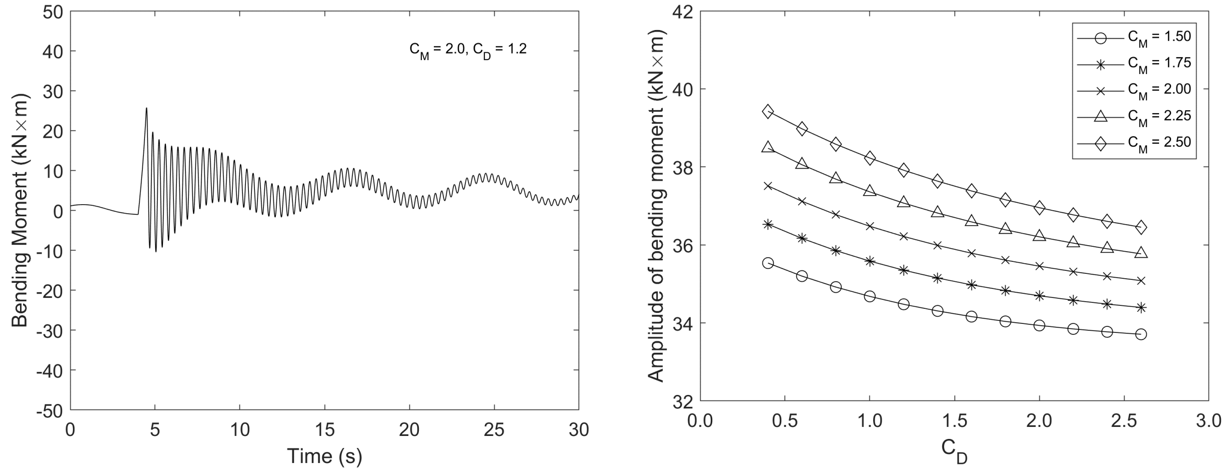


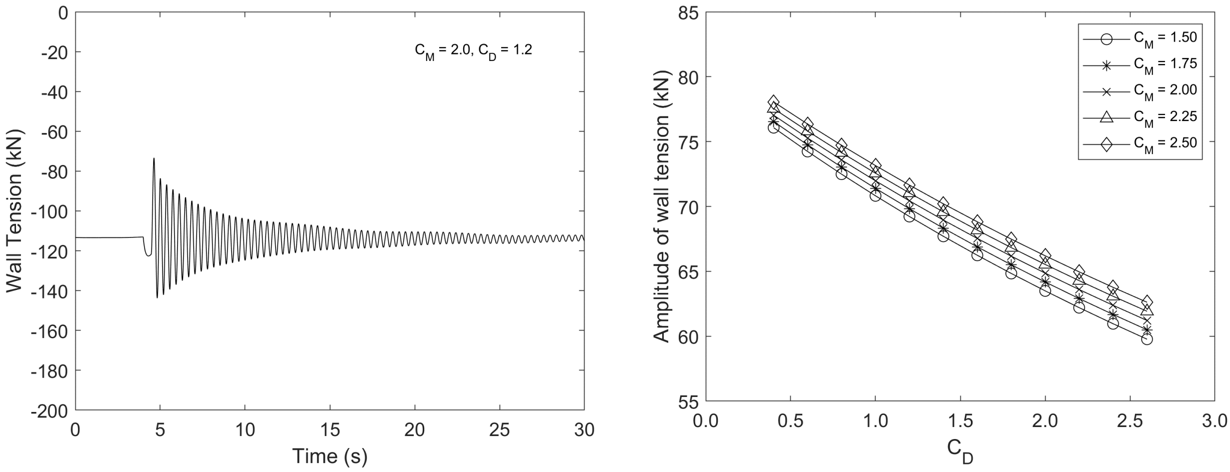
Figure 9. Vertical Displacement at Vertical Connection Module

The results were obtained considering the typical case, with $C_M = 2.0$ and $C_D = 1.2$. Figures 10 – 12 show the range of values for the bending moment, wall tension and shear force, respectively, where the inertia coefficient was varied. In all the results from simulations, variables are observed at the position of the VCM flanged connection. Figure 10a shows the time history of the bending moment for the typical case, and the Fig. 10b, shows the amplitude of the time varying bending moment by varying hydrodynamic inertia coefficient. In a similar way, the Fig. 11b shows the amplitude of wall tension and the Fig. 12b the amplitude of shear force.



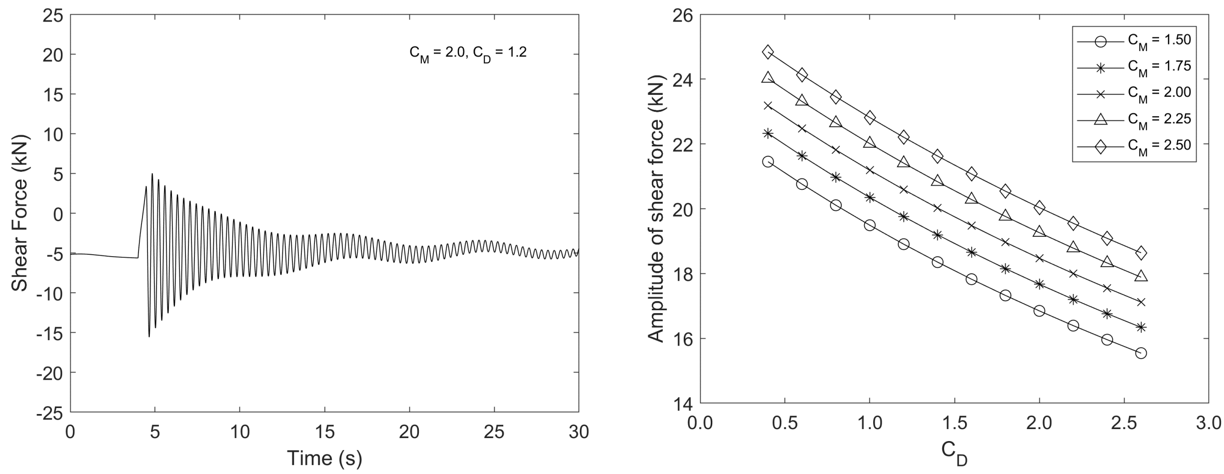
a) Bending moment time history b) Amplitude of bending moment

Figure 10. Bending moment



a) Wall tension time history b) Amplitude of wall tension

Figure 11. Wall tension



a) Shear force time history b) Amplitude of shear force

Figure 12. Shear force

The reaction loads verified in the VCM flanged connections are mainly associated with the vertical movement of VCM, in the lower extremity of the flexible pipe, and the PLSV motion at the top. Accordingly, the results show a tendency to exhibit a higher frequency load excitation added to a lower frequency one. Comparatively, the reaction loads of bending moment and shear force show more dependency of PLSV motion than tension results.

Damping forces are responsible for energy dissipation in the system. Since the structural damping term was considered constant for all cases, the differences in load amplitudes observed is related to the drag term of Morison equation, which represent the viscous interaction between the flexible pipe and the surrounding fluid.

It can be observed from results that the highest ranges of bending moment, wall tension, and shear force are expected for larger inertia coefficient and lower drag coefficient. According to Eq. (2), the added mass component increases the system's inertia term. Therefore, it is expected that larger inertia coefficient makes higher the reaction forces and moments in the flanged connection, since the system needs higher values of force to accelerate and deaccelerate involved equipment components. The drag term is related to the velocity of the VCM, consequently lower drag coefficient means that the VCM hits the supporting beam with larger velocity, thus the supporting beam behaves with greater vertical deflections. Since reactions in the flanged connection is related to the beam deflection, larger are the beam deflections bigger will be the reaction forces and moments. The results of wall tension (Fig. 11) and shear force (Fig. 12) are in accordance with bending moment reactions. Since the hydrodynamic coefficients are dependent on the geometry, from the design point of view, loads acting in the flanged connection during the Direct Vertical Connection can be reduced from a careful analysis of the equipment geometry. Perhaps, an optimal geometry could be found with hydrodynamic coefficients which allows to minimize the reaction forces.

4. FINAL REMARKS

In the present work, Vertical Connection Module installation process were described and a numerical model was developed for simulations in the OrcaFlex software. The bending reaction of the receptacle for the Vertical Connection Module at the Subsea Equipment during the installation process was replaced by an equivalent cantilever beam behavior.

The main objective of the present study was to investigate the influence of hydrodynamic coefficients in the behavior of the system during the Direct Vertical Connection operation. Several inertia and drag coefficients were used in order to obtain a range of results and study its influence.

It was observed that hydrodynamic forces during the Direct Vertical Connection maneuvering are important, since they affect the dynamics of the flexible pipe and the VCM. The reactive bending moment in the flanged connection for different inertia and drag coefficient in the numerical simulations have shown that the highest amplitude of reaction load happens for larger inertia coefficient and lower drag coefficients of the flanged connection. Same pattern was observed for wall tension, and shear forces.

From the results, it can be observed that during the design phase of a VCM, improvements can be made for the system response in the Direct Vertical Connection procedure by analyzing geometries of equipment component since it affects hydrodynamic coefficients.

5. ACKNOWLEDGEMENTS

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