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Mooring Analysis of a Subsea Pipelay Barge

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Abstract : *Oil companies use vast amounts of pipeline to transport crude oil from the offshore fields to shore facilities. The laying process of such pipelines needs special vessels equipped with all the facilities to join segments of pipelines and to lay the pipeline onto the seaocean floor. During the laying operation, it should be properly moored to the seabed to limit the motions of the vessel. This paper describes the detailed mooring analysis of a pipelay barge using 8 point anchor mooring system suitable for construction work in shallow water environments and specifies proper mooring rope/wire for the operation. The barge modeling is done in ANSYS Design Modeler and hydrodynamic analysis carried out in ANSYS AQWA. The RAO data is then input to ORCAFLEX where a model with mooring lines attached as per the proposed anchor pattern is analyzed.*
Keywords: *8-point mooring, Pipelay barge, Mooring analysis, RAO, Vessel response.*

I. Introduction

A barge is flat-bottomed vessel, built mainly for transport of heavy goods, laying pipelines and other constructional activities. When it is used for laying pipelines, it should be properly moored to the seabed. Mooring is basically done to forestall the motion of a vessel within the permissible limits under the action of environmental loads.

An anchor mooring fixes a vessel's position relative to a point on the bottom of a waterway without connecting the vessel to shore. Proper mooring line materials and configuration ensure that loads do not exceed the limit values.

1.1 Pipelay Barge

This type of barge is specifically used for laying of subsea pipelines that transport processed/unprocessed petroleum from offshore facilities to the shore.

The main functions of a pipelay barge are: (a) to receive pipelengths (b) weld them to a single length (c) coat the joints (d) lay the pipeline over the stern onto the seabed.

The layout of a typical pipelay barge is illustrated in Figure 1.

The main components of the barge are:

1) *Welding Stations*: To weld individual pipe lengths to a single length.

2) *Non Destructive Testing Unit*: *To carry out X-Ray Radiography.*

3) *Tensioner: To keep the pipeline being laid under tension at all times and thus prevents buckling.*

4) *Joint Coating Unit: To apply coatings at the weld joint to prevent corrosion.*

5) *Stringer: Truss like structure with rollers to support the pipeline and limit curvature as it is being laid.*

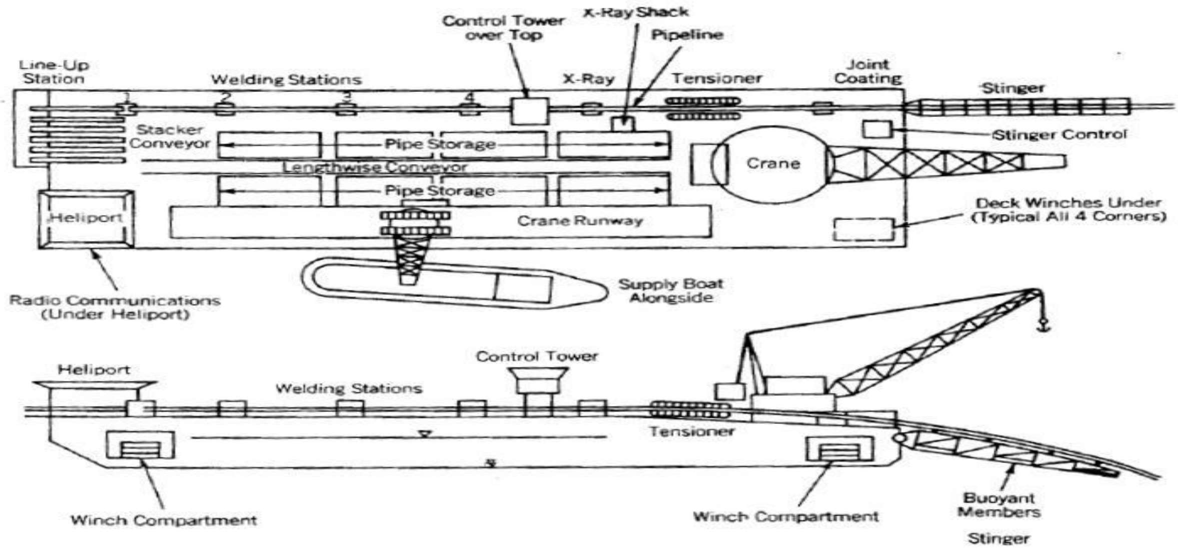

Fig. 1.Layout of a typical S-lay barge.

1.2 Mooring Systems

A Mooring refers to any permanent structure to which a vessel may be secured. Examples include quays, wharfs, jetties, piers, anchor buoys, and mooring buoys. A ship is secured to a mooring to forestall free movement of the ship on the water. There are various types of mooring arrangements viz. Catenary Anchor Leg Mooring, Single Anchor Leg Mooring, Turret Mooring, Spread Mooring, Taut Leg Mooring etc.

An anchor mooring fixes a vessel's position relative to a point on the bottom of a waterway without connecting the vessel to shore. In a catenary mooring system, the anchor chains or cables assume the shape of a catenary under its own weight and supported at the ends. This is the most common type of mooring system in use for offshore oil and gas activities. The configuration of a catenary mooring system is shown in Figure. 2.

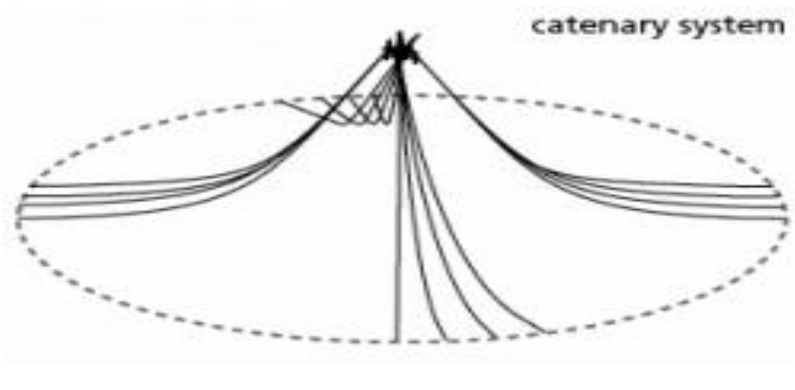

Fig. 2. Typical catenary mooring layout.

The following are the characteristics of a catenary mooring system:

a. The mooring line arrives at the seabed horizontally.
b. The anchor point is subjected to horizontal loads only.
c. The restoring force is generated by the weight of the mooring line.

We have considered catenary mooring with lines of 6×19 steel wire with fibre core material with two different line diameters for analysis in this paper. The fibre core not only provides the necessary foundation, but also adds to the pliability (The property of being easily bent without breaking) of a wire rope.

1.3 Approaches to Mooring Analysis

Mcnatt (1982) described an overall design methodology for ocean catenary mooring systems and also highlighted the need for a comprehensive design approach. The various design requirements like design criteria, environmental definition, performance analysis etc. are described. Methods of dynamic mooring analysis using tools like LARSTRAN and FLOATMOOR are described and several specific areas are identified which require differing analysis approaches. And finally, the need for system testing as a design verification tool is presented and difficulties with small scale model testing are illustrated.

Schellin et al (1982) described two mathematical models to account for the problem while mooring the vessels such as construction vessels, crane barges or pipelaying barges in shallow, unprotected waters. The first method models the vessel behavior directly by solving the motion equations under the influence of the combined first-order wave and second order wave (drift) forces. The second method calculates first order oscillating wave motions and second-order drift motions of the moored vessel separately and superimposes them to obtain total vessel motions. Line tensions due to the total vessel motions are calculated quasistatically with both methods. The time series showing vessel response and corresponding tensions of the most highly stressed mooring lines are calculated for 300s interval.

Natrajan R. and Ganpathy C. (1997) performed the model experiments of moored ship to investigate their behavior under wave and current loadings. The model experiments were conducted on two different models of ship and barge in 30 m x 2 m × 1 m wave-current flume. Nylon ropes of 5 mm diameter were used as mooring ropes. Concrete blocks were used to ballast the model for the required displacement. Berth and spread mooring tests were performed and the motion of the models and the tension of the mooring ropes were measured for different environmental conditions.

Allen et al (2006) described the FPSO designed for Indonesian coast in the west Natuna Sea followed by the mooring system design for its turret using 8 and 12 line catenary separately. SESAM software was used to calculate the mooring loads and mooring component specifications needed to keep the vessel within specified watch circles in stable and damaged states. Outputs from the mooring calculations were then used to calculate the Response Amplitude Operators (RAO) of the vessel. These frequency response spectrums were then compared to the frequencies of the environment to see if any dangerous responses of the vessel were possible.

1.4 Software

ANSYS AQWA software is an engineering analysis suite of tools for the investigation of the effects of wave, wind and current on floating and fixed offshore and marine structures.

Hydrodynamic Diffraction analysis system represents the first phase of the integration of ANSYS AQWA technology into the ANSYS Workbench platform. This provides direct links to ANSYS Design Modeler software, external CAD geometry import, and geometric parameterization and integrated meshing technologies.

The Workbench version of the wave diffraction and radiation analysis uses the3-D panel method and performs the following tasks.

- Description of geometry.
- Representing the singularity points and velocity potential on the body surface.
- Numerical integration of singularity points.
- Linearization and solution of the combined function.
- Analysis of results and determination of desired hydrodynamic properties.

When calculating the response of vessel in regular waves, it is often possible to neglect the effects of viscosity in certain modes of motion. Fairly accurate results can then be found by using potential theory and this method is used by ANSYS AQWA.

The potential function given as (1)

$$\boldsymbol{\varphi = \frac{ag}{\omega}\cosh k(z+d) \times \sinh(kx-\omega t)} \quad (1)$$

φ = velocity potential

a = wave amplitude(m)

g = acceleration due to gravity ($\mathrm{m/s^2}$)

ω =frequency (rad/s)

k = wave number

z = free surface elevation(m)

d = water depth (m)

t = time (s)

The potential function satisfies Laplace's equation and hence (2)

$$\nabla^2 \varphi = 0 \qquad (2)$$

The calculations are often subdivided into two groups:

- Finding the forces on the ship when it is restrained from motion and subjected to regular waves. The forces acting on the body are:- (a) The Froude–Krylov force, which is the pressure in the undisturbed waves integrated over the wetted surface of the ship. (b)The Diffraction forces, which are pressures that occur due to the disturbances in the water because of the ship being present

- Finding the forces on the ship when it is forced to oscillate in still water conditions. The forces are divided into:- (a)Added mass forces due to having to accelerate the water along with the ship. (b) Damping forces due to the oscillations creating outgoing waves which carry energy away from the ship. (c) Restoring forces due to bringing the buoyancy/weight equilibrium out of balance.

The linearization of problem permits the decomposition of velocity potential into diffraction () and radiation () and components. Hence (3),

$$\varphi = \varphi_D + \varphi_R \qquad (3)$$

The RAO transfer function is only defined when the ship motions can be assumed to be linear. The above forces can then be assembled into an equation of motion in which the excitation force on the body is given by the first sub-part while the added mass and damping is being taken care by second sub-part. The equation of motion is (4),

$$[\boldsymbol{M} + \boldsymbol{A}(\boldsymbol{\omega})]\ddot{\boldsymbol{x}} + \boldsymbol{B}(\boldsymbol{\omega})\dot{\boldsymbol{x}} + \boldsymbol{C}\boldsymbol{x} = \boldsymbol{F}(\boldsymbol{\omega}) \qquad (4)$$

Where,

ω is oscillation frequency (rad/s)

M is the structural mass (kg)

A (ω) is the added mass (frequency dependent) (kg)

B(ω) is the linear damping (frequency dependent) (kg/s)

C is the restoring force coefficient (N)

F ω is the harmonic excitation force proportional to *x* (m)and the wave height ζa (m).

This can be resolved for x and *RAO* is given as (5)

$$\text{RAO}=\frac{x}{\zeta_a}=\frac{F_0}{C-\left(M+A(\omega)\right)\omega^2-iB(\omega)\omega} \tag{5}$$

where, $F_0$is the linear excitation force complex amplitude per wave height.

ORCAFLEX is a marine dynamics program developed by Orcina for static and dynamic analysis of a wide range of offshore systems.

To analyse a marine system using ORCAFLEX, the mathematical model of the real world system is to be built using the various modelling facilities provided by ORCAFLEX. The model consists of the marine environment to which the system is subjected, plus a variable number of objects chosen by the user, placed in the environment and connected together as required. The objects represent the structures being analysed and the environment determines the current, wave excitation, etc. to which the objects are subjected.

Orcaflex performs both static and dynamic analyses.

There are two objectives for a static analysis:

- To determine the equilibrium configuration of the system under weight, buoyancy, hydrodynamic drag, etc.
- To provide a starting configuration for dynamic simulation.

Static equilibrium is determined in a series of iterative stages:

- At the start of the calculation, the initial positions of the vessels and buoys are defined by the data: these in turn define the initial positions of the ends of any lines connected to them.
- The equilibrium configuration for each line is then calculated, assume the line ends are fixed.
- The out of balance load acting on each free body (node, buoy, etc.) is then calculated and a new position for the body is estimated. The process is repeated until the out of balance load on each free body is zero.

The dynamic analysis is a time simulation of the motions of the model over a specified period of time, starting from the position derived by the static analysis. Before the main simulation stage(s) there is a build-up stage, during which the wave and vessel motions are smoothly ramped up from zero to their full size.

ORCAFLEX implements two complementary dynamic integration schemes, Explicit and Implicit.

The equation of motion which ORCAFLEX solves is as follows:

$$M(p,a) + C(p,v) + K(p) = F(p,v,t) \tag{6}$$

Where,

M(p,a) is the system inertia load.
C(p,v) is the system damping load.
K(p) is the system stiffness load.
F(p,v,t) is the external load.
p, v and a are the position, velocity and acceleration vectors respectively.
t is the simulation time.

Both schemes recompute the system geometry at every time step and so the simulation takes full account of all geometric non-linearities, including the spatial variation of both wave loads and contact loads.

II. Hydrodynamic Analysis

2.1 Specifications of the Barge

- **Dimensions**
  - Length, overall 79.40 m
  - Breadth 35.35 m
  - Depth 4.27 m
  - Draft 2.50 / 3.00 m
- **Mass Properties**

  The mass properties of barge are tabulated in TABLE 1 below:

TABLE 1: Mass properties

S N	Part	Weight	LCG	TCG	VCG	k_{xx}	k_{yy}	k_{zz}
		[t]	[m]	[m]	[m]	[m]	[m]	[m]
1	Lightship (incl consumables)	3462.14	46.26	0	3.7	II. 10.20	III. 24.90	IV. 22.80
2	Crane	384	8.05	0	13.86	5.80	5.80	1.20
3	Deckload	500	9.4	0	5.27	8.80	6.00	10.40
Total		4346.14	38.64	0	4.78	10.10	27.10	25.60

- **Barge Model**

The barge surface model made using given table of offsets as given in TABLE 2.

TABLE 2: Offset Table

Table of offsets (mm)				
FR	Half breadth		Above BL height	
	M Deck	Chine	Kee l	Chine
2 0	17675	17675	0	0
2 1	17500	17000	0	30
2 2	17000	16000	0	200
2 3	16000	15600	0	400
2 4	14700	14300	0	800
2 5	12700	12300	600	1700
2 6	5600	5600	356 7	2567

The barge was modeled in ANSYS Design Modeler and the centre of gravity specified as a point mass as per the specifications. The model is shown in Fig. 3

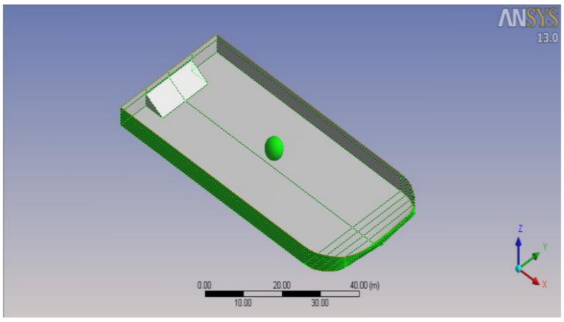

Fig. 3. Barge Surface Model

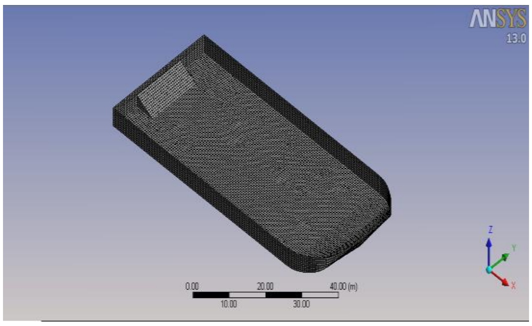

Fig. 4. Meshed Model

The model was then meshed using the program controlled option with a max element size of 1m (after convergence check), a defeaturing tolerance of 0.05m and the meshed surface is as shown in Fig. 4.

The wave parameters considered for the analysis is summarized below

- **Wave Input**

Wave Range	180° to 180°
Interval	45°
Number of Intermediate Directions	7

- **Wave Frequency**

Range	Program Controlled
Total Number of Frequencies	50
Equal Intervals Based Upon	Frequency

The RAOs are obtained for each 45° interval for the wave ranging from -180° to 180°. The RAOs vs . Frequency plots for a sample wave direction of 135̊ is shown in Fig. 5.

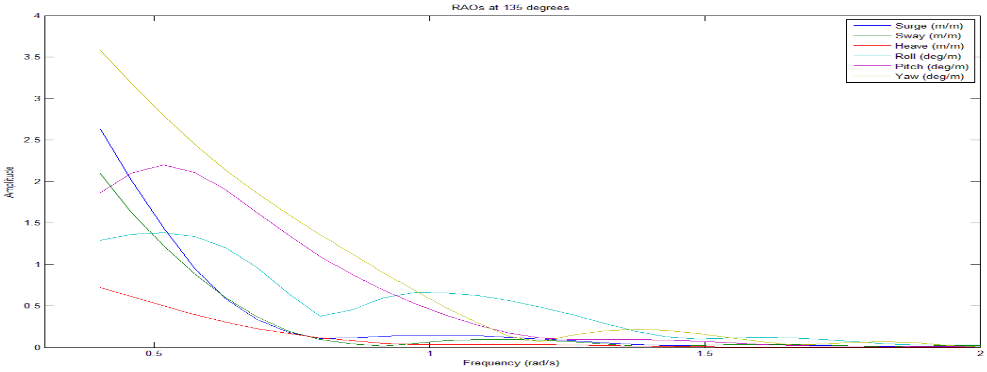

Fig. 5. RAO for wave heading of 135̊.

The added mass, stiffness and damping matrices are also obtained for all the frequencies as a result of hydrodynamic analysis.

V. Mooring Analysis

The barge was modeled again in ORCAFLEX by using the given specifications. The initial orientation of barge is 180°. Fig. 6 shows the model, it consists of:

- Lay barge
- Rigid stringer with rollers hinged to the back of barge
- Tensioner of 25t capacity
- Homogeneous lay pipe (200 mm OD & 10 mm WT)

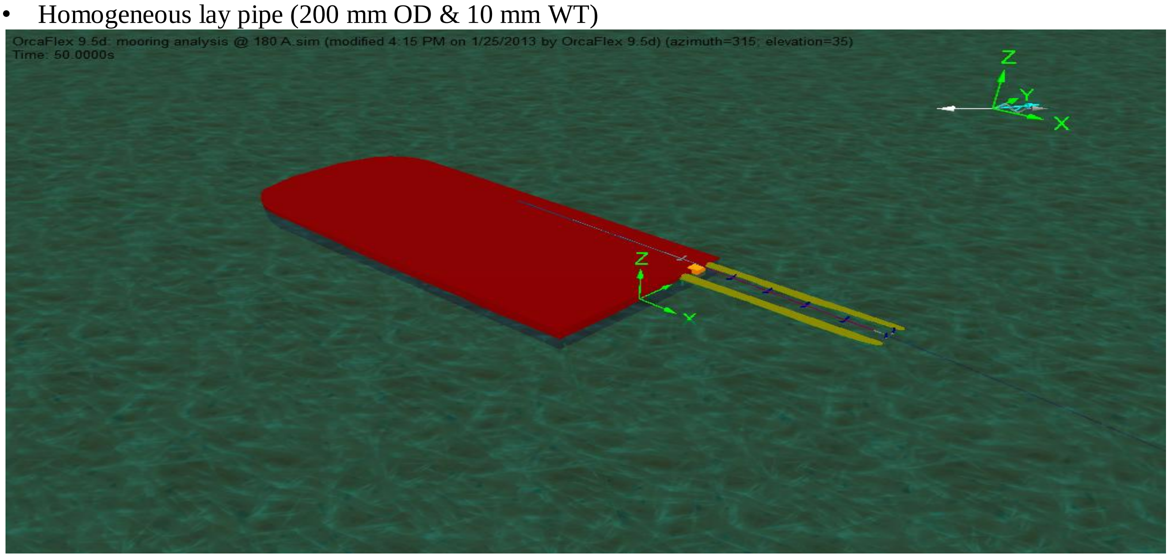

Fig. 6. ORCAFLEX Model of barge showing the stinger, rollers and pipeline

The environmental conditions used for analysis are tabulated below in Table 3.

TABLE 3. Environmental conditions

Water depth = 6m				
Return period = 1 year				
Swell waves			**Associated wind wave**	
Max. wave height (m)	4.5	A.	Sig. wave height (m)	1.1
Sig. wave height (m)	2.02	B.	Direction (degrees)	45
Direction (degrees)	60	C.	Period (sec)	6.3
Period (sec)	15	D.	γ (Jonswap)	1.8
σ (Gaussian spectral width)	0.007	E.		
Wind			**Current (Inline with wave)**	
Wind speed (knot)	14	F.	Surface speed (knot)	0.5
Direction (degrees)	225		3 ft off bottom (knot)	0.3

While performing the laying operation, the barge will move from A to B position, but the connection points will remains same for both the positions. Only the mooring line lengths will change. The mooring connection pattern is obtained from the given data. The anchor locations are already known, the fairlead coordinates are obtained by using the given directions, anchor coordinates, bearing angles and line lengths. The complete mooring pattern is tabulated below in Table 4..

Anchor Number	Anchor Coordinates		Fairlead Coordinates		Position A (Aft centre at 0,0)			Position B (Aft centre at -500,-3.49)		
	X	Y	x	y	Line length (m)	Bearing (degrees)	Lay azimuth (degrees)	Line length (m)	Bearing (degrees)	Lay azimuth (degrees)
S1	250.06	487.28	0.16	-16.67	533	28	242	887	58	212
S2	-56.18	524.55	2.87	-17.34	510	354	276	670	41	229
S3	-667.61	494.99	73.87	-14.19	764	309	39	494	349	281
S4	-923.48	226.05	74.47	-14.37	875	284	14	412	302	328
P1	392.36	-204.81	0.64	16.31	437	126	144	912	102	168
P2	131.10	-517.06	2.71	17.67	517	165	105	807	128	142
P3	-664.78	-527.08	74.59	14.04	782	229	41	519	190	80
P4	-921.20	-240.56	75.05	13.84	876	255	15	410	238	32

Table 4-Mooring Pattern

Where, S1, S2, S3 and S4 represents the Starboard side anchor connection points

P1, P2, P3 and P4 represents the Port side anchor connection points

The mooring pattern for both the positions A and B while performing laying operation is shown in Fig. 7.

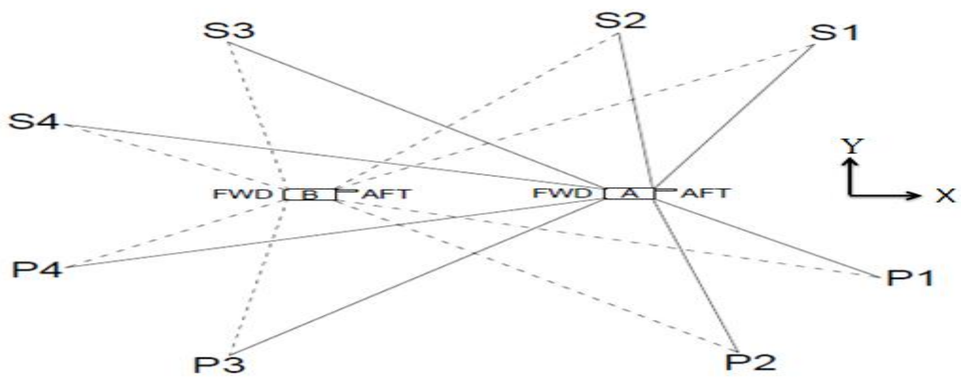

Fig. 7. Initial and Final Mooring Pattern

Once the mooring pattern is finalized, the mooring analysis is performed using ORCAFLEX for two different line diameter cases as described below:

-Case I: 6×19 steel wire with fibre core material with 82 mm line diameter.
- Case II: 6×19 steel wire with fibre core material with 38 mm line diameter.

6×19 steel wire with fibre core material is selected for the analysis. This is due to the fact that the fibre core not only provides the necessary foundation, but also adds to the pliability (The property of being easily bent without breaking) of a wire rope.

Simulations were carried out for the respective cases with barge mooring system equipped with the 4 double drum anchor winches (8 drums in total), each consists of 6×19 steel wire with fibre core of 82 mm or 38mm diameter wire as per the case and 1200 m length.

The mooring line properties for both the positions are tabulated below in Table 5

TABLE 5-Mooring Line Properties

Moooring line	S1	S2	S3	S4	P1	P2	P3	P4
Length at A (m)	533	510	765	875	437	517	783	877
Length at B (m)	885	685	493	410	887	803	517	415
Line type	Wire							
Construction	6×19 Wire with fibre core							
	Case I:				Case II			
Diameter	82 mm				38 mm			
Axial stiffness	367000 kN				77657 kN			
Min. breaking load	5841.752 kN or 595.693 te				1236.115 kN or 126.049 te			
Weight in water	0.301 kN/m or 0.031 te/m				0.064 kN/m or 0.0065 te/m			

The dynamic analysis is performed in ORCAFLEX for both the positions A and B separately. The simulation is further extended to different wave heading angles s tarting from 0° in 45° step to ensure the safety of mooring system for different wave directions.

IV. Results

The mooring lines are checked for their safety as per API RP 2SK guidelines. The spectral responses of barge are also analyzed with and without mooring.

4.1 Maximum Effective Tension

As per API RP 2SK, the allowable tension should be 50 % of the breaking tension. i.e. the minimum FOS of 2.
For case I, Minimum Breaking Strength (MBS) = 5841.752 kN
Therefore, Allowable tension = 2920.876 kN
The mooring line tensions for both the positions for different wave headings are shown in Table 6.

TABLE 6

	Line	0°	45°	90°	135°	180°	225°	270°	315°
Position A	S1	782.87	2008.19	1975.49	1234.96	747.35	2141.28	1966.05	993.94
	S2	324.28	1628.57	2283.47	2217.41	332.11	1925.32	2290.17	1958.61
	S3	744.40	671.80	925.33	1098.23	758.40	509.38	833.96	1123.88
	S4	1080.32	996.71	796.68	1277.13	1108.95	987.88	770.94	1259.02
	P1	1556.17	814.78	1634.96	2506.50	1470.07	887.93	1643.20	2506.82
	P2	491.61	1343.01	2204.23	2097.53	476.34	1601.06	2209.22	1899.97
	P3	375.50	1000.06	644.87	55.65	401.22	981.06	639.94	139.14
	P4	520.85	763.10	108.88	424.45	562.32	782.04	82.24	402.98
Position B	Line	0°	45°	90°	135°	180°	225°	270°	315°
	S1	1730.21	2236.55	1797.33	1515.64	1936.47	2286.76	1795.16	1491.21
	S2	465.70	1283.58	1079.99	323.76	667.83	1398.65	1083.27	207.41
	S3	548.47	1946.27	2706.04	2113.59	626.96	1522.41	2708.06	2371.06
	S4	1458.01	1062.73	1606.03	2277.25	1915.48	899.14	1631.69	2637.06
	P1	2175.25	2129.21	1837.58	2545.02	2409.07	2130.38	1847.03	2532.52
	P2	1519.86	1200.16	1752.82	2198.24	1730.98	1222.40	1764.78	2134.39
	P3	634.65	2361.16	2717.51	1663.18	704.35	2157.88	2744.64	2041.13
	P4	11.89	119.39	72.21	36.22	23.20	87.87	82.41	57.79

The maximum line tension for various headings are represented graphically in Fig.8 below

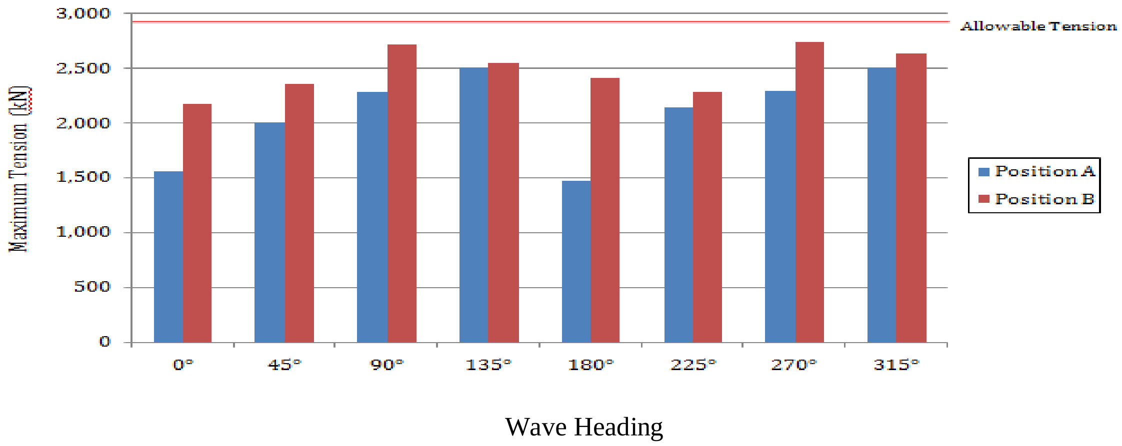

Fig. 8. Maximum Line Tensions Vs Wave Heading

The time domain response of barge is determined for both the positions and the response values obtained from it are tabulated in Table 7 for without and with mooring case.

TABLE. 7: Barge Responses With & Without Mooring

POSITION A (0,0)						
Motion	Without mooring			With mooring		
	Min	Max	Total	Min	Max	Total
Surge (m)	-1.58	1.52	**3.10**	-1.42	1.38	**2.80**
Sway (m)	-2.37	2.50	**4.87**	-2.23	2.02	**4.25**
Heave (m)	-3.69	-1.38	**2.30**	-3.98	-2.09	**1.89**
Roll (deg)	-1.65	1.81	**3.47**	-1.51	1.26	**2.78**
Pitch (deg)	-1.25	1.38	**2.63**	-0.72	1.00	**1.72**
Yaw (deg)	178.09	182.11	**4.02**	179.12	180.89	**1.77**
POSITION B (-500,-3.49)						
Motion	Without mooring			With mooring		
	Min	Max	Total	Range		Total
Surge (m)	-501.51	-498.49	**3.02**	-500.03	-499.74	**0.29**
Sway (m)	-6.04	-1.21	**4.83**	-3.53	-3.41	**0.12**
Heave (m)	-3.64	-1.33	**2.32**	-2.77	-2.34	**0.44**
Roll (deg)	-1.72	1.69	**3.41**	-1.21	0.76	**1.97**
Pitch (deg)	-1.26	1.22	**2.48**	-0.34	1.47	**1.81**
Yaw (deg)	178.05	182.11	**4.06**	179.03	180.43	**1.40**

Using Fast Fourier Transforms in Matlab, the spectral responses for all 6 DOF were also obtained and a sample graph is shown in Fig. 9.

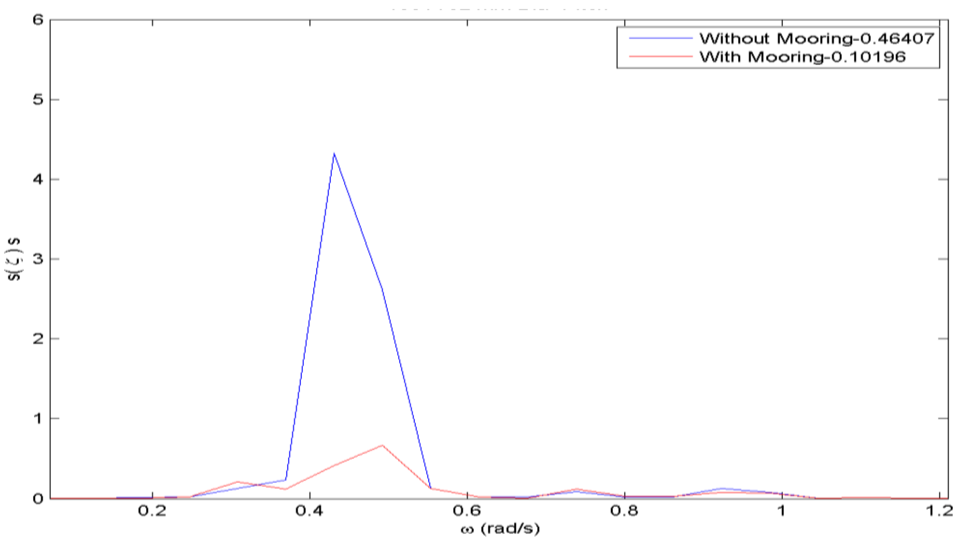

Fig. 9. Heave Spectral Response- With & Without Mooring Line

A significant reduction in the spectrum energy is observed with mooring lines attached. This shows that the response of the barge is reduced after attaching the mooring lines. The percentage reduction in spectrum response is shown in Table 8.

TABLE 8: Spectral response % reduction (Case I)

Motion	Position A			Position B		
	Without mooring	With mooring	% Reduction	Without mooring	With mooring	% Reduction
Surge	0.697	0.505	27.53	0.754	0.005	99.34
Sway	1.884	1.081	42.61	1.865	0.001	99.95
Heave	0.447	0.233	47.85	0.387	0.011	97.23
Roll	0.892	0.317	64.46	0.661	0.224	66.06
Pitch	0.464	0.102	78.03	0.354	0.218	38.42
Yaw	1.281	0.152	88.13	1.216	0.089	92.65

Similar analyses were carried out for Case II and the results tabulated and compared.

V. Conclusion

On comparison of the results, the following conclusions were made,

- For the mooring analysis, the free floating response of the barge is taken so that the maximum loads on the mooring lines can be found.
- The mooring analysis is performed in given environmental conditions and the results are analyzed. The maximum line effective tensions for the given case are found to be within limits. The tensions are again checked for different wave heading angles and found to be safe as per API RP 2SK.
- The most heavily loaded line differs from case to case depending on the wave heading and line length.
- It is observed that,as the diameter reduces from 82 mm to 38 mm:
  - MBS is reduced by 78.84%
  - Maximum tension is reduced by 80.66%
  - Weight per unit length is reduced by 79.03%
  - Axial stiffness is reduced by 78.84%
  - FOS is almost same

Cost is reduced by almost 4 times

- The range of response is analyzed from the values obtained from time series and found to be reduced with mooring lines attached.
- For position A, for time series response, as the diameter reduces from 82 mm to 38 mm:
  - Surge, sway and heave are reduced by 60, 90 and 70% (appx.)
  - Roll, pitch and yaw show comparable results.
- For position B, for time series response, as the diameter reduces from 82 mm to 38 mm:
  - All motions show comparable results for both cases.

- The barge spectral responses are also observed and found to be significantly reduced with mooring lines attached.
- For position A, for spectral response, as the diameter reduces from 82 mm to 38 mm:
  - The percentage reduction in spectral energy for surge, sway and heave is found to be increased by almost double as compared to roll, pitch and yaw which are comparable for both the cases.
- For position B, for spectral response, as the diameter reduces from 82 mm to 38 mm:
  - All motions show comparable results for both cases.

- The overall results in terms of line tensions, vessel response and economy are found to be optimum for Case II as compared to that of Case I.

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