Offshore Heavy Lift Design and Operations: Sling Tension in Heavy Lifts with Quadruple Sling Arrangement.

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OFFSHORE HEAVY LIFT DESIGN AND OPERATIONS: SLING TENSION IN HEAVY LIFTS WITH QUADRUPLE SLING ARRANGEMENT

Abstract

Offshore heavy lift design requires a comprehensive study of the engineering properties of the rigging assembly and the geometric configuration of the structure to be lifted subsea. In this study, the author looked at some key constraint of a quadruple sling arrangement lifting design such as the geometric configuration of the structure, its weight & centre of gravity, member strength of the rigging assembly and sea state of the environment where the subsea lift will be taking place. Key algebraic equations in addition to industry codes of standards and best practices were used to optimize the solution for the lifting design. In addition, the author concludes by recommending safety measures that may be incorporated into the rigging assembly in order to mitigate hazards arising from elastic vibration and pendulum type oscillation during lifting operation.

Key Words: Sling Load, Minimum Breaking Load, Safe Working Load, Dynamic Amplification Factor, Center of Gravity

1.0 Introduction and Objectives of Study

Offshore heavy lifts design and operations are required to be conducted in safe and economical manner. The author is motivated to investigate the impact of rigging geometry on the successful design and implementation of lifting and rigging operations for an offshore projects. Thus, the objectives of this study are;

- To investigate the cost effectiveness and safety of a four sling rigging geometry for offshore heavy lift installation of structures.
- Study current design codes such as DNV, ANSI, ISO and API for lift design and highlight key design considerations for heavy lift operations.
- Investigate the mechanical behaviour of the rigging components and the structure being lifted to tension using static equations for equilibrium of forces.

2.0 Design Considerations: Load and Safety Factors

In order to ensure a safe working condition for lifting the structure under study (figure 1), the calculations to be carried out will include allowances and safety factors due to loads and environmental effects according to standard codes of practice relating to lifting operations. Key critical safety factors are discussed on the next page.

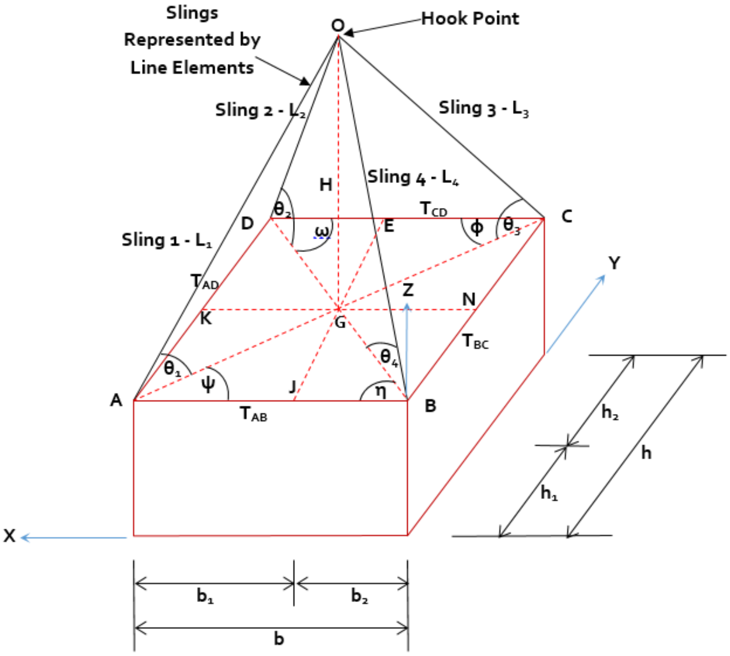


Figure 1: Geometry of Rigging

2.1 Sling Angle Factor (SAF)

The Sling Angle Factor (SAF) is a multiplier used to determine the required sling size when angle formed between sling and load is less than 90°. A pictorial example of sling angle is shown in figure 2. Sling angle less than 45° is usually avoided because the lower the sling angle, the higher the tension factor on the sling. According to ANSI B30.9 – 2010 (Codes of Practice for Fabrication, Attachment, Use, Inspection, Testing and Maintenance of Slings), table 1 below shows the various sling angles and their corresponding sling angle factor. ANSI B30.9 – 2014 recommends against the use of horizontal sling angle less than 30°. The sling angle factor is estimated to the nearest 5° [1].

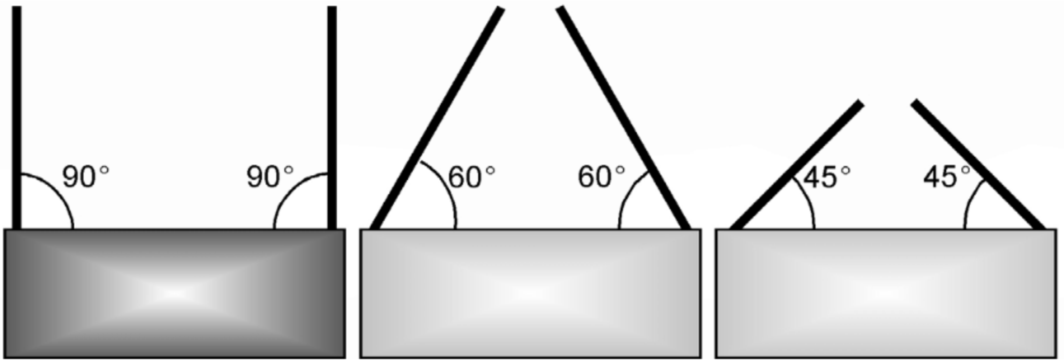


Figure 2: Sling Angles on Structures

Table 1: Sling Angle and Sling Angle Factors according to ANSI B30.9 (2014)

Sling Angle (θ)	Sling Angle Factor (ε)	Sling Angle (θ)	Sling Angle Factor (ε)	Sling Angle (θ)	Sling Angle Factor (ε)
90°	1.000	60°	1.155	30°	2.000
85°	1.004	55°	1.221	25°	2.366
80°	1.015	50°	1.305	20°	2.924
75°	1.035	45°	1.414	15°	3.864
70°	1.064	40°	1.555	10°	5.759
65°	1.103	35°	1.742	5°	11.47

2.2 Dynamic Amplification Factor (DAF)

During offshore rigging and lifting operations, all lifts are exposed to dynamic effects due to variations in hoisting speeds, crane and vessel motions and cargo barge movements due to environmental conditions [2]. In accordance to DNV-OS-H205 - Offshore Standards for Lifting Operations: Part 2-5 (2014), careful consideration should be given to dynamic effects during lifting operations. The global dynamic load effects is accounted for by using the Dynamic Amplification Factor (DAF) as shown in Table 2 below. These factors are applied to the Static Hook Load (SHL) of the structure being lifted.

Table 2: Dynamic Amplification Factors according to DNV-OS-H205 (2014)

Static Hook Load (SHL)	Dynamic Amplification Factor		
	Onshore	Inshore	Offshore
SHL < 100 t	1.10	1.15	1.30
100 t < SHL < 300 t	1.05	1.12	1.25
300 t < SHL < 1000 t	1.05	1.10	1.20
1000 t < SHL < 2500 t	1.03	1.08	1.15
SHL > 2500 t	1.03	1.05	1.10

2.3 Center of Gravity Shift Factor (SF_{COG}): The centre of gravity of the structure under study (point G from figure 1) is the point around which its entire weight may be concentrated. To make a level lift, the crane hook or point of suspension must be clearly above this point. While slight variations are usually permissible, if the crane hook is too far to one side of the COG, dangerous tilting may occur. For this reason, when the COG is closer to one point of the sling attachment than to the other, the slings must be of unequal length [3]. Sling angles and sling tension will also be unequal. The Centre of Gravity Shift Factor (SF_{COG}) is used to account for additional loads due to possible shift in COG during lifting operations. For the case under study, the SF_{COG} for quadruple lift points is negligible (SF_{COG} = 1).

2.4 Tilt Factor (TF) and Yaw Factor (YF): Similar to SF_{COG}, the Tilt Factor (TF) is used to account for additional load that may arise due to the tilting of the crane hook while the Yaw Factor (YF) is used to account for the tolerances in lift radii of the crane hook. For the case under study, this factor will be considered negligible due to the 4 slings rigging geometry (TF = YF = 1).

2.5 Skew Load Factor (SLF): The skew load factor (SLF) is used to take care of additional loading caused by equipment/fabrication tolerances and other uncertainties with respect to asymmetry and associated force distribution in the rigging arrangement [2, p. 18]. For the case under study, the structure is assumed to have negligible fabrication tolerances (SLF = 1). Additionally, in accordance with DNV-OS-H205, "For statically determinate rigging arrangements (with or without spread bar), with typical geometry and sling lengths within tolerances of ±0.5% of their nominal length, a SLF of 1.0 may be applied".

2.6 Rigging Weight Factor (RWF): The rigging weight factor is used to take care of additional loading caused by the rigging arrangement, i.e. equipment such as shackles, slings and spreader bars or frames. For the case under study, the weight of ancillary rigging equipment when compared to the load is negligible (RWF = 1).

2.7 Hydrodynamic Factor (HDF)

As the structure is lifted into subsea, it will get lighter due to the effects of buoyancy. However, the effects of waves as the structure is passed from air into water and the effects of current as the structure is lowered on the seabed all need to be accounted for. When the object is being lifted into sea, it will experience slamming wave forces which could cause severe damage to the object (figure 3). As can be seen in figure 4, there are 4 main stages of added hydrodynamic weight for subsea lifting. **Stage 1** is when the object is fully suspended in air. In this case there is no added hydrodynamic weight. In **stage 2**, the object is in direct contact with the still water line and is on the verge of feeling the hydrodynamic effect of its own weight due to the volume of water displaced beneath it. In **stage 3**, the object is partially submerged and the volume of water displaced by the sides of the structure is beginning to gather at the top. Consequently, **stage 4** is the fully submerged stage of the object where it is now fully experiencing hydrodynamic effects due to the volume of water displaced by it. In addition to this, load tolerances caused by

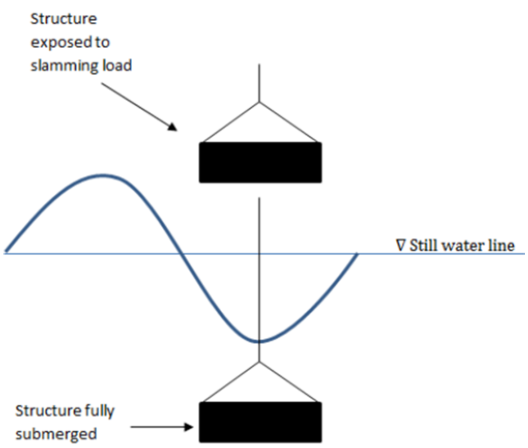


Figure 3: Lifting into Splash Zone *[4]*

vessel motions due to the effects of wind and current also need to be compensated for. For the case under study, the added hydrodynamic weight will be 60% of the object's weight in air.

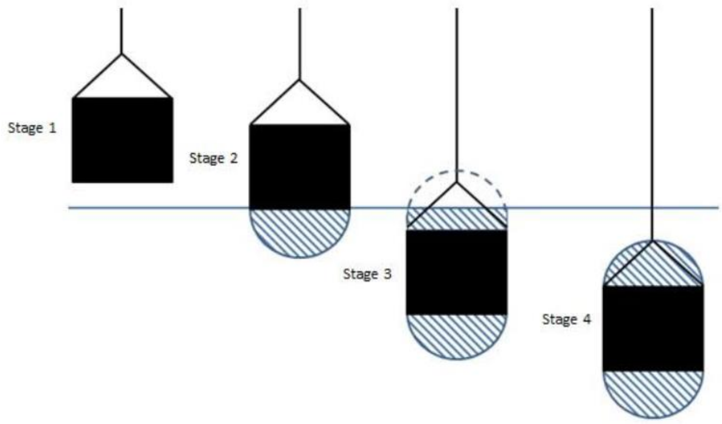


Figure 4: Stages in Added Hydrodynamic Mass during Subsea Lifting *[4]*.

3.0 Rigging and Lift Design Process Flow Chart

Figure 5 below shows the rigging and lift design process flow chart for the case under study.

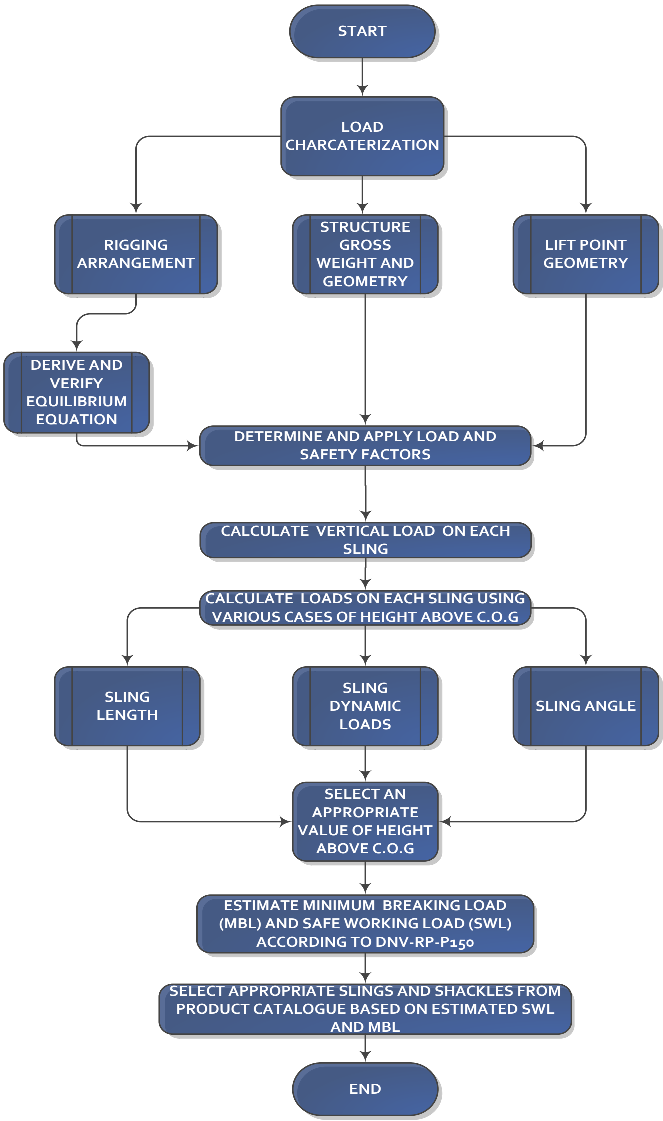


Figure 5: Rigging and Lift Design Process Flow Chart

4.0 Methodology

Every object in contact with the earth's surface is said to be "at rest" and in a state of static equilibrium. In other words, all object seeks a state of static equilibrium. External forces such as wind or lateral forces can change the equilibrium state thus making the object to be in a state of unstable equilibrium. Once this happens, the object will move to gain equilibrium again [5].

4.1 Equilibrium of Forces

The equilibrium equations are equations that describes the necessary and sufficient conditions to maintain the equilibrium of a body. A body is said to be in equilibrium when the external forces acting on it from a system of force is zero (equation 4.1). When this condition is satisfied, it can be concluded that the object is in **translational equilibrium**. In addition, the sum of external moments (or torques) acting on it must be equal to zero (equation 4.2). When this condition is satisfied, it can be concluded that the body is in **rotational equilibrium**. Consequently, a body is said to be in **static equilibrium** when it satisfies both the condition for rotational and translational equilibrium. Considering the structure under study as previously shown in figure 1, the necessary and sufficient conditions for the equilibrium of the structure in three dimensions (3D) is;

$$\sum F = 0 \qquad (e.q\ 4.1)$$

$$\sum M_O = \sum (r \times F) = 0 \qquad (e.q\ 4.2)$$

In other words;

$$\sum F_x = 0 \qquad \sum F_y = 0 \qquad \sum F_z = 0 \qquad (e.q\ 4.3)$$

$$\sum M_x = 0 \qquad \sum M_y = 0 \qquad \sum M_z = 0 \qquad (e.q\ 4.4)$$

Where $F_x, F_y\ and\ F_z$ are the force components in the x, y and z axis respectively and $M_x, M_y\ and\ M_z$ are the moments in the x, y and z axis respectively and r is the force displacement. Evidently, the equations above depicts that reactions and internal forces for the structure under consideration cannot be found by statics alone because of more unknown forces than independent equations of equilibrium. i.e., the number if independent static equilibrium equations is insufficient for solving all the external and internal forces in the system. Since the reactions involves more number of unknowns than the number of independent equilibrium equations, the solution is said to be statically indeterminate **(Please see appendix I for a more detailed derivation of the algebraic expressions).**

Let us now consider two dimensional (2D) statically determinate analysis for the structure. Assuming all the moments are in the x-y plane only, and vertical forces in the z axis, then; $F_x = 0,\ F_y = 0\ \ and\ M_z = 0$ are automatically satisfied. Thus the number of independent equilibrium equations are reduced from 6 to 3 as shown below;

$$\sum M_x = \sum F_z \times r_x = 0, \ \sum M_y = \sum F_z \times r_y = 0, \ \sum F_z = 0 \qquad (e.q\ 4.5)$$

Where r_x and r_y represents the force displacement in the x and y axis respectively.

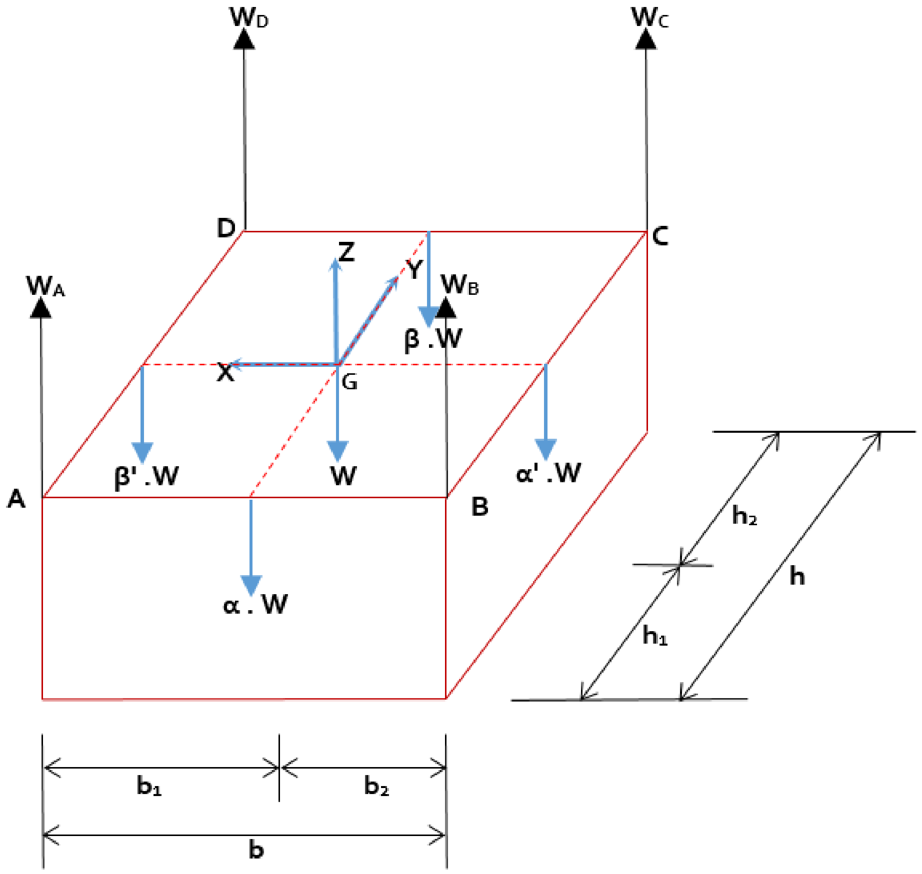


Figure 6: Sling Vertical Loads

For a statically determinate system when compared to an indeterminate one, the vertical support reactions at anchor points W_A, W_B, W_C and W_D as depicted in figure 6 can be obtained using only the static equilibrium equations for a 2D statically determinate body assuming one side (either AB, CD, BC or AD) takes an unknown percentage of the load whereas the corresponding opposite side takes the remaining percentage. Let the weight of the structure acting downwards in the COG (point G) along the z axis be represented by **W and** let **α, β, α',** and **β'** be the fraction of the object's weight carried by side AB, CD, BC and AD respectively. Considering the side of the structure AB as a single rigid beam and assuming it bears a portion of the load **(α.W)** and its adjacent side CD takes the remaining portion of the load **(β.W)**, the equilibrium of forces acting on the beam element is depicted in figure 7 below;

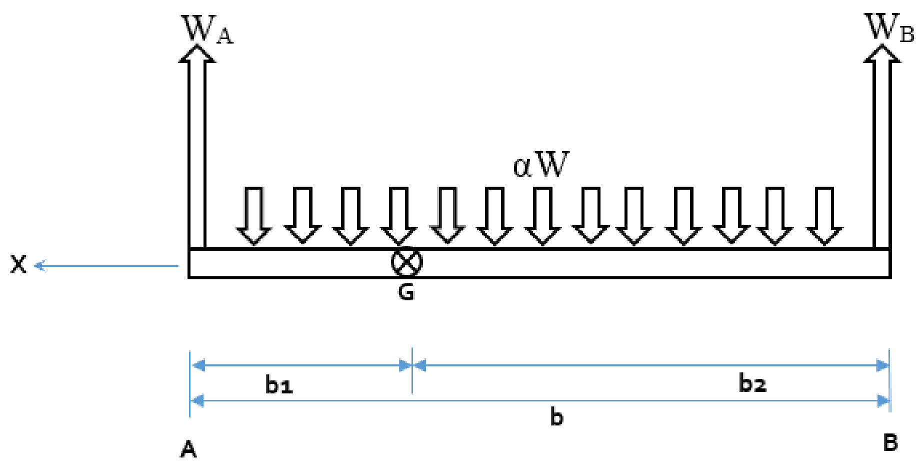


Figure 7: Free Body Diagram of the Beam Element AB

From the free body diagram shown on figure 7, the supporting force W_A and W_B represents the vertical components of the sling tension for slings 1 and 4 respectively as previously illustrated in figure 1. From equation 4.5, force equilibrium in the vertical direction along the x axis for beam element AB gives;

$$\sum_{AB} F_z = W_A + W_B = \alpha W \qquad (e.q\ 4.6)$$

Where G is the location of the COG, taking moments about the right end B and taking counter clockwise as positive gives;

$$\sum_{B} M_x = (W_A \times b) - (\alpha\, W \times b_2) = 0$$

$$\therefore W_A = W \cdot \frac{\alpha b_2}{b} \qquad (e.q\ 4.7)$$

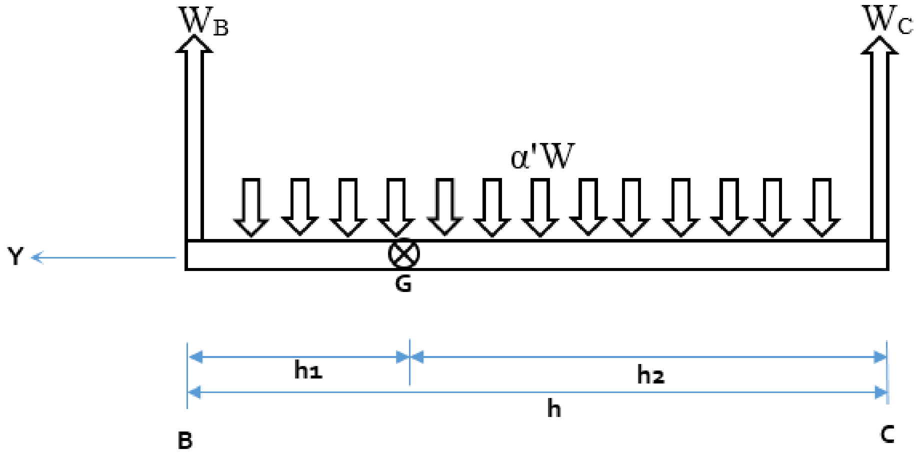


Figure 8: Free Body Diagram of the Beam Element BC

As shown on figure 8 above, same methodology may also be applied for the beam element BC. Thus, force equilibrium in the vertical direction along the Y axis for beam BC gives;

$$\sum_{BC} F_z = W_B + W_A = \alpha' W \qquad (e.q\ 4.8)$$

Taking moments about the right end C and taking counter clockwise as positive gives;

$$\sum_{C} M_y = (W_B \times h) - (\alpha'\, W \times h_2) = 0$$

$$\therefore W_B = W \cdot \frac{\alpha' h_2}{h} \qquad (e.q\ 4.9)$$

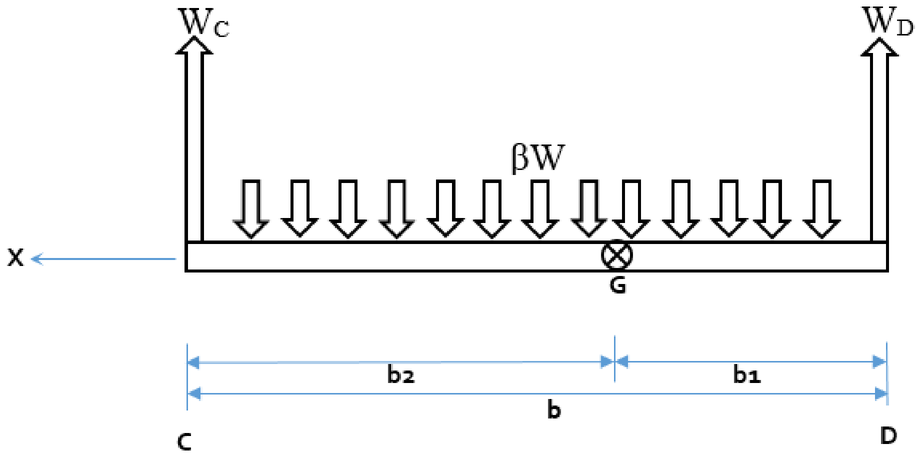


Figure 9: Free Body Diagram of the Beam Element CD

Similarly, let us consider the beam element CD adjacent to AB as shown in figure 9 above. Force equilibrium in the vertical direction along the X axis for beam element CD gives;

$$\sum_{CD} F_z = W_C + W_D = \beta W \qquad (e.q\ 4.10)$$

Also, taking moments about the right end D and taking counter clockwise as positive gives;

$$\sum_{D} M_x = (W_C \times b) - (\beta\, W \times b_1) = 0$$

$$\therefore W_C = W \cdot \frac{\beta b_1}{b} \qquad (e.q\ 4.11)$$

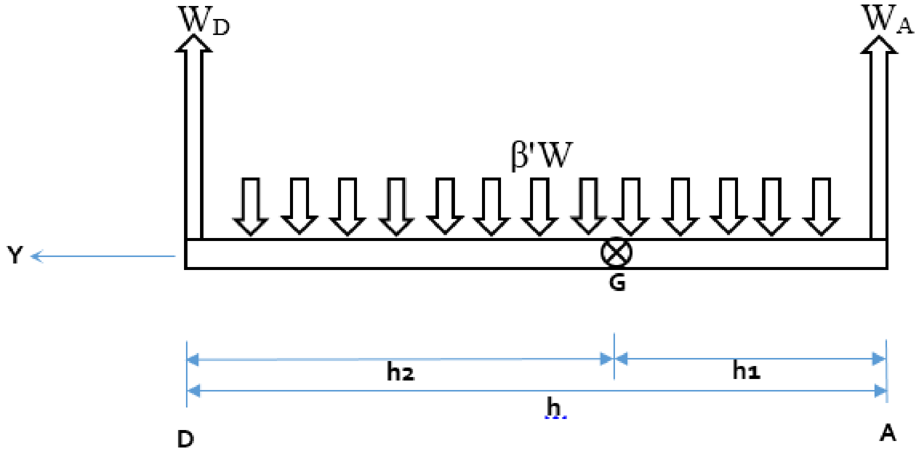


Figure 10: Free Body Diagram of the Beam Element DA

As depicted in figure 10 above, the force equilibrium in the vertical direction along the y axis for beam DA adjacent to side BC gives;

$$\sum_{DA} F_z = W_D + W_A = \beta' W \qquad (e.q\ 4.12)$$

Taking moments about the right end A and taking counter clockwise as positive gives;

$$\sum_{A} M_y = (W_D \times h) - (\beta'\, W \times h_1) = 0$$

$$\therefore W_D = W \cdot \frac{\beta' h_1}{h} \qquad (e.q\ 4.13)$$

The equations highlighted above (4.7, 4.9, 4.11 and 4.13) are the equilibrium equations needed to calculate the vertical components of the sling tension in the slings which are the four unknowns (W_A,W_B,W_C, and W_D) in these equation. However, there is still need to express these vertical sling forces in the form of W, h_1, h_2, h, b_1, b_2, and b by determining the unknown α, β, α', and β' . This will be determined by using the resultant vertical forces in the z axis ($\sum F_z = 0$).

From equation 4.6;

$$\sum_{AB} F_z = W_A + W_B = \alpha W$$

Substituting the equation 4.7 and 4.9 into this will give;

$$W \cdot \alpha \frac{b_2}{b} + W \cdot \alpha' \frac{h_2}{h} = \alpha W$$

Simplifying further, we have;

$$\alpha \frac{b_2}{b} + \alpha' \frac{h_2}{h} = \alpha$$

Thus;

$$\alpha' \frac{h_2}{h} = \alpha - \alpha \frac{b_2}{b}$$

Furthermore;

$$\alpha' \frac{h_2}{h} = \alpha \left(1 - \frac{b_2}{b}\right) = \alpha \frac{b - b_2}{b} = \alpha \frac{b_1}{b}$$

Thus;

$$\alpha' \frac{h_2}{h} = \alpha \frac{b_1}{b}$$

Since α' and α are ratios;

$$\therefore \boldsymbol{\alpha'} = \frac{\boldsymbol{b_1}}{\boldsymbol{b}} \;\; and \;\; \boldsymbol{\alpha} = \frac{\boldsymbol{h_2}}{\boldsymbol{h}}$$

Similarly, from equation 4.10;

$$\sum_{CD} F_z = W_C + W_D = \alpha W$$

Substituting the equation 4.11 and 4.13 into this will give;

$$W \cdot \beta \frac{b_1}{b} + W \cdot \beta' \frac{h_1}{h} = \beta W$$

Simplifying further, we have;

$$\beta \frac{b_1}{b} + \beta' \frac{h_1}{h} = \beta$$

Thus;

$$\beta' \frac{h_1}{h} = \beta - \beta \frac{b_1}{b}$$

Furthermore;

$$\beta' \frac{h_1}{h} = \beta \left(1 - \frac{b_1}{b}\right) = \beta \frac{b - b_1}{b} = \beta \frac{b_2}{b}$$

Thus;

$$\beta' \frac{h_1}{h} = \beta \frac{b_2}{b}$$

Since β' and β are ratios;

$$\therefore \boldsymbol{\beta'} = \frac{\boldsymbol{b_2}}{\boldsymbol{b}} \;\; and \;\; \boldsymbol{\beta} = \frac{\boldsymbol{h_1}}{\boldsymbol{h}}$$

Substituting α, α', β, and β' into equations 4.7, 4.9, 4.11 and 4.13 respectively will yield;

$$W_A = W \cdot \frac{h_2}{h} \cdot \frac{b_2}{b} \tag{4.14}$$

$$W_B = W \cdot \frac{b_1}{b} \cdot \frac{h_2}{h} \tag{4.15}$$

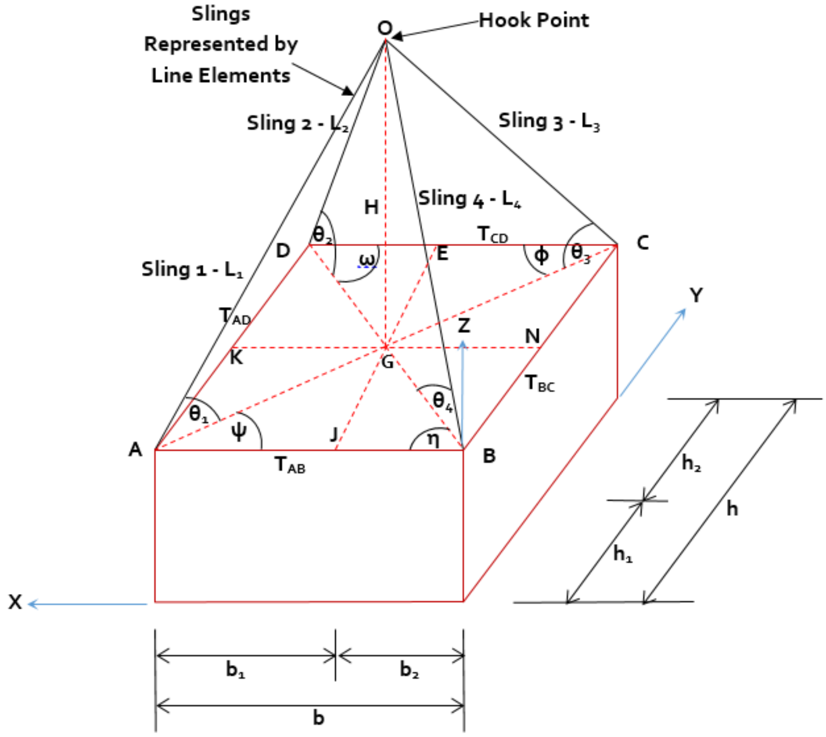
$$W_C = W \cdot \frac{h_1}{h} \cdot \frac{b_1}{b} \tag{4.16}$$

$$W_D = W \cdot \frac{b_2}{b} \cdot \frac{h_1}{h} \tag{4.17}$$

Please see appendix I showing details of derivation for checks in consistency.

4.2 Sling Geometry

As demonstrated in section 4.1, we have established the equilibrium equations needed to calculate the vertical force components of the slings. Hence, this section is aimed at demonstrating how the sling angle and sling lengths will be estimated. This will be achieved using simple trigonometric principles. As shown below (from figure 1), G is the centre of gravity (COG) for the structure (located on the x, y coordinate as b_1, h_1). The COG is directly under the hook point, O and has a vertical distance H from it.



From Figure 1: Geometry of Rigging

The angle, ψ can also be expressed as;

$$\psi = \tan^{-1}\left(\frac{\overline{GJ}}{\overline{AJ}}\right) = \tan^{-1}\left(\frac{h_1}{b_1}\right) \quad (e.q\ 4.18)$$

Consequently;

$$\eta = \tan^{-1}\left(\frac{\overline{GJ}}{\overline{BJ}}\right) = \tan^{-1}\left(\frac{h_1}{b_2}\right) \quad (e.q\ 4.19)$$

$$\Phi = \tan^{-1}\left(\frac{\overline{EG}}{\overline{CE}}\right) = \tan^{-1}\left(\frac{h_2}{b_2}\right) \quad (e.q\ 4.20)$$

$$\omega = \tan^{-1}\left(\frac{\overline{EG}}{\overline{DE}}\right) = \tan^{-1}\left(\frac{h_2}{b_1}\right) \quad (e.q\ 4.21)$$

Thus, the diagonal distance between the edges and COG can be expressed as;

$$\overline{AG} = \frac{\overline{AJ}}{\cos\psi} = \frac{b_1}{\cos\psi} \quad (e.q\ 4.22)$$

$$\overline{BG} = \frac{\overline{BJ}}{\cos\eta} = \frac{b_2}{\cos\eta} \quad (e.q\ 4.23)$$

$$\overline{CG} = \frac{\overline{CE}}{\cos\Phi} = \frac{b_2}{\cos\Phi} \quad (e.q\ 4.24)$$

$$\overline{DG} = \frac{\overline{DE}}{\cos\omega} = \frac{b_1}{\cos\omega} \quad (e.q\ 4.25)$$

Hence, the sling angle to the horizontal can be calculated as;

$$\theta_1 = \tan^{-1}\left(\frac{H}{\overline{AG}}\right) \quad (e.q\ 4.26)$$

$$\theta_2 = \tan^{-1}\left(\frac{H}{\overline{DG}}\right) \quad (e.q\ 4.27)$$

$$\theta_3 = \tan^{-1}\left(\frac{H}{\overline{CG}}\right) \quad (e.q\ 4.28)$$

$$\theta_4 = \tan^{-1}\left(\frac{H}{\overline{BG}}\right) \quad (e.q\ 4.29)$$

Where θ_1, θ_2, θ_3, and θ_4 represents the sling angle to the horizontal for sling 1, 2, 3 and 4 respectively.

Having calculated the sling angle to the horizontal for each sling, the length for each sling can be calculated as;

$$L_1 = \sqrt{H^2 + \overline{AG}^2} \quad (e.q\ 4.30)$$

$$L_2 = \sqrt{H^2 + \overline{DG}^2} \quad (e.q\ 4.31)$$

$$L_3 = \sqrt{H^2 + \overline{CG}^2} \quad (e.q\ 4.32)$$

$$L_4 = \sqrt{H^2 + \overline{BG}^2} \quad (e.q\ 4.33)$$

Where L_1, L_2, L_3, and L_4 represents the sling length for sling 1, 2, 3 and 4 respectively.
So far, we have demonstrated how the sling angle (θ), and sling length (L) can be calculated. The next task will be to calculate the loads on the slings with respect to its vertical load. Figure 11 below is a diagrammatical expression of the sling load with respect to its vertical components.

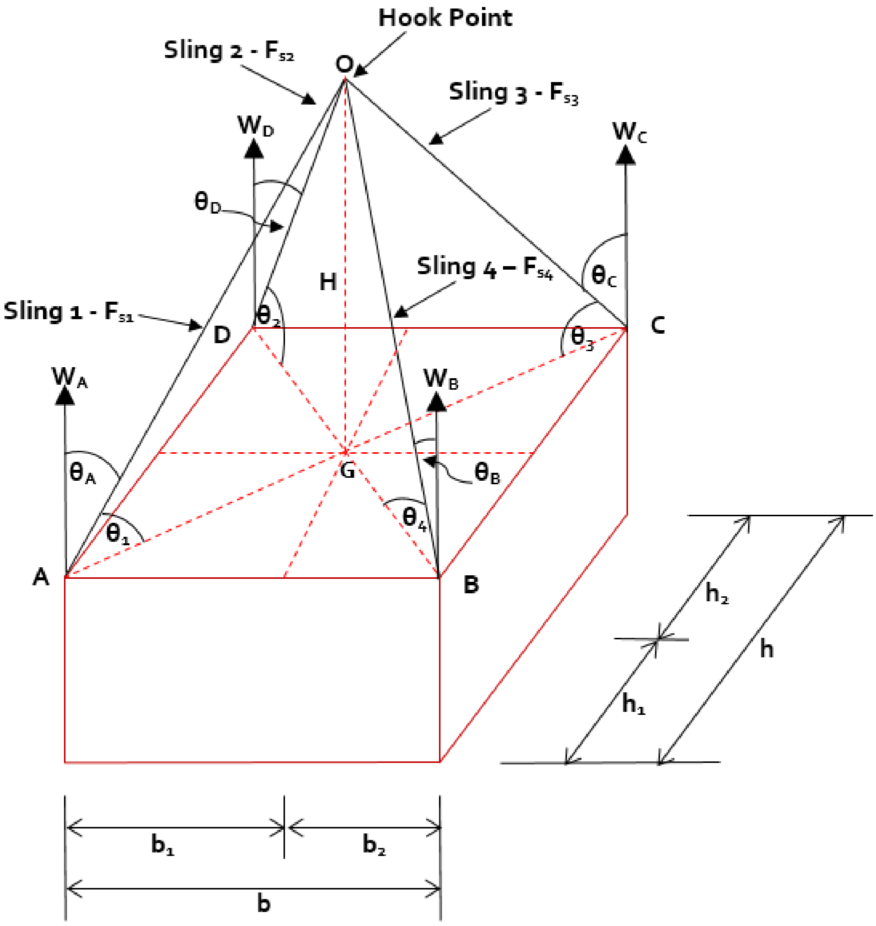


Figure 11: Vertical Force Components of Slings and Sling Tension

Let F_{S1}, F_{S2}, F_{S3} and F_{S4} be the sling load on slings 1, 2, 4 and 4 respectively. Hence from figure 11 on page 12;

$$\theta_A = 90 - \theta_1$$

Similarly;

$$\theta_B = 90 - \theta_4$$

$$\theta_C = 90 - \theta_1$$

$$\theta_D = 90 - \theta_2$$

From angles in a right angled triangle rule;

$$\cos\theta_A = \frac{W_A}{F_{s1}}$$

$$\therefore F_{s1} = \frac{W_A}{\cos\theta_A} = \frac{W_A}{\cos(90-\theta_1)}$$

From sine and cosine rule;

$$\cos(90-\theta) = \sin\theta$$

Thus;

$$F_{s1} = \frac{W_A}{\sin\theta_1} \qquad (e.q\ 4.34)$$

Consequently;

$$F_{s2} = \frac{W_D}{\sin\theta_2} \qquad (e.q\ 4.35)$$

$$F_{s3} = \frac{W_C}{\sin\theta_3} \qquad (e.q\ 4.36)$$

$$F_{s4} = \frac{W_B}{\sin\theta_4} \qquad (e.q\ 4.37)$$

The average force per sling will calculated by;

$$F_{avg} = \frac{F_{s1}+F_{s2}+F_{s3}+F_{s4}}{4} \qquad (e.q\ 4.38)$$

5.0 Discussion and Results

For the case under study, shown on table 3 below is the geometry and characterization of the load to be rigged from the vessel into subsea.

Table 3: Load Characterization and Geometry

LOAD CHARACTERIZATION Structure Type: Manifold			
Parameters	Symbol	Value	S.I Unit
Submerged Weight	W_{sub}	110.00	tons
Weight in Air (Static Hook Load)	W_{air}	126.44	tons
Breadth of Manifold	b	10.60	m
Length of Manifold	h	9.60	m
Dynamic Applification Factor	DAF	1.25	Dimensionless
Air Lift due to DAF (Dynamic Hook Load)	W_{air}^{Lift}	158.05	tons
Structure C.O.G Co-ordinate	b_1	4.60	m
	h_1	3.60	m
Hydrodynamic Factor	HDF	60%	Dimensionless
Added Hydrodynamic Weight	W_{hyd}	66.00	tons
Weight Lift in Subsea	W_{sea}	176.00	tons

5.1 Slings Tension and Sling Angle Calculation

The lift in air W_{air}^{lift} or Dynamic Hook Load (DHL) was calculated using this expression;

$Dynamic\ Hook\ Load\ (DHL) = Static\ Hook\ Load(SHL) \times DAF$, which is also same as;

$$W_{air}^{lift} = W_{air} \times DAF = \frac{W_{sub}}{0.86} \times DAF \qquad (e.q\ 5.1)$$

From table 2, according to DNV-OS-H205 (2014), for 100 t < SHL < 300 t, DAF is equal to 1.25. The weight lift in subsea, W_{sea} due to added hydrodynamic weight, W_{hyd} was calculated by;

$$W_{sea} = W_{sub} + W_{hyd} = W_{sub} + (HDF \times W_{sub}) = W_{sub}(1 + HDF) \qquad (e.q\ 5.2)$$

Based on the equilibrium equations derived in section 4 (equations 4.34, 4.35, 4.36 and 4.37), the tension on each sling as a function of its angle to the horizontal, and its vertical components of tension was calculated. Figure 12 below shows a snapshot of the summary calculations done on excel to estimate the values for vertical components of sling tension, sling angle, sling length, dynamic load on each sling and average force per sling for seven (7) guess estimates of hook distance from the centre of gravity (COG). **Please see appendix II containing an embedded excel file for a more detailed calculation using Microsoft Excel™ (Excel File Tab Titled "PART A")**

SUMMARY OF RESULTS - SLING LOAD & LIFT POINT GEOMETRY										
Parameters	Symbol	S.I Unit	Referenced Equation/Tables	Guess Estimates of Hook Distance from C.O.G						
				H = 0.9h	H = h	H = 1.1h	H = 1.2h	H = 1.3h	H = 1.4h	H = 1.5h
Hook Distance from C.O.G	H_{COG}	m		8.64	9.60	10.56	11.52	12.48	13.44	14.40
Vertical Components of Sling Tension	W_A	tons	Eqn. 4.14	62.26	62.26	62.26	62.26	62.26	62.26	62.26
	W_B	tons	Eqn. 4.15	47.74	47.74	47.74	47.74	47.74	47.74	47.74
	W_C	tons	Eqn. 4.16	28.64	28.64	28.64	28.64	28.64	28.64	28.64
	W_D	tons	Eqn. 4.17	37.36	37.36	37.36	37.36	37.36	37.36	37.36
Sling Angle	θ_1	degrees	Eqn. 4.26	55.94	58.68	61.05	63.11	64.92	66.51	67.92
	θ_2	degrees	Eqn. 4.27	48.81	51.78	54.40	56.72	58.79	60.64	62.30
	θ_3	degrees	Eqn. 4.28	45.52	48.53	51.22	53.63	55.79	57.73	59.49
	θ_4	degrees	Eqn. 4.29	51.00	53.91	56.47	58.73	60.72	62.50	64.08
Length of Slings	L_1	m	Eqn. 4.30	10.43	11.24	12.07	12.92	13.78	14.65	15.54
	L_2	m	Eqn. 4.31	11.48	12.22	12.99	13.78	14.59	15.42	16.26
	L_3	m	Eqn. 4.32	12.11	12.81	13.55	14.31	15.09	15.89	16.71
	L_4	m	Eqn. 4.33	11.12	11.88	12.67	13.48	14.31	15.15	16.01
Dynamic Load on Each Sling	F_{s1}	tons	Eqn. 4.34	75.16	72.88	71.15	69.81	68.75	67.89	67.19
	F_{s2}	tons	Eqn. 4.35	49.64	47.55	45.95	44.69	43.68	42.86	42.19
	F_{s3}	tons	Eqn. 4.36	40.14	38.23	36.74	35.57	34.63	33.87	33.24
	F_{s4}	tons	Eqn. 4.37	61.43	59.07	57.26	55.85	54.73	53.82	53.07
Average Force Per Sling	$F_{s(avg)}$	tons	Eqn. 4.38	56.59	54.43	52.78	51.48	50.45	49.61	48.93

Figure 12: Summary of Result for Sling Load and Lift Point Geometry

5.2 Slings and Shackles Requirement

As can be seen from figure 12, seven guess estimates of hook distance from COG were checked in order to determine the most suitable height above COG that will facilitate a safe, reliable and economical lifting and rigging operation. In accordance with ANSI B30.9, it is recommended not to have sling angles less than 45° to the horizontal in order to ensure a safe and reliable lifting operation. Based on the numerical calculations shown on figure 12 above, the sling angles satisfies this criteria for all guess estimates of vertical height above the COG investigated. With this in mind, the appropriate height among the seven cases investigated will be determined based on the height above COG that characterized a much higher sling angle for each sling. Hence, from an operational safety perspective, height above COG, H = 14.4 m (H = 1.5h) will be the most preferred option. However, this has some financial implication as the slings will be much longer, thus increasing the cost of purchase per unit length. Nevertheless, the benefits outweighs the cost in the long run.

Table 4: Chosen Sling Geometry from H_{COG} Analysis

SLING LOAD & LIFT POINT GEOMETRY H_{COG} = 14.4 m				
Sling	Sling Angle θ (°)	Vertical Load for Each Sling W (tons)	Length of Slings L (m)	Dynamic Load on Each Sling F (tons)
1	67.92	62.26	15.54	67.19
2	62.30	37.36	16.26	42.19
3	59.49	28.64	16.71	33.24
4	64.08	47.74	16.01	53.07
Average Force Per Sling (tons)				48.93

Table 4 above shows the chosen sling geometry based on H_{COG} analysis carried out. The next task now will be to determine the Safe Working Load (SWL) / Working Load Limit (WLL) and the Minimum Breaking Load (MBL) for the selected rigging geometry in lieu to recommending the appropriate slings and shackles specification for the lifting operation.

5.3 Safe Working Load (SWL) / Working Load Limit (WLL)

The term **Safe Working Load (SWL)** is the maximum load (as specified by the manufacturer) that a rigging component "**may**" lift, lower or statically suspend under a normal or stipulated service condition. In other words, it is considered to be the breaking load of a rigging component divided by an appropriate factor of safety. However, due to numerous environmental factors, the term **"Safe Working Load"** is no longer used by manufacturers to specify the maximum rated load a rigging component can lift [6]. This was as a result of the need to adequately assign load limits in order to avoid **"Plastic Deformation"** or stress during the continuous usage of that rigging component.

The term **Working Load Limit (WLL)** is now being used to tag all load carrying ancillary equipment for lifting and rigging operations. The WLL of a rigging component is the maximum load (as specified by the manufacturer) that it is "**designed**" to lift, lower or statically suspend under normal or stipulated service condition. In other words, it is the maximum load that should ever be applied to the load carrying equipment of the rigging arrangement in a specified configuration or application. It may also be referred to as the **"Maximum Safe Working Load" or "Maximum Rated Load"**. Normally, SWL should be equal to WLL. But the rigging component may be de-rated with time. When this happens, the SWL becomes less than the WLL (SWL < WLL).

5.4 Minimum Breaking Load (MBL)

The Minimum Breaking Load (MWL) is the minimum amount of load that must be applied to a rigging component before failure occurs. For slings, it is referred to as the minimum tensile strength. According to section 4.1.5 of DNV-OS-H205 [2, p. 25], the minimum breaking load must fulfil the criteria stated in equation 5.7 below;

$$WLL_{sling} < \frac{MBL_{sling}}{\gamma_{sf}} \qquad (e.q\ 5.7)$$

Where MBL_{sling} is the Minimum Breaking Load for the sling, WLL_{sling} is the Working Load Limit of the sling which can also be the expected maximum dynamic load F_{sling} for the sling during lifting operation and γ_{sf} is the nominal safety factor for the slings which is given by;

$$\gamma_{sf} = \gamma_f \cdot \gamma_c \cdot \gamma_r \cdot \gamma_w \cdot \gamma_m \cdot \gamma_{tw} \qquad (e.q\ 5.8)$$

Or;

$$\gamma_{sf} = 2.3 \cdot \gamma_r \cdot \gamma_w \cdot \gamma_{tw} \qquad (e.q\ 5.9)$$

Where;

γ_f: Load Factor due to skew load effects = 1.3

γ_c: Consequence Factor due to the failure of one or more slings during lifting = 1.3

γ_r: Reduction Factor due to end termination or bending = 1.25

γ_w: Wear and Application Factor due to usage = 1.10

γ_m: Material Factor due to the material type of the sling = 1.50 (Steel Wire)

γ_{tw}: Twist Reduction Factor due to risk of twisting the sling during lifting = 1.3

γ_{sf} should be taken as the greatest between equation 5.8 and equation 5.9. Based on the values of the factors highlighted above, γ_{sf} = 4.53 according to equation 5.8 and γ_{sf} = 4.11 according to equation 5.9. Thus, the desired nominal safety factor will be 4.53.

According to BS 6166-1:1986, Lifting Sling Part 1 – Method of Rating, the methodology for determining the WLL, SWL and MBL is shown in the figure 13 below;

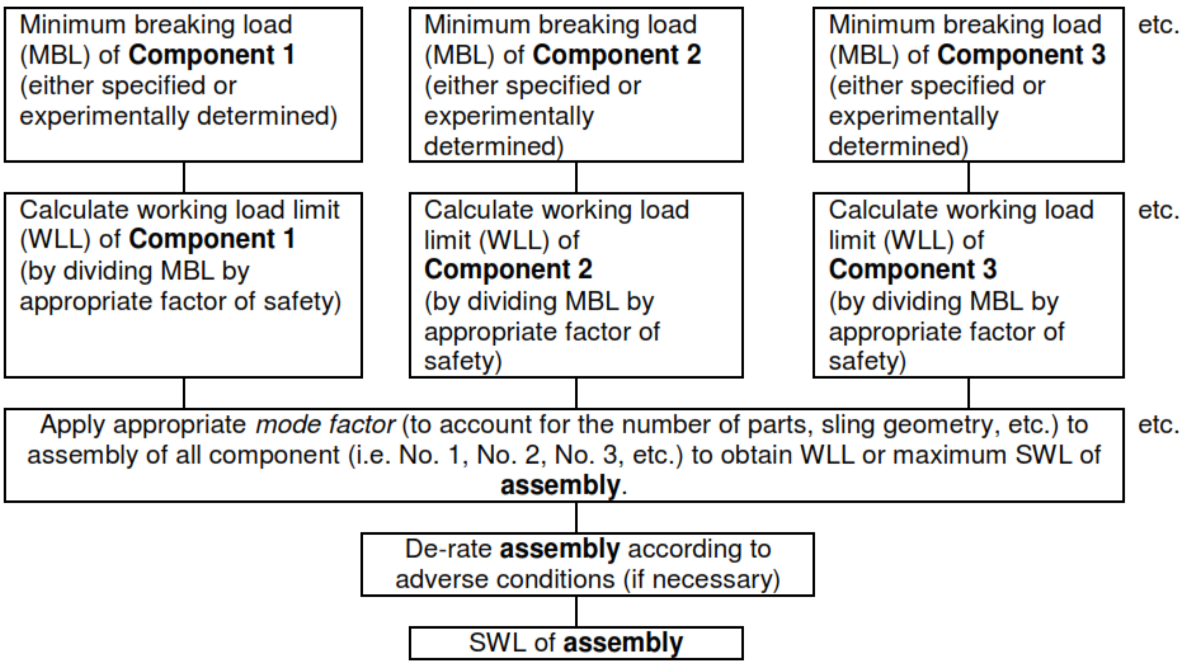


Figure 13: SWL, WLL, and MBL Rating Methodology According to BS 6166-1:1986

From table 4, the largest sling dynamic load (67.19 tons) is experienced by sling 1. For conservatism and since the slings carries unequal loads, this will be taken to be WLL for each of the slings to be recommended. It is noteworthy to mention that by Load Factor and Resistance Design (LFRD) principles, it will be inappropriate to use the average force per sling as the WLL per sling. Using $F_{s(avg)}$ will result to under-designing the sling tension specification for two of the slings because $F_{s(avg)} < F_{S4} < F_{S1}$. Thus, in accordance with DNV-OS-H205 criteria for minimum breaking load expressed in equation 5.7, the desired MBL for each sling will be;

$MBL_{sling} > \gamma_{sf} WLL_{sling} = \gamma_{sf} F_{sling} = 4.53 \times 67.19 = 304.37\ tons\ per\ sling$

$\therefore MBL_{sling} > 304.37$ tons per sling

Consequently, the WLL of the rigging assembly will be;

$WLL_{assembly} = F_{sling} \times Number\ of\ Slings = \ 67.19\ \times 4 = 268.76\ tons$

If adverse rigging conditions will not be expected, the Safe Working Load (SWL) of the rigging assembly will be equal to its Working Load Limit (WLL). Thus;
$WLL_{assembly} = SWL_{assembly} = 268.76\ tons$

Table 5: Summary Estimation of Operating Loads

Parameters	Operating Loads W_{sub} = 176 tons, γ_{sf} = 4.53	
	Per Sling (tons)	Lifting Assembly (tons)
Minimum Breaking Load (MBL)	304.37	1,217.48
Working Load Limit (WLL)	67.19	268.76
Safe Working Load (SWL)[a]	67.19	268.76

Table 5 shows a summary of the estimated value for MBL, WLL and SWL for the rigging geometry. The next task now will be to select the appropriate rigging components (slings and shackles) that can meet the requirements of the operating loads summarised on table 5.

5.5 Sling Sizing and Selection

It has been established that an estimated Minimum Breaking Load (MBL) of 292.6 tons per sling and Safe Working Load (SWL) / Working Load Limit (WLL) of 58.52 tons per sling is required to ensure a safe and reliable rigging/lifting operation. The rigging geometry showed sling angles between the ranges of 0° to 90°. With this in mind and based on the sling product catalogue provided, the most appropriate sling will be;
Rope Diameter, **D** = 71 mm, **SWL/WLL** = 139.80 tonnes and **MBL** = 333.00 tonnes
Please see item highlighted in green on the catalogue shown on figure 14.

6 x 19 6 x 36 GROUPS STEEL CORE - GRADE 1770 N/mm2

ROPE DIA	SAFE WORKING LOAD					MIN BREAK LOAD	PROOF LOAD PER LEG @ 0 DEGREES
	SINGLE LEG	LEG ANGLE 0-90 DEGREES		LEG ANGLE 90-120 DEGREES			
		2 LEG	3 & 4 LEG	2 LEG	3 & 4 LEG		
mm	tonne	tonne	tonne	tonne	tonne	tonne	tonne
8	0.82	1.10	1.70	0.82	1.20	4.11	1.64
9	1.00	1.40	2.10	1.00	1.50	5.20	2.00
10	1.30	1.80	2.70	1.30	1.90	6.42	2.60
11	1.50	2.20	3.20	1.50	2.30	7.77	3.20
12	1.80	2.60	3.90	1.80	2.80	9.25	3.60
13	2.10	3.00	4.50	2.10	3.20	10.80	4.40
14	2.50	3.50	5.30	2.50	3.80	12.60	5.00
16	3.30	4.60	6.90	3.30	4.90	16.40	6.60
18	4.10	5.80	8.70	4.10	6.20	20.80	8.40
19	4.60	6.40	9.70	4.60	6.90	23.10	9.20
20	5.10	7.20	10.80	5.10	7.70	25.70	10.20
22	6.20	8.70	13.00	6.20	9.30	31.10	12.40
24	7.40	10.30	15.50	7.40	11.10	37.00	14.80
26	8.70	12.10	18.20	8.70	13.00	43.40	17.40
28	10.10	14.10	21.10	10.10	15.10	50.40	20.20
32	13.10	18.40	27.60	13.10	19.70	65.70	26.20
35	15.70	22.00	33.00	15.70	23.60	78.70	31.40
36	16.60	23.30	35.00	16.60	25.00	83.30	33.20
38	18.50	26.00	39.00	18.50	27.80	92.80	37.00
40	20.60	28.80	43.20	20.60	30.90	103.00	41.20
44	24.80	34.70	52.10	24.80	37.20	124.00	49.60
48	29.60	41.40	62.10	29.60	44.40	148.00	59.20
52	34.80	48.70	73.10	34.80	52.20	174.00	69.60
54	37.40	52.30	78.50	37.40	56.10	187.00	74.80
56	40.20	56.30	84.40	40.20	6.03	201.00	80.40
60	46.20	64.70	97.00	46.20	69.30	231.00	92.40
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
71	66.60	93.20	139.80	66.60	99.90	333.00	133.20
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

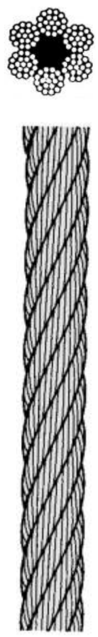


Figure 14: Sling Catalogue and Cross Section of Steel Wire Sling (6 x 19 x 6 x 36)

[a] Assuming no adverse rigging conditions

5.6 Shackle Sizing and Selection

In order to ensure uniformity in material strength for the rigging component, the shackle to be selected will have an approximately same WLL as the sling. On this note, Green Pin®'s Heavy Duty Shackle with WLL of 150 tons and MBL of (5 x WLL) = 750 tons will be most suitable.

working load limit	diameter bow	diameter pin	width inside	length inside	width bow	weight each
	a	b	c	d	e	
tons	mm	mm	mm	mm	mm	kg
120	95	95	144	381	238	110
150	105	108	165	400	275	160
200	120	130	175	500	290	235
250	130	140	200	540	305	285
300	140	150	200	600	305	340
400	170	175	225	650	325	560
500	180	185	250	700	350	685
600	200	205	275	700	375	880
700	210	215	300	700	400	980
800	210	220	300	700	400	1100
900	220	230	320	700	420	1280
1000	240	240	340	700	420	1460
1250	260	270	360	750	450	1990
1500	280	290	360	800	450	2400

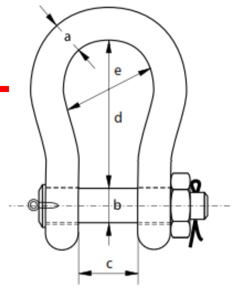


Figure 15: Shackle Catalogue and Cross Section of Shackle Dimensions

Table 6: Summary of Comparison for Selected Rigging Component Rating and Operating Load

Parameters	Design Loads W_{sub} = 176 tons, γ_{sf} = 4.53		Selected Component Rating	
	Per Sling (tons)	Sling Assembly (tons)	Per Sling (tons)	Per Shackle (tons)
Minimum Breaking Load (MBL)	304.37	1,217.48	333.00	750.00
Working Load Limit (WLL)	67.19	268.76	139.80	150.00
Safe Working Load (SWL)	67.19	268.76	139.80	150.00

Table 6 above shows a summary of comparison between the selected rigging component rating and operating load.

6.0 Natural Periods of Rigging Oscillations

The rigging and lift arrangement been considered will exhibit the characteristics of a free vibration body during subsea lifting. A free vibration body is one which occurs naturally without any form of external energy added to the vibrating system. The vibration for the rigging arrangement system will be as a result of the vessel/crane motion due to the six degree of freedom that the vessel is subjected to (Roll, Pitch, Yaw, Heave, Sway and Surge). The vibration will start from the crane hook and will die away with time as the energy is dissipated.

For this study, we will consider only two degree of freedom in the vertical direction (linear elastic vibration oscillation) and horizontal direction (pendulum oscillation). Table 7 below shows the crane-hook wire rope properties. It is assumed that the hook will be supported by two parallel strongest rope available on the sling catalogue. This was found to be the 77 mm steel wire rope with a MBL of 389 tonnes. It was also established that the length of the steel wire rope (L_r) supporting the hook from the crane block will be two times the height of the hook above the COG.

$$L_r = 2 \times H_{COG} = 2 \times 14.4 = 28.80\ m$$

The effective cross sectional area of the hook wire rope was estimated by;

$$A_{wire} = \frac{\pi \cdot D_r}{4} \cdot F_f \qquad (e.q\ 6.1)$$

Consequently, since the hook is supported by two parallel ropes, the total effective cross sectional area will be given by;

$$A_{wire}^{total} = 2 \times A_{wire}$$

Where D_r , is the diameter of the steel is rope and F_f is the fill factor for the steel rope.

Table 7: Crane Hook Wire Properties

CRANE - HOOK WIRE ROPE PROPERTIES			
Parameters	Symbol	Value	S.I Unit
Diameter	D_r	0.0770	m
Length	L_r	28.80	m
Young's Modulus	E	2.00E+11	N/m²
Fill Factor of Wire Rope	F_f	1.00	Dimensionless
Effective Cross Sectional Area of Wire	A_{wire}	0.00466	m²
Number of Lines	n	2.00	tons
Total Effective Cross Sectional Area	A_{wire}^{total}	0.00931	m²
Air Lift due to DAF	W_{air}^{Lift}	158.05	tons
Weight Lift in Subsea	W_{sea}	176.00	tons

6.1 Key Assumptions for Rigging Oscillation Analysis

The intention of these assumptions is to ensure that the (environmental) design criteria is not exceeded during the lifting operation. This will be achieved by giving simple assumptions for Metocean data of the environment where the subsea lifting operation will take place. The main assumptions are;

- The subsea rigging operation is being carried out in the UK Continental Shelf (UKCS) in a water depth of about 600 m.
- The horizontal extent (breadth, b) of the lifted object is small compared to the wavelength (λ) of the sea i.e. λ >>> b
- The vertical motion of the object is equal the vertical crane tip motion.
- Object motion during subsea lift is dominated by vertical motion of the crane tip and sea motion (Current and Waves). All other motions are negligible.
- The lifting operation will be carried out in minor sea states with typical significant wave height (H_s) of about 3.5m.
- The operation reference period, T_R for the subsea lifting operation, taking into account the planned operation period, T_{POP} and estimated maximum contingency time T_C will be 12 hours.
- From a worst case scenario point of view, the oscillating system of the rigging arrangement will be un-damped when the structure is submerged into the sea.

6.2 Analysis for Elastic Vibration Type Oscillation

Natural oscillations occur as a result of the restoring force facilitated by a spring. The steel wire rope used in deploying the structure subsea behaves like a string because it produces a force or torque directly proportional to its displacement whenever it is stretched, compressed, bent or twisted due to vessel motion caused by wave , wind and current. The elastic vibration system of the rigging geometry is shown on figure 16. K_c is the stiffness of the crane master on top of the cable while K_s is the stiffness of the slings on top of the object being lifted. For the case under study, we will only be considering the stiffness of the hoisting line, K_l and the effective stiffness of the sling assembly K_{seff} due to the available data. In accordance with DNV-RP-H103, the stiffness of the steel wire rope can be calculated as;

$$K = \frac{EA}{L} \quad (e.q\ 6.2)$$

Where E, A and L is the modulus of elasticity, cross-sectional area and length of the steel wire respectively. Thus, the total vertical stiffness of the system will be [7];

$$\frac{1}{K_v} = \frac{1}{K_l} + \frac{1}{K_{seff}} \quad (e.q\ 6.3)$$

Where;

$$K_{seff} = K_{s1}\sin\theta_1 + K_{s2}\sin\theta_2 + K_{s3}\sin\theta_3 + K_{s4}\sin\theta_4$$

Simplifying further, we have;

$$K_{seff} = EA_s\left(\frac{\sin\theta_1}{L_{s1}} + \frac{\sin\theta_2}{L_{s2}} + \frac{\sin\theta_3}{L_{s3}} + \frac{\sin\theta_4}{L_{s4}}\right) \quad (e.q\ 6.4)$$

Where $A_s, L_{s1}, \theta_1, L_{s2}, \theta_2, L_{s3}, \theta_3, L_{s4}$ *and* θ_4 have their usual meaning as shown on table 8 below. The K_{seff} was calculated to be 1.06 × 10^8 N/m.

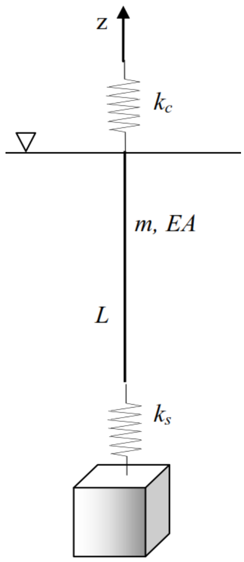


Figure 16: Forced Elastic Oscillation in Lifted Objects [7].

Table 8: Calculation for Sling Effective Stiffness

SLING EFFECTIVE STIFFNESS D_s= 71 mm, E = 200 GPa, A_s = 0.00239 m^2			
Sling	Sling Angle θ (°)	Length of Slings L_s (m)	Stiffness K_s (N/m)
1	67.92	15.54	2.85E+07
2	62.30	16.26	2.60E+07
3	59.49	16.71	2.46E+07
4	64.08	16.01	2.69E+07
Effective Sling Stiffness, K_{Seff}			1.06E+08

K_l will be calculated by;

$$K_l = \frac{EA_s}{L_r + d} \quad (e.q\ 6.5)$$

Where L_r is the length of the steel rope between the crane master and the hook and d is the water depth. As shown on table 7 of the previous page, the length of the hoist line between the crane master and hook is assumed to be 2 times the height of the hook above COG of the object. The frequency of natural oscillation for a linear elastic vibration is given by;

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K_v}{M}} \quad (e.q\ 6.6)$$

Where f_n is the natural frequency of oscillation expressed in Hertz (Hz) and M is the weight lift subsea (W_{sea}) expressed in kilogram (kg) except for air lift at 0 m water depth where the dynamic lift in air (W_{air}^{Lift}) will be applicable. This equation is valid for all elastic oscillations. Consequently, the natural period of Oscillation T_n in seconds will be calculated as;

$$T_n = \frac{1}{f_n} \quad (e.q\ 6.7)$$

Based on equations 6.2 through to 6.7, and the hook wire and sling properties enumerated on table 7 and 8 respectively, the natural periods of linear elastic oscillation for the subsea lift was investigated at different water depths and the results are presented on table 9 below.

Table 9: Frequencies and Natural Periods of Oscillation for Linear Elastic Vibration (Assuming Un-Damped Conditions during Subsea Lift)

NATURAL PERIODS OF RIGGING OSCILLATIONS | ANALYSIS FOR LINEAR ELASTIC OSCILLATION										
Parameters	Symbols	S.I Unit	Referenced Equation	WATER DEPTH						
				0 m	100 m	200 m	300 m	400 m	500 m	600 m
Hoist Line Stiffness	K_l	N/m	Eqn. 6.5	6.47E+07	1.45E+07	8.14E+06	5.66E+06	4.34E+06	3.52E+06	2.96E+06
Sling Effective Stiffness	K_{seff}	N/m	Eqn. 6.4	1.06E+08	1.06E+08	1.06E+08	1.06E+08	1.06E+08	1.06E+08	1.06E+08
Total Vertical Stiffness	K_V	N/m	Eqn. 6.3	4.02E+07	1.27E+07	7.56E+06	5.38E+06	4.17E+06	3.41E+06	2.88E+06
Natural Frequency	F_n	Hz	Eqn. 6.6	78.44	44.15	34.03	28.70	25.28	22.85	21.01
Natural Periods	T_n	Sec	Eqn.6.7	0.0127	0.0227	0.0294	0.0348	0.0396	0.0438	0.0476

Also shown in Figure 17 below is a plot of natural frequencies and natural periods of linear elastic oscillation for the hoisting assembly versus water depth. As can be seen, there was a sharp decline (approx. 50%) in natural frequency as the object is submerged into the sea. Could this be as a result of the added hydrodynamic weight or damping??

We have now established the natural frequencies and periods of the hoisting assembly due to elastic linear vibration as shown on table 9 above. However, we still need to put the environmental forces into consideration to know if the lifting operation will be safe or not. We have made some key assumptions regarding the sea state of the environment where this subsea lifting operation will be taking place. We have assumed a significant wave height (H_S) of approximately 3.5 m and a reference period (T_R) of 12 hours. According to DNV-OS-H101, for H_S < 5.7 m, the zero crossing wave period range can be estimated as [8];

$$8.9\sqrt{\frac{H_S}{g}} \leq T_z \leq 13 \qquad (e.q\ 6.8)$$

$$\therefore 8.9\sqrt{\frac{3.5}{9.81}} \leq T_z \leq 13$$

$$5.32\ sec \leq T_z \leq 13\ \ sec$$

Since the range of zero crossing period for the sea state (5.32 sec ≤ T_z ≤ 13 sec) is greater than the natural periods of oscillation (0.0127 sec ≤ T_n ≤ 0.0476sec) for the elastic vibration of the hoisting system, the linear elastic vibration of the system cannot pose any hazards during the lifting operation.

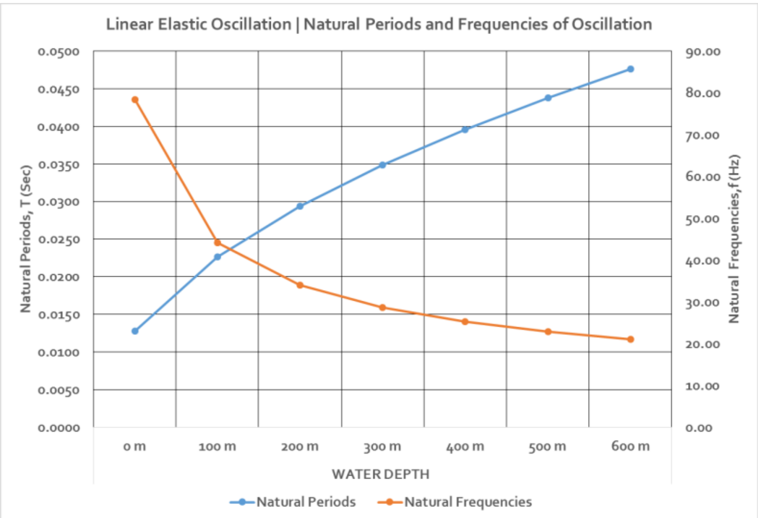


Figure 17: Plot of Natural Frequencies and Natural Periods Vs. Water Depth (Linear Elastic Vibration)

6.3 Analysis For Pendulum Type Oscillation

The pendulum type oscillation (figure 18) is characterized by the horizontal displacement of the structure during lifting operation due to the effects of current subsea. The current induces a drag force on the structure causing it to be displaced at an angle (θ) from the vertical. A restoring force (torque force) which is a function of the object's weight tries to restore it to rest due to the effects of gravity. The natural frequency of oscillation for pendulum type oscillation can be calculated as;

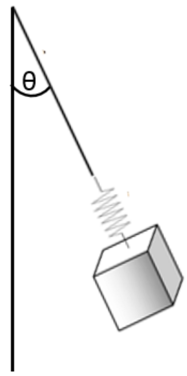


Figure 18: Forced Pendulum Type Oscillation in Lifted Objects

$$f_n = \frac{1}{2\pi} \cdot \sqrt{\frac{g}{L_r + d}} \qquad (e.q\ 6.9)$$

Where g is the acceleration due to gravity (9.81 ms^{-2}) and L_r and d have their usual meaning. Consequently, the natural period of oscillation can be calculated using equation 6.7. The natural frequencies and natural periods of the pendulum type oscillation for the system was estimated and the results are presented on table 10 below;

Table 10: Frequencies and Natural Periods of Oscillation for Pendulum Type Oscillation (Assuming Un-damped Conditions during Subsea Lift).

NATURAL PERIODS OF RIGGING OSCILLATIONS | ANALYSIS FOR PENDULUM OSCILLATION										
Parameters	Symbols	S.I Unit	Referenced Equation	WATER DEPTH						
				0 m	100 m	200 m	300 m	400 m	500 m	600 m
Frequency	F_n	Hz	Eqn. 6.9	0.0929	0.0439	0.0330	0.0275	0.0241	0.0217	0.0199
Natural Periods	T_n	Sec	Eqn. 6.7	10.7657	22.7669	30.3440	36.3757	41.5406	46.1308	50.3039

We had earlier established the zero crossing periods for the sea state under consideration to be 5.32 sec ≤ T_z ≤ 13 sec. As can be seen from table 10 above, the natural periods of oscillation for the pendulum type oscillation was estimated to be in the range of 10.77 sec ≤ T_n ≤ 50.30 sec. Since the natural periods of oscillation is higher than the zero crossing periods of the sea state, the pendulum type oscillation of the load can cause hazards during lifting operation. **Please see appendix II containing an embedded excel file for a more detailed calculation using Microsoft Excel™ (Excel File Tab Titled "PART C")**

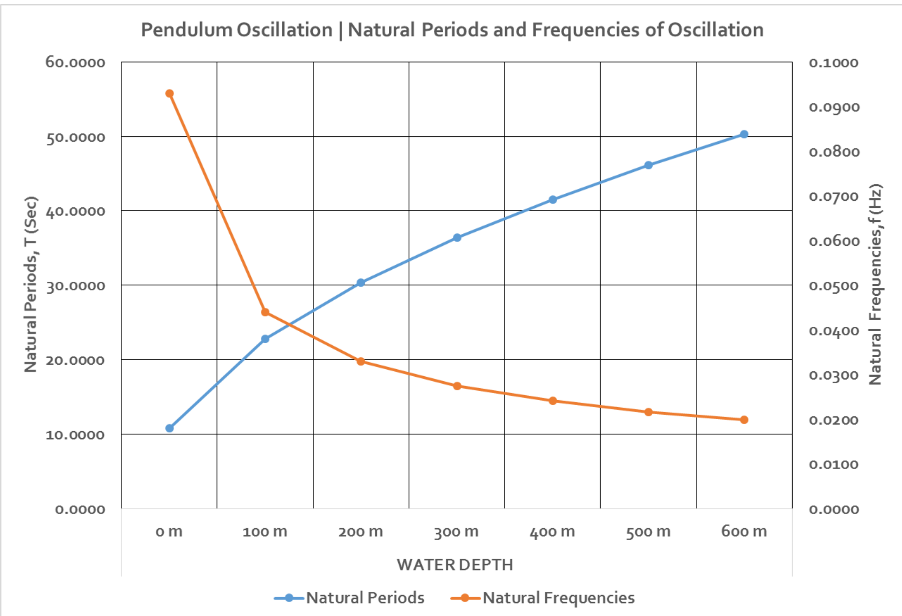


Figure 16: Plot of Natural Frequencies and Natural Periods Vs. Water Depth (Pendulum Type Oscillation)

6.4 Conclusion and Recommendation for Hazard Mitigation Strategies

Low frequency oscillations as characterized by the pendulum type oscillation poses some serious hazards to offshore lifting and rigging operations as the load sways back and forth in large horizontal displacement when lifted in air due to instability caused by either one or more of the vessel's 6 degree of freedom. However, this oscillation becomes damped once the object is immersed completely just below the sea surface. Even though one has no control over the forces of nature, conscious efforts must made towards mitigating these hazards.

The rigging geometry under consideration consist of lifting the manifold from a single hook point, thus making the system vulnerable to a single point of failure. On this note, I will recommend the integration of **Spreader Bars** into the rigging configuration. The idea behind a spreader bar (figure 17) is to simply distribute the load of a lift across more than one point, increasing stability and decreasing the loads applied during hoisting. Most commonly used when the object being lifted is too large to be lifted from a single point, and not designed to take any adverse loading caused from angled slings during the lift [9]. As shown in the figure below, there are various configurations of the spreader bar system for four point lifting geometry and selection of either of them would depend on the installation techniques and operating environment.

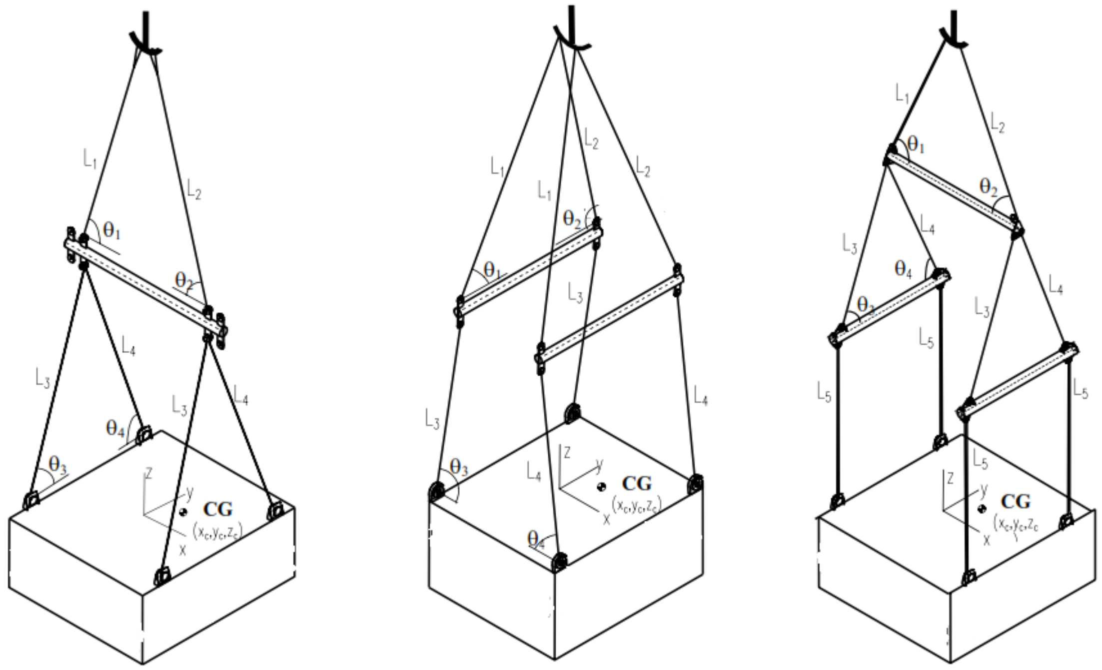


Figure 17: One (left), Two (Centre), and Three (Right) Spreader Bar Rigging Geometry.

In addition, since the pendulum type oscillation varies according to the length of the crane-hook steel wire from the hook, the spreader bars help to distribute this theoretical length around the perimeter of structure which ultimately translate to higher frequency of oscillation and lower oscillation periods.

6.5 Further Work

Based on the detailed analysis carried out by the author on this subject and the results of the findings, further research will done to assess the impact of rigging geometry optimization in lifting operations towards achieving a safer and cost saving offshore rigging and lifting operation. Also, studies on the impact of accidental loading on the rigging assembly will be carried out.

7.0 References

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8.0 Appendices

Appendix I – Statistical Indeterminacy and Verification for Equations of Equilibrium

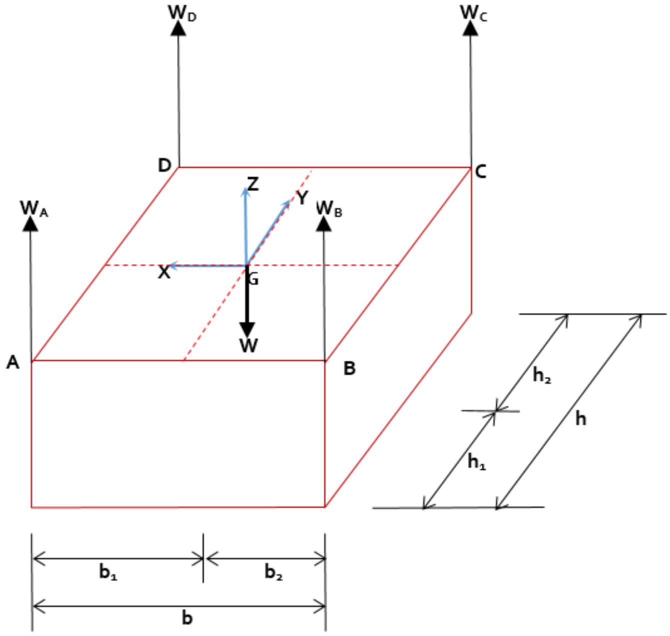

Figure 18: Free Body Diagram of Component forces acting on Object

From static equilibrium;

$$\sum \boldsymbol{F_z} = 0 \qquad (e.q\ 9.1)$$

$$\sum \boldsymbol{M_x} = 0 \qquad (e.q\ 9.2)$$

$$\sum \boldsymbol{M_y} = 0 \qquad (e.q\ 9.3)$$

As can be seen, there are 3 equilibrium equations and four unknowns, consequently making the free body diagram statically indeterminate. We will now carry out some "algebraic manipulations" to establish equilibrium on both sides of the structure. From figure 18 above resolving the forces in the vertical z axis will give;

$$\sum \boldsymbol{F_z} = W_A + W_B + W_C + W_D - W = 0 \qquad (e.q\ 9.4)$$

Taking moments in the x axis and taking counter clockwise moments as positive to the centre of gravity gives the following equations;

$$\sum_{\boldsymbol{AB}} \boldsymbol{M_x} = W_A \cdot b_1 - W_B \cdot b_2 = 0 \qquad (e.q\ 9.5)$$

and

$$\sum_{\boldsymbol{DC}} \boldsymbol{M_x} = W_D \cdot b_1 - W_C \cdot b_2 = 0 \qquad (e.q\ 9.6)$$

Thus, total moments on the x axis will be;

$$\sum \boldsymbol{M_x} = \sum_{\boldsymbol{AB}} \boldsymbol{M_x} + \sum_{\boldsymbol{DC}} \boldsymbol{M_x} = 0$$

$$\sum \boldsymbol{M_x} = W_A \cdot b_1 - W_B \cdot b_2 + W_D \cdot b_1 - W_C \cdot b_2 = 0$$

$$\therefore b_1(W_A + W_D) - b_2(W_B + W_C) = 0$$

Then;

$$W_A + W_D = (W_B + W_C)\frac{b_2}{b_1} \qquad (e.q\ 9.7)$$

Substituting equation 9.7 into equation 9.4 will yield;

$$\sum F_z = (W_B + W_C)\frac{b_2}{b_1} + W_B + W_C - W = 0$$

Rearranging;

$$W_B + W_C = \frac{W}{1 + \frac{b_2}{b_1}} = W\frac{b_1}{b} \qquad (e.q\ 9.8)$$

Similarly;

$$W_A + W_D = \frac{W}{1 + \frac{b_1}{b_2}} = W\frac{b_2}{b} \qquad (e.q\ 9.9)$$

Are the algebraic expressions derived above consistent???

Now, let us check if the algebraic expressions derived above is consistent by taking moments in the y axis. Taking counter clockwise moments as positive to the centre of gravity gives the following equations;

$$\sum_{BC} \boldsymbol{M_y} = W_B \cdot h_1 - W_c \cdot h_2 = 0 \qquad (e.q\ 9.10)$$

and

$$\sum_{AD} \boldsymbol{M_y} = W_A \cdot h_1 - W_D \cdot h_2 = 0 \qquad (e.q\ 9.11)$$

Thus, total moments on the y axis will be;

$$\sum \boldsymbol{M_y} = \sum_{BC} \boldsymbol{M_y} + \sum_{AD} \boldsymbol{M_y} = 0$$

$$\sum \boldsymbol{M_y} = W_B \cdot h_1 - W_c \cdot h_2 + W_A \cdot h_1 - W_D \cdot h_2 = 0$$

$$\therefore h_1(W_A + W_B) - h_2(W_C + W_D) = 0$$

Then;

$$W_A + W_B = (W_C + W_D)\frac{h_2}{h_1} \qquad (e.q\ 9.12)$$

Substituting equation 9.12 into equation 9.4 will yield;

$$\sum F_z = (W_C + W_D)\frac{h_2}{h_1} + W_C + W_D - W = 0$$

Rearranging;

$$W_C + W_D = \frac{W}{1 + \frac{h_2}{h_1}} = W\frac{h_1}{h} \qquad (e.q\ 9.13)$$

Similarly;

$$W_A + W_B = \frac{W}{1 + \frac{h_1}{h_2}} = W\frac{h_2}{h} \qquad (e.q\ 9.14)$$

Recall from equation 9.9;

$$W_A = W\frac{b_2}{b} - W_D$$

And also from equation 9.8;

$$W_B = W\frac{b_1}{b} - W_C$$

Substituting W_A and W_B into equation 9.14 will yield;

$$W\frac{b_2}{b} - W_D + W\frac{b_1}{b} - W_C = W\frac{h_2}{h}$$

Rearranging we have;

$$W_C + W_D = W\frac{b_1}{b} + W\frac{b_2}{b} - W\frac{h_2}{h}$$

Thus;

$$W_C + W_D = W\left(\frac{b_1}{b} + \frac{b_2}{b} - \frac{h_2}{h}\right) = W\left(1 - \frac{h_2}{h}\right) = W\frac{h_1}{h} \qquad (e.q\ 9.15)$$

As shown, the algebraic expression in equation 9.15 is equal to the algebraic expression in equation 9.13. **Thus, the algebraic expression is consistent.**

A similar approach can also be employed by substituting W_C and W_D into equation 9.13 where;

From equation 9.9;

$$W_D = W\frac{b_2}{b} - W_A$$

and;

From equation 9.8;

$$W_C = W\frac{b_1}{b} - W_B$$

Substituting W_C and W_D into equation 9.13 will yield;

$$W\frac{b_1}{b} - W_B + W\frac{b_2}{b} - W_A = W\frac{h_1}{h}$$

Rearranging we have;

$$W_A + W_B = W\frac{b_1}{b} + W\frac{b_2}{b} - W\frac{h_1}{h}$$

Thus;

$$W_A + W_B = W\left(\frac{b_1}{b} + \frac{b_2}{b} - \frac{h_1}{h}\right) = W\left(1 - \frac{h_1}{h}\right) = W\frac{h_2}{h} \qquad (e.q\ 9.16)$$

As shown, the algebraic expression in equation 9.16 is equal to the algebraic expression in equation 9.14. **Thus, the algebraic expression is consistent.**

Recall from section 4.1, we have derived the algebraic expression for calculating the vertical load on each sling. For completeness, this is restated below;

$$W_A = W \cdot \frac{h_2}{h} \cdot \frac{b_2}{b} \qquad W_B = W \cdot \frac{b_1}{b} \cdot \frac{h_2}{h}$$

$$W_C = W \cdot \frac{h_1}{h} \cdot \frac{b_1}{b} \qquad W_D = W \cdot \frac{b_2}{b} \cdot \frac{h_1}{h}$$

This can also further be checked for consistency.

$$W_A + W_B = W \cdot \frac{h_2}{h}\left(\frac{b_1}{b} + \frac{b_2}{b}\right) = W \cdot \frac{h_2}{h} = \boldsymbol{e.q\ 9.14} = \boldsymbol{e.q\ 9.16}$$

Similarly;

$$W_C + W_D = W \cdot \frac{h_1}{h}\left(\frac{b_1}{b} + \frac{b_2}{b}\right) = W \cdot \frac{h_1}{h} = \boldsymbol{e.q\ 9.13 = e.q\ 9.15}$$

$$W_A + W_D = W \cdot \frac{b_2}{b}\left(\frac{h_1}{h} + \frac{h_2}{h}\right) = W \cdot \frac{b_2}{b} = \boldsymbol{e.q\ 9.9}$$

$$W_B + W_C = W \cdot \frac{b_1}{b}\left(\frac{h_1}{h} + \frac{h_2}{h}\right) = W \cdot \frac{b_1}{b} = \boldsymbol{e.q\ 9.8}$$

Appendix II – Excel Spread Sheet Showing Detailed Calculations and Formulas

S/N	DESCRIPTION	FILE	COMMENTS
1	The attached spread sheet workbook contains two sheets titled "PART A" and "PART C". PART A shows the detailed calculations carried out in determining the; • Vertical Load Components of the Sling, • Sling Angle, • Sling Length, • Dynamic Sling Tension and • Average Load per Sling. PART C shows the detailed calculations for; • Natural Frequencies of Oscillation for Elastic Vibration and Pendulum Type Oscillation, • Natural Periods of Oscillation for Elastic Vibration and Pendulum Type Oscillation, and Plots for; • Natural Frequencies of Oscillation and Natural Periods of Oscillation versus Water Depth for Elastic Vibration Type Oscillation and • Natural Frequencies of Oscillation and Natural Periods of Oscillation versus Water Depth for Pendulum Type Oscillation.	Calculation Spreadsheet.xlsx	Please Double Click File Icon to Open Embedded Document.

Appendix III – Given Data for Assignment

Student Name	W in water (tons)	b1 in m	h1 in m	b in m	h in m	
ASHIRU,ADEOLA OLAKITAN	70	3	2	9	8	
ASHOK,GAUTHAM ANTHONY	75	3.2	2.2	9.2	8.2	
ATASSI,MOHAMAD GHAITH	85	3.6	2.6	9.6	8.6	
AYOB,MOHD FARIZSHAN BIN	80	3.4	2.4	9.4	8.4	
BATZIA,PANAGIOTA	95	4	3	10	9	
BLISS,ODIKI OGBANGA	90	3.8	2.8	9.8	8.8	
BRICENO VARGAS,ADONIS JOHAN	100	4.2	3.2	10.2	9.1	
CARRIGAN,COLLETTE ARLENE	105	4.4	3.4	10.4	9.4	
CLEMENT,CHIMA	110	4.6	3.6	10.6	9.6	