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Stability Analysis for the Design of 5000-Tonnes Offshore Work Barge

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ABSTRACT

There have been several development or giant strides made in the field of marine engineering in general and the design of barges in particular. The design of a 5000-tonne offshore work barge with a deck crane is one of these feats. The determinations of optimal scantling to ensure good stability characteristics, estimation of the principal dimensions and analysis of the stability of the work barge when the crane is in offshore working condition were carried out. The hydrostatic curves for the vessel were plotted and used to determine the optimal values for safe operation of the work barge. Analysis of stability of the entire barge to ensure that the limit of load to be carried by the crane is not exceeded or points loads does not exceed a safe value for the vessel shows that the design is feasible.

Keywords: *Stability analysis; Deck crane; 5000-tonnes offshore work barge; Volume displacement.*

1. INTRODUCTION

A barge is usually a flat bottom vessel mainly used as cargo tanker, equipment supply carriers, crane platform and support accommodation bases in offshore drilling. Most barges do not operate under their own power but require a tugboat to pull or push them to their destination. Only in few cases do we see self- propelled barges [1]. Therefore barges are specially designed for specific purposes, depending on the type of barges, which is characterized by the function of the said barge, its design procedures are slightly different or rather the chosen characteristic may differ in one way or the other [2].

The design of a barge follows almost the same process, but with a little or simple variation in choosing some parameter as to compensate for the service that will be taken care of. The design processes from [3] of the barge under consideration gave similar information as using principal dimensions of the ship through various ratios of dimensions. This work barge will serve a multipurpose offshore function for oil industries, marine establishment and other companies that require manpower to work offshore without possible return of the workers daily to shore.

1.1 Illustration Definitions [4]

Centre of gravity (G) is an imaginary point in the exact middle of a weight where the entire weight may be considered to act. The force of weight always acts vertically downwards.

Centre of buoyancy (B) is an imaginary point in the exact middle of the volume of *displaced* water where the entire buoyancy may be considered to act. The force of buoyancy always acts vertically upwards.

Metacentre (M) is a point in space where the vertical line upwards through the centre of buoyancy *(B) of the 'inclined' vessel* cuts through the vertical line upwards through the centre of buoyancy *(B) of the 'upright' vessel*.

Metacentric height (GM) is the vertical distance between the Centre of Gravity *(G)* and the Metacentre *(M)*. If *M* is above *G* the vessel will want to stay upright and if *G* is above *M* the vessel will want to capsize i.e. *GM* positive is Stable, *GM* negative is Unstable.

Righting lever (+GZ) or Overturning lever (-GZ) is the (horizontal) distance between the two (vertical) 'lines of action' of the buoyancy force (upwards), and the gravity force (downwards). The size of *GZ* is the measure of how stable or unstable the vessel is at any particular angle of heel

2. MATERIALS AND METHOD

To achieve this procedure, the approach from the principles of dynamic similarity of vessel from [5], was used to obtain the principal dimension of the barge.

2.1 Estimation of Masses and Main Dimensions

Estimating the mass of the Barge

$$M = \rho LBTC_B \quad (1)$$

Let the volume be expressed in terms of L^3

$$M \propto \rho L^3 C_B \tag{2}$$

$$B/L = K_1 \tag{3}$$

$$T/L = K_2 \tag{4}$$

From Equation 1

$$M = \rho L^3 \left(\frac{B}{L}\right)\left(\frac{T}{L}\right) C_B \tag{5}$$

$$M = \rho L^3 K_1 K_2 C_B \tag{6}$$

Hence the Breadth to Draught ratio will result to, from Equation 3 and 4

$$B = K_1 L, \qquad T = K_2 L$$

$$\frac{B}{T} = \frac{K_1 L}{K_2 L}$$

Let $B/T = K_3 = K_1/K_2$

$$\therefore \quad K_1/K_3 = K_2 \tag{7}$$

Therefore substituting Equation 7 into 6 becomes

$$M = \rho L^3 K_1 \left(\frac{K_1}{K_3}\right) C_B \tag{8}$$

2.2 Displacement and Form Coefficient

Mass Displacement (Δ)

$$\Delta = \Delta_{WTO} + \Delta_{LS} \tag{9}$$

Volume Displacement

$$\nabla = \frac{\Delta}{\rho \ x A_C} \tag{10}$$

$$A_C = 1.005$$

$$\rho = 1025 Kg / m^3 = 1.025 tonnes / m^3$$

Block Coefficient $C_B = \dfrac{\nabla_0}{L x B_0 \, x T_0}$ (11)

2.3 Stability Analysis

Fig. 1 is the inclined experiment used transversely to determine some stability characteristics of the work barge

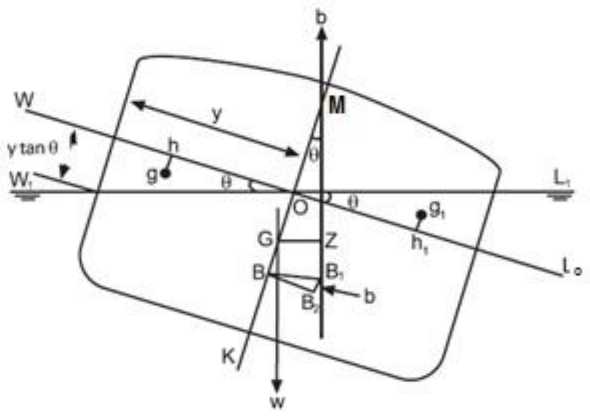

Fig.1: Transverse stability analysis diagram [6]

For a pontoon shaped barge an approximation for the metacentric height GM can be obtained from the *rectangular block formula* which says:-

$$GM = KB + BM - KG \tag{12}$$

$$= t/2 + B^2/12t - h \tag{13}$$

This formula assumes the barge is a rectangular block with the lightship centre of gravity *at deck level*. *KB* is the vertical distance from the keel to the centre of buoyancy, *BM* is the vertical distance from the centre of buoyancy to the metacentre, and *KG* is the vertical distance (from the keel to the centre of gravity). The vertical distance between the centre of buoyancy (*B*) and the metacentre (*M*), is the *BM* [7].

$$\mathrm{BM} = I/\nabla \tag{14}$$

where *I* is the *inertia of the water plane area**, and ∇ is the volume of displacement.

[6] stability analysis shows that for $\theta \approx (10^0 - 20^0)$

$$BB_1 = \frac{V \times g_e g_i}{\nabla} = \frac{V \times d}{\nabla} \tag{15}$$

V_w = *Volume of wedge*

g = *Centroid of wedge*

g_1 = *Centroid of wedge*

gg_i = d

Weight = *Mg* acting downwards

Buoyancy force acting upward

Therefore a couple of *W GZ* is formed

GZ = *righting level*

GM = *metacentric height*

From [6] 2001 analysis

$$BB_1 = \frac{V \times g_e g_i}{\nabla} = \frac{V \times d}{\nabla}$$

$$\Rightarrow BB_1 \times \nabla = V \times gg_1$$

From the triangle BB_1M

$$Tan\theta = \frac{BB_1}{BM}$$

$$\therefore BM = \frac{BB_1}{\tan\theta}$$

$$BB_1 = \frac{V \times g_e g_i}{\nabla}$$

$$BM = \frac{V \times g_e g_i}{\nabla} \times \frac{1}{\tan\theta}$$

For a work badge

Considering the triangle L_oOL_1

$$h = \tan\theta$$

$$x = x\tan\theta$$

While the area of the triangle L_oOL_1 will be

$$= {}^{1}\!/_{2}\ x\ (x\tan\theta)$$

$$= {}^{1}\!/_{2}\ x^2\ \tan\theta$$

The distance from g to centre O $= {}^{2}\!/_{3}\ x$

$$\therefore gg_1 = {}^{2}\!/_{3}\ x \times 2$$

2.4 Stability of the Barge when Crane is Working

From [4], when using cranes and other lifting gear such as A-frames that are barge mounted, it must be noted that the weight of the lifted load acts *at the point of suspension* – not at the base of the crane. The *overturning moment* on the barge, tending to cause it to capsize, is the *product* of the weight of the lifted load, and the (horizontal) distance (d_1) of the *point of suspension* (p) from the *centre of buoyancy* (B) as shown in Fig 2.

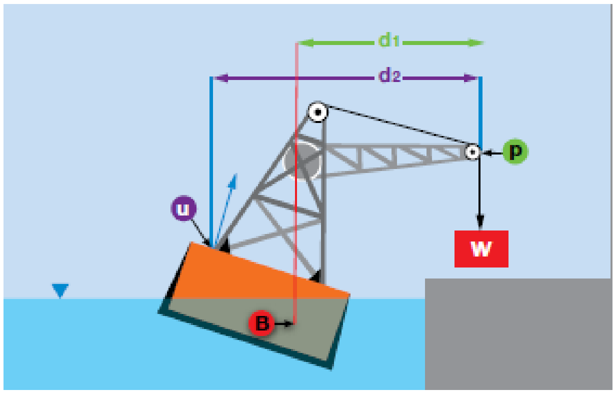

Fig. 2: Crane outreach [4]

The greatest uplift or detachment force, acts *at the point of attachment* (of the crane to the barge) *furthest from the point of suspension*. This is the force tending to turn the crane over and the moment of this force is the product of the weight of the lifted load, and the (horizontal) distance (d_2) of the point of suspension (p) from the point of uplift (u).

At zero list and roll the crane is more effective and the stability of the barge is better than when it has a percentage of list and roll. On the other hand, during the analysis of the stability of the barge when the crane is working, an increase in the radius will be followed with a decrease in Boom angle degree and also a decrease in the rating of the load it is carrying. Therefore a decrease in boom angle increases the barge stability [8]. Hence analysis was taken in the following position as shown in Fig. 3. Positions A, B, C, D, and E are considered the lifting positions of the crane in the analysis of the stability of the work barge when the crane is in offshore working condition. The positions F, G, H and I are considered the loading positions when considering the loading condition of the barge in the analysis of the stability of the work barge when the crane is in offshore working condition at different draft condition.

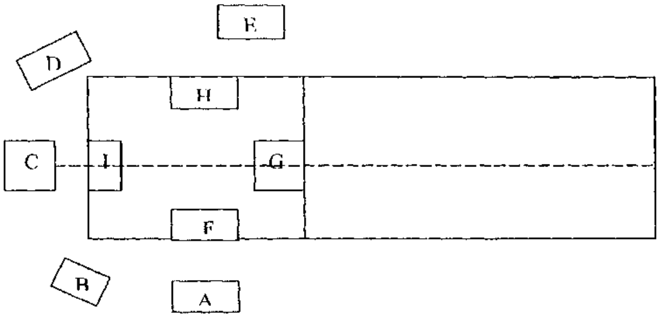

Fig.3: Stability analysis diagram with the crane is working

For the work barge only position A was considered in the analysis of the stability, because every safe value at this location will be safe at other locations .

Since the amount of load lifted is directly proportional to the draft of the barge, hence, the analysis was based on different levels of the draft to calculate other parameters. These curves also view to great extents location where weights of larger tonnes could not be placed for the safety of the personnel on board the vessel. Since the work barge floating at many different drafts when the crane is in working condition, the analysis of the stability of the barge in such conditions cannot be overemphasis. Hence the hydrostatic curves of the barge in these conditions become very important. These diagrams include the plotting of the draft versus several parameters that their factor plays a significant role in the stability of the barge. They include amongst others:

1. Volume of displacement *(Δ)*
2. Center of buoyancy *(KB)*
3. Metacentric radius *(BM)*
4. Moment of inertia of water plane *(I)*
5. Center of gravity *(KG)*
6. Moment to change trim by 1cm *(MCT.1)*
7. The metacentric height *(KM)*

Hence each graph has its significant role to help analyze the stability of the work barge at different loads carried by the crane. For instant, the graph of draft versus volume displacement is useful to find the displacement of the barge for any average draft when floating. The loading condition can also be determined for safe working condition in seawater.

All conditions of equilibrium were replaced during the analysis. The laws of static and dynamics, transverse and longitudinal stabilities of the work barge were also strictly adhered to. The experimental analysis, calculations etc, and the following results are thus obtained through the help of the hydrostatic curves.

3. ANALYSIS AND DISCUSSION OF RESULTS

There are many ways to estimate the ship mass and the main dimension of the ship for the purpose of basic design. However these approaches are approximate and are either based on experience and performance characteristics of existing designs or on results obtained from model testing carried out for years past [9]. For the importance of this Barge under consideration and its advance implementation in the oil industry, a model work barge was designed. The Model Ship Dimension used;

Model Barge Dimension

Length (L_0) = *91.5m*
Breadth (B_0) = *27.5m*
Depth (D_0) = *6.0m*
Draught (T_0) = *4.5m*
Deadweight (Δ_{WTO}) = 3000tonnes
Light weight (Δ_{LS}) = 2000tonnes

3.1 Displacement and Form Coefficient

To calculate for a stable vessel, the following considerations have to be taken:

Mass Displacement (Δ_0)

from equation 1

$$\Delta_0 = \Delta_{WTO} + \Delta_{LS}$$

$$= 2000 + 3000 = 5000\,Tonnes$$

Mass Displacement Δ_0 = 5000*Tonnes*

Volume Displacement (∇_0 **)**

From equation 2, Volume Displacement $\nabla_0 = \dfrac{\varDelta_0}{\rho \; x \, A_C}$

Density (ρ) = *1025Kg/m*^{3} = *1.025 Tonnes/m*^{3}

Substitution into equation 10

$$\nabla_0 = \frac{5000}{1.025 \; x \; 1.005} = \frac{5000}{1.03}$$

$$= 4855m^3$$

Block coefficient (C_B **)**

From equation 11, Block Coefficient for the model barge is,

$$C_{B_0} = \frac{5678}{91.5x27.5x4.5} = 0.501$$

Deadweight Displacement Ratio $(\eta_{\Delta WT0}) = \dfrac{\Delta_{WT0}}{\Delta_0}$

$$\Rightarrow \eta_{\varDelta WT0} = \frac{3000}{5000} = 0.6$$

Hence from equation 6

$$M = \rho L^3 \left(\frac{B}{L}\right)\left(\frac{T}{L}\right) C_B$$

$$L^3 = \frac{M}{\rho\left(\frac{B}{L}\right)\left(\frac{T}{L}\right)C_B} \qquad (16)$$

From the estimation

$$B/L = 27.5/91.5 = 0.30$$

$$T/L = \frac{4.5}{91.5} = 0.049$$

$$C_{B_0} = 0.501$$

$$\rho = 1.025 \ tonnes / m^3$$

$$M = 5000 tonnes$$

Substituting values into equation 16, we have

$$L^3 = \frac{5000}{1.025 \ x \ 0.301 \ x \ 0.045 \ x \ 0.501}$$

$$L = 86.49m$$

Selected length for this work barge under design is 80m to enhance compensation in the width of the barge. Similarly,

$$B/L = 0.301$$

$$B = 0.301 \times L = 0.301 \times 86.49 = 26.03m$$

Selected breadth for the work barge is 30m though the compensation was from the length overall and

$$T/L = 0.049$$

$$T = 0.049 \times L = 0.049 \times 86.49 = 4.25m$$

Selected Draft for the work barge is 4.5m through the compensation made from the length. Thus the dimensions for the design of the work barge are as follow:

∇ = 5000 tonnes
L = 80m
B = 30m
T = 4.5m

$$C_B = \frac{5000}{80x30x4.5} = 0.463$$

3.2 Determination of Metacentric Height *[6]*

$$Area \ of \ wedge = 1/3 \ x^2 \tan\theta$$

Ref: $\theta = 10^0$

$$x = \frac{Molded \ \ Breadth}{2}$$

$$\therefore \ x = 15$$

While $\tan\theta = \tan 10$

$$= 0.1763$$

$$Calculated \ Area = 19.83m^2$$

$$Volume \ \ of \ \ wedge = \ Area \times Length = 1586.4m^3$$

The volume moved from one side to the other by $4/3 \, x$

$$I_T = \frac{V \times g_e g_i}{\tan\theta} \qquad (17)$$

By substitution

$$I_T = 179{,}965.97m^4$$

$$\nabla = L \times B \times T \times C_B = 4860m^3$$

$$\therefore BM = \frac{I_T}{\nabla} = 37.03m$$

Since it is a barge

$$KB = T/2 = 2.25m$$

$$KM = KB + BM = 39.28m$$

centre of gravity is at 2.84m, which is KG.

$$KM = KG + GM$$

$$\therefore GM = KM \quad KG = 36.44m$$

$KM; \ D = f(T)$

$$KM = \frac{T}{2} + \frac{B^2}{12T} \qquad (18)$$

To find the minimum KM that will cause an increase in draft,

$$\frac{d}{dT}KM = 0$$

$$KM = \frac{T}{2} + \frac{B^2}{12T}$$

$$\frac{d}{dT}KM = \frac{1}{2} + \frac{B^2}{12T^2}$$

$$\Rightarrow \frac{1}{2} + \frac{B^2}{12T^2} = 0$$

$$\therefore T^2 = \frac{2B^2}{12}$$

$$T = 12.25m$$

3.3 Longitudinal Stability Analysis *[10]*

Fig. 4 is the inclined experiment used longitudinally to determine some stability characteristics of the work barge.

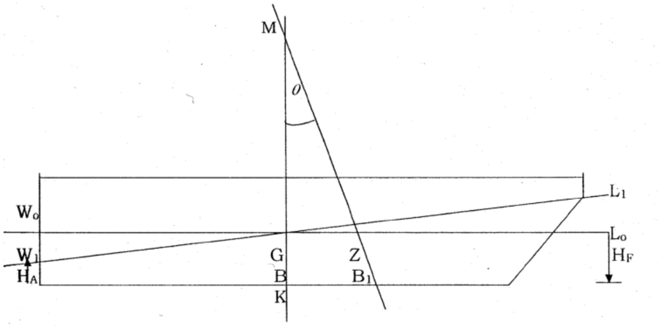

Fig. 4: Longitudinal stability analysis diagram

From triangle *GMZ* in figure 4,

$$\tan\theta = \frac{GZ}{GM}$$

$$GZ = KM \tan\theta$$

$$GM = KM \quad KG = 36.44 \qquad (19)$$

Figure 3.3 is the experimental procedure used when the barge is under ring parallel sinkage to determine some stability characteristics of the work barge.

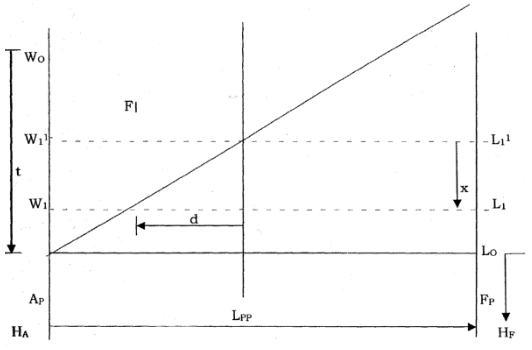

Fig. 5: Parallel sinkage stability analysis diagrams

Trim is the difference in draught forward and aft.

If $H_A > H_F$ Trimming by the stern

While $H_A < H_F$ Trimming by the Bow

H_F = Draught forward

H_A = Draught Aft

Trim = $H_A - H_F$ (20)

And angle of Trim $= \dfrac{H_A - H_F}{L}$ (21)

L = Length between perpendicular

F = Centre of flotation

Since the center of flotation is not at Midship

$$\therefore W_0W_1 \neq L_0L_1$$

$$W_1n = W_0W_1 + W_0n = W_1W_0 + L_1L_0$$

The similar triangle

$$W_1 \; W_0 \; F \;\&\; W_1nL_1$$

$$\frac{W_0W_1}{W_1n} = \frac{FW_0}{nL_1} = \frac{FW_0}{W_oL_o} = \frac{FW_0}{L_{PP}} \qquad (22)$$

W_0W_1 is the alteration of draught at the stern and W_1n is the total change in trim. On the other hand alteration of draught forward is given as $L_0L_1 = \dfrac{FL_0 \; x \; W_0n}{L_{PP}}$

(23)

Mean Draught $= \dfrac{H_A + H_F}{2}$ (24)

$$x/d = \frac{Total\ \ Trim}{length}(t) \qquad (25)$$

d = distance of F from Midship

x = distance between parallel water line

$$x = td/L$$

$$true\ mean\ draught = Arithmetic\ mean\ draught + x$$

$$= \left[\frac{H_A + H_F}{2} + \frac{td}{L}\right] \qquad (26)$$

By calculating

Angle of inclination $\tan\theta = t/L_{PP}$

θ = 50

$$t = L_{PP} \tan\theta = 6.56m \quad (total\ trim)$$

$$\tan\theta = \pi = \frac{GG_1}{GM_L} = \frac{W_b}{\Delta GM_L} \qquad (27)$$

$$\therefore W_b = \frac{T\Delta GM_L}{L}$$

$$\text{MCT.1cm} = \frac{\Delta GM_L}{100L} \qquad (28)$$

$$= L \times B \times d \times \frac{\rho \times L^2}{12d} \times \frac{1}{100L}$$

$$= \frac{L^2 \rho}{12 \times 100} = 360.4m = 36040cm$$

4. RESULTS AND DISCUSSION

4.1 Results

The weight of 5, 000-tonnes off-shore work badge was estimated to be 3361.1-tonnes with all necessary equipments. There by having the capacity of carrying external load up to 1000-tonnes within the vessel depending on the safety factor and the available space. After design and estimation, it was observed that the center of gravity is acting at 2.84m above the keel (bottom) of the barge, 1.39m fore of the chosen centre (longitudinally) and 19mm port of the chosen centre (transversely). This is safe in ship design; it would have been unsafe if the centre of gravity acts above 3.0m from the bottom of the ship.

Table 1 shows the values of stability characteristics used to plot the hydrostatic curves of the work barge. The relations used for hydrostatic curves are as follows:

1. $BM = \frac{I}{\nabla} = \frac{I}{L \times B \times T \times C_B}$
2. $\nabla = L \times B \times T \times C_B$
3. $MCT.1 = \frac{L^2 \times B \times \rho}{12 \times 100}$
4. $KB = T/2$
5. $KM = KB + BM$
6. $I = BM \times \nabla$
7. $KG = \frac{\sum MZ}{\sum M}$

Table 1: Calculated values of stability characteristics of the work barge

T	Δ	∇	KB	BM	KM	KG	MCT_1	I
0.5	553.5	540	0.25	333.28	333.53	0.315	145.68	179971.2
1.0	1107	1080	0.50	166.6	167.1	0.630	147.62	179982.0
1.5	1660.5	1620	0.75	111.1	111.85	0.945	149.57	179982.0
2.0	2214	2160	1.00	83.3	84.3	1.260	151.54	179928,0
2.5	2767.5	2700	1.25	66.7	67.95	1.575	153.51	186090.0
3.0	3321	3240	1.50	55.5	57.0	1.890	155.50	179820.0
3.5	3874.5	3780	1.75	47.6	49.35	2,205	157.51	179928.0
4.0	4428	4320	2.00	41.7	43.7	2.52	159.52	18044.0
4.5	4981.5	4860	2,25	37.0	39.25	2.84	161.55	179820.0

With these results we obtained the hydrostatic curves, which enable us to determine the various analytical results for the work barge under service condition.

4.2 Discussions

In anticipation of the barge floating in an upright condition at many different water lines (or draft) in the course of its services, it is usual to calculate, in advance, the main geometrical characteristics of the ship form at each draft [11]. This data in

Table 1 which is plotted as curves against the draft are known as *hydrostatic curves*. These hydrostatic curves are represented in Figs. 6 to 10 which shows different calculated values plotted against different draft due to variation of loads.

Fig. 6 shows a graph of draft plotted against the displacement of the vessel. Result shows that the working barge can carry a maximum load of 4981.5-tonnes without the barge sinking. The result also shows that there is coherence between the loading conditions (or configuration) with that of the draft. The perfect straight line suggests that the draft varies directly with the displacement of the barge.

Similarly, fig. 7 shows that, the centre of buoyancy varies directly to the draft of barge, which is a good representation in the totality of ship design.

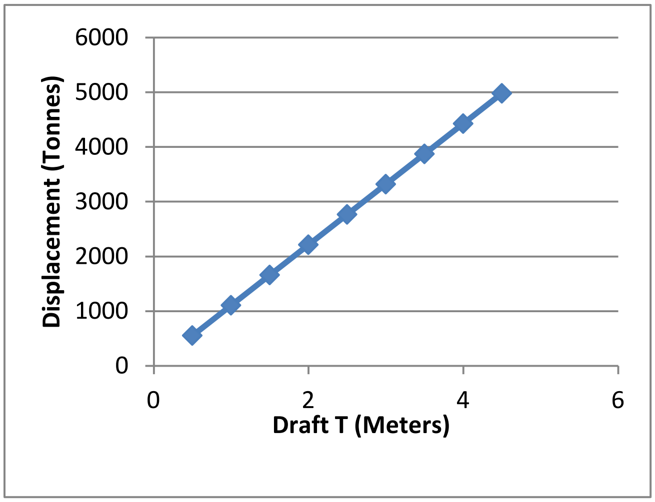

Fig. 6: Displacement versus draft

From Fig. 7, the draft versus BM (distance between the centre of buoyancy and the metacenter and the draft or simply represented at the metacentric radius and the draft), this shows that he draft is inversely proportional to the metacentric radius. This suggests that as the draft is increasing the metacentric radius is reducing. At draft 5m the metacentric radius is less than 100. This is a correct representation in ship design.

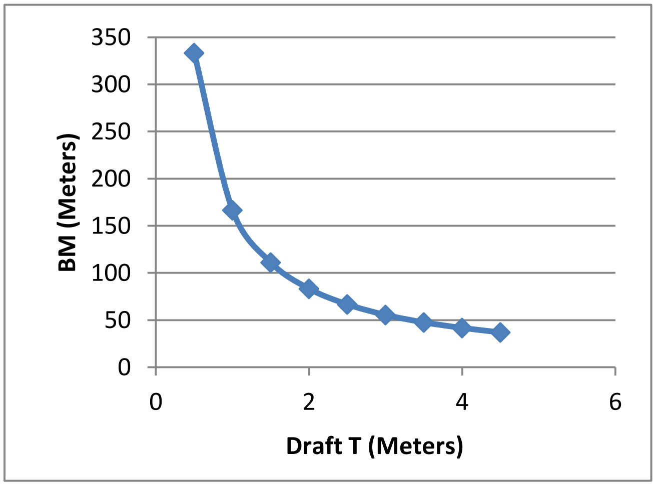

Fig. 7: Metacentric radius versus draft

Fig. 8 is a graph of the centre of gravity versus draft. This is one of the most important representations in a ship design as it relates to stability of the barge and to prove the structural rigidity is correct. This proportional graph as distortion at three different locations but it would not have so much effect on the entire design and the stability of the offshore work barge. It is not a major threat to the safety of the vessel, personnel and equipment.

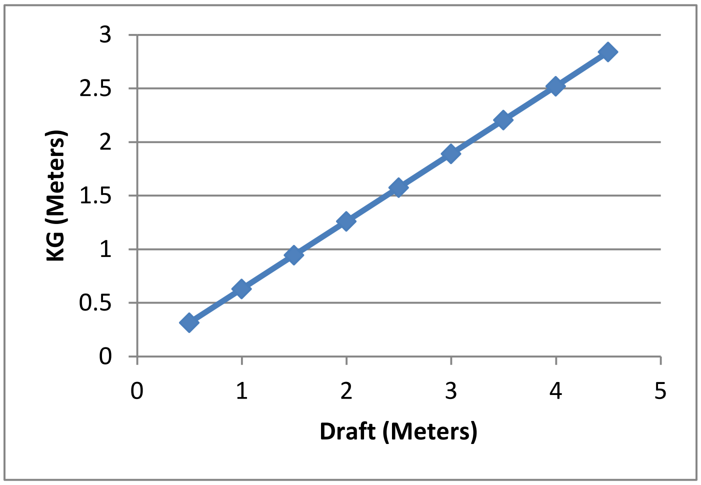

Fig. 8: Center of gravity versus draft

Figure 9 is representation of a graph of draft against the moment to change trim by 1.cm. This is the value of the moment coursed by longitudinal shifting of a mass on a ship, which involves the trim of 1cm, when a ship is immersed up to the water line. The graph shows that draft is proportional to moment to change trim by 1cm. This also is strategic in the design of ships.

Fig. 10 is a representation of the distance from keel to the metacenter. This shows that the draft varies inversely to the distance between the keel and the metacenter, which is also a good representation in general, ship design.

5. CONCLUSION AND RECOMMENDATION

From the design of the 5000 tonnes work barge with a deck crane, the stability analysis of the vessel when the crane is at working gives a representation that at certain loading, the vessel becomes unstable. Every necessary care has to be made not to carry such load at these stipulated locations. This is in order to make the vessel safe for the personnel.

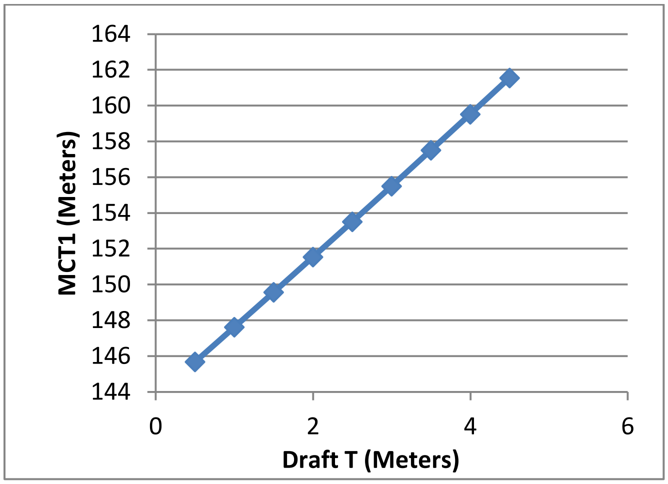

Fig. 9: Moment per cm trim versus draft

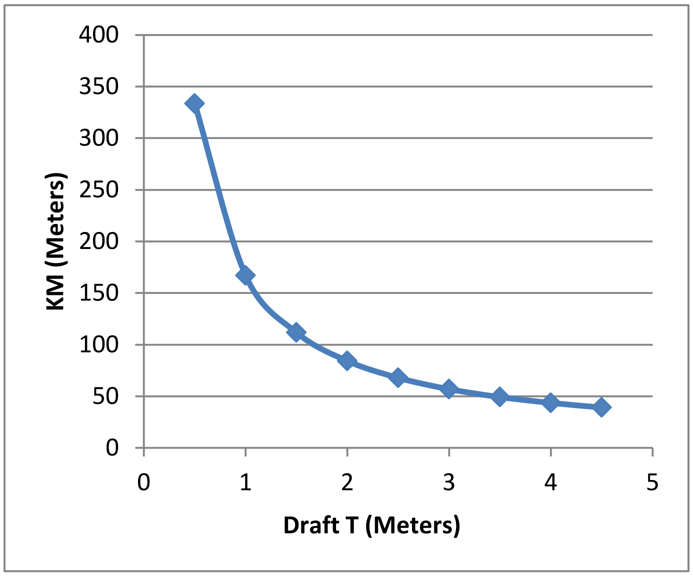

Fig. 10: Metacentric height versus draft

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