British Journal of Applied Science & Technology
16(1): 1-9, 2016, Article no.BJAST.25704
ISSN: 2231-0843, NLM ID: 101664541

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The Effects of Weight Changes on Ship's Stability

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Authors' contributions

This work was carried out in collaboration between all authors. Author RP designed the study, wrote the draft of the manuscript and managed literature searches. Authors TWO, CANJ and EAO supervised the study and literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/BJAST/2016/25704
Editor(s):
(1) Manoj Gupta, Department of Mechanical Engineering, NUS, 9 Engineering Drive 1, Singapore 117576, Singapore.
Reviewers:
(1) Zhi Shang, Louisiana State University, USA.
(2) Sumit Gandhi, Jaypee University of Engineering and Technology, Guna, India.
(3) Imdat Taymaz, Sakarya University, Turkey.
Complete Peer review History: http://sciencedomain.org/review-history/14594

Original Research Article

Received 16th March 2016
Accepted 14th April 2016
Published 12th May 2016

ABSTRACT

Over the years, there had been increase in the use of offshore structures. This might not be unconnected with the awareness of the importance of the maritime sector as well as the rise in energy demand. Consequently, the construction, transportation of offshore structures has drastically increased. The loading of offshore structures such as barges requires thorough and careful planning so as to ensure that the barge is stable. This is achieved where following the loading and offloading of the vessel, the position of the centre of gravity, trim and heel are always in acceptable level. This research therefore, employed a rectangular barge on which ballasting procedures were carried out aimed at eliminating trim and heel. This is done by pumping into the barge 1802.84 tonnes of water which was distributed to tanks 2S and 4S. At the end trim and heel are taken to be corrected when LCG = 33.53 m and TCG = 0 where the reference point was the body system orientation (taken from the bow). However, owing to the little quantity of water to be distributed compared to the size of the given tanks, the result showed that trim and heel are taken to be corrected when X_{CG} (LCG) = 28.49 m and Y_{CG} (TCG) = 0.12 m.

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Keywords: Stability; loading and offloading; ballasting; trim and heel.

NOMENCLATURES

h_1 = *Excess height to correct (m),*
T = *Tidal reading (m),*
Hq = *Water level below quay (m),*
L = *Quay elevation (above LLW) (m),*
D_1 = *Barge draft (m),*
LLW = *Low Low Water,*
H = *Barge depth (m),*
S = *Starboard,*
P = *Port.*

1. INTRODUCTION

Loading and offloading are two very essential operations in offshore structures that could either be carried out by phase 0 (crane loading) or rolling and skidding. Either means could lead to stability problem. Ship stability is a term used to describe the tendency of a ship to return back to her equilibrium when she is inclined from an upright position [1]. Ship stability performance depends on two main factors which are the shape of the hull and distribution of weights. The first one is a constant value and in moderate term and can be changed very rarely during rebuilding of a vessel [2]. [3] studied the impact of sloshing liquids on ship stability for various dimensions of partly filled tanks that showed that the weights distribution changes in every port due to cargo operations, bunkering and related operations such as ballasting. These changes in the weight distribution play a very prominent role in determining the stability of the ship.

The stability of ships in terms of the movement of the ships' center of gravity can also be seen when ships move through water of different densities [4]. Simple explanation for this is the mass, volume and density relation. As the ship moves from water of lower density to that of higher density, volume of water displaces is lower and therefore, the draught of the submerged part of the vessel reduces. [5] studied the influence of liquid sloshing phenomenon taking place in ships' tanks on ship transverse stability.

In the study, a review of several existing ships specifications was made. Effort specifically was made on ballast tanks, their shapes and dimensions. The data collected in the course of the study covered items such as general specification of a ship; total number of ballast tanks; number of ballast tanks in every listed group that is, double bottom tanks, side deep-tanks, wing tanks, fore and after peaks; possibility of ballasting of cargo holds; tanks dimensions (breadth, height and length of each tank); location of tanks in ship's hull; shape of each tank; free surface correction values according to ships stability booklet provided on-board; recommended algorithms of computation of a free surface effect for partly filled tanks. Location and function of ships' tanks on the basis of collected data describing the most significant characteristics of ships' tanks and the classification of tanks were prepared. The very first criteria for distinguishing groups of tanks are their location and shape as well as their use which were strictly defined. According to such assumption, several groups of tanks can be placed starboard and portside and labeled according to their functions.

Ballasting operations could result to two types of stability situations, transverse (rolling) and longitudinal (pitching) stabilities. In applying phase 0 (crane loading), [6] demonstrated the ballasting requirements for loadout operations in varying tidal conditions. The results showed that zero trim and zero lists could be achieved as Y_{CG} and X_{CG} equal to zero where the point of reference is taken at the center. Study of stability is very important as stability of any loaded ship depends on its main dimensions, shape of the submerged hull and on the actual location of her centre of gravity KG [7]. Therefore, in investigating the link between ballasting and stability, this research seeks to apply computer model to study the effects of loading and distribution of the weights in a rectangular barge on its centre of gravity where the reference points X_{CG}, Y_{CG} and Z_{CG} axes are made from the bow [8].

2. MATERIALS AND METHODS

Since the ballasting operation was done in a jetty, a hydrographical surveyor was employed to conduct the survey (sounding) of the location so as to ascertain the depth of the waterway. The reference datum is the "Low Low Water" (LLW). The values of the centre of gravity longitudinally and transversely were considered from the body system orientation. This is done when the reference points, X_{CG}, Y_{CG} and Z_{CG} are taken from the bow. This also corresponds with the approach adopted in [9].

Tables with hydrostatic properties that gave the values of the different loads against the reference points were employed for the calculations. Of the 10 tanks available, only tanks 2S and 4S were used to correct the existing trim and heel. For a better understanding of the calculation process, a flowchart is drawn and Java program was used for the computation of the water needed. The calculated ballast water was then distributed to the tanks to correct the heel and trim.

Presented in Figs. 1 and 2 are the side and plan views of the barge respectively. The X, Y and Z plane are taken positive when considered in the direction as shown but in the reverse direction, they are negative.

Also, Tables 1 and 2 show the tanks and the barge particulars respectively. In table 1, P is taken as port while S is starboard.

2.1 Leveling of the Barge with the Quay

It is required to pump in certain quantity of water into the barge for ballasting purpose, but before then, the value of h_1 which is the excess height to correct is known. From calculation if the excess height to correct is negative (deficit), loadout cannot be carried out but if it is positive, (excess) then water can be pumped into the barge to level the barge with the quay.

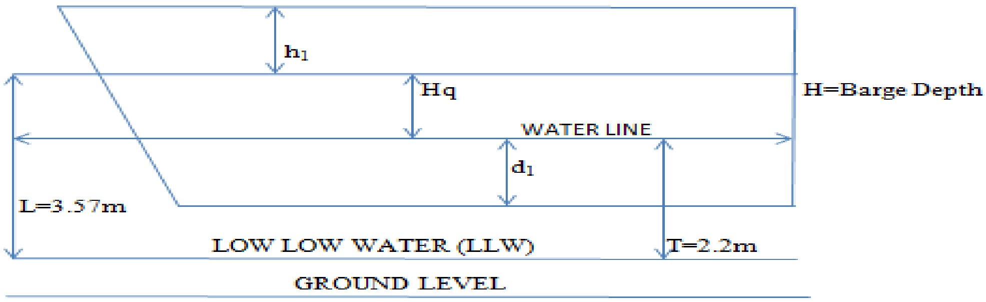

Fig. 1. Side view of the barge

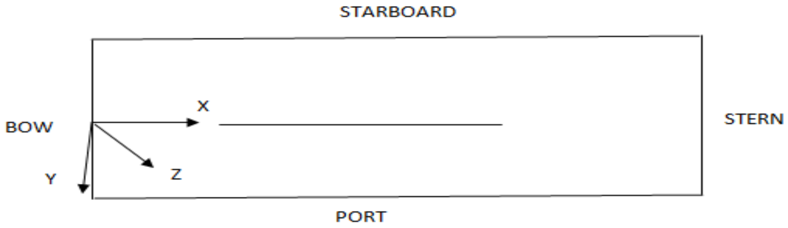

Fig. 2. Plan view of the barge showing the reference point and the directions of X, Y and Z

Table 1. Tanks with dimensions, capacities and their functions

S/No.	Tank	Length (m)	Breadth (m)	Depth (m)	Capacity/Vol. (m^3)	Function	Capacity/ Weight (kg)
1	1S	30	36	15	16200	Not used	16605
2	1P	30	36	15	16200	Not used	16605
3	2S	30	36	15	16200	Ballast tank	16605
4	2P	56	36	15	30240	Ballast tank	30996
5	3S	52	36	15	28080	Tide control	28782
6	3P	52	36	15	28080	Tide control	28782
7	4S	52	36	15	28080	Ballast tank	28782
8	4P	52	36	15	28080	Ballast tank	28782
9	5S	30	36	15	16200	Not used	16605
10	5P	30	36	15	16200	Not used	16605

Table 2. Parameters of the rectangular barge

Lightweight of the barge	**905.29 tonnes**
Center of gravity of the barge without weight	X_G = 33.53 m, Y_G = 0.00 m, Z_G = 2.74 m
Weight of load (piles) altogether	578.74 tonnes
The piles are placed at center of gravity	X_G = 30.01 m, Y_G = -1.29 m, Z_G = 5.64 m
GM_t	11.20 m
GM_l	127.10 m
H	4.57 m
Lov	67.06 m
Beam of barge	21.95 m
Lpp	64.37 m
Quay Elevation (above LLW), L	3.57 m
Tidal Reading, T	2.2 m
Load Draught, d_2	3.2 m
Block coefficient, Cb	0.92

2.2 Determination of Excess Height to Correct, h_1 and Volume of Water Needed for Ballasting

$$h_1 = H - d_1 - H_q \text{ [6]} \tag{1}$$

And $$H_q = L - T \tag{2}$$

If the value of h_1 comes out to be positive, the elevation of the barge deck can now be align with the quay at a draught of:

$$d_2 = d_1 + h_1 \tag{3}$$

The volume of water, V needed to pump into the barge is:

$$V = V_2 - V_1 \tag{4}$$

Where:

$V_1 = L \times B \times d_1 \times C_b =$ Volume of water at draught d_1;
$V_2 = L \times B \times d_2 \times C_b =$ Volume of water at draught d_2

2.3 Heel and Trim Correction

Tanks 2p, 2s, 4p and 4s are used for both heel and trim correction. The heel correction is effected by employing the moment required to change heel per one unit. This is determined as:

$$MCT = \frac{\Delta \times GM_l}{L_{pp}} \text{ [10]} \tag{5}$$

Where:

GM_l: Transverse metacentric height; L_{pp} : Length between perpendiculars
Δ : Mass displacement and it can be determined from:

$$\Delta = L \times B \times d_2 \times C_b \times \rho_{\text{salt water}} \text{ [11]} \tag{6}$$

The total trim is estimated as:

$$T_T = \frac{([LCG - LCB] \times \Delta)}{MCT} \tag{7}$$

Where:

LCB : Longitudinal center of buoyancy; LCG : longitudinal center of gravity

A positive value of T_T means trim by bow. To obtain trim a desirable trim value, certain quantity of water is needed to be pumped into the trim control tank and this amount of water can be expressed as:

$$W_T = \left(\frac{GG_1 \times \Delta}{GG_1 - d_T}\right) \text{ [12]} \tag{8}$$

d_T : Trimming distance is the center of gravity of the barge in the longitudinal direction when there is no external load on the barge less the center of gravity of the barge in the longitudinal direction when the piles are loaded and it is given as:

$$d_T = 33.53\text{m} - 29.99 = 3.54\text{m}$$

GG_1: Trimming lever and it is calculated thus:

Table 3. Table showing the ship's light weight, piles weight and their centre of gravity from centre

Weight, W (t)	KG (m)	Moment (tones*m)	CG from centerline	Moment starboard	Moment portside (M_P)
905.29	2.74	2480.49	0.00	0	Nil
578.47	5.64	3262.57	-1.29	Nil	746.23
∑W=1483.76		5743.06			$\sum M_P$=746.23P

Table 3 shows the light weight (W) of the barge and its centre of gravity (KG), the weight of the piles loaded and the KG is also shown. Negative sign indicates portside and then the trimming lever is calculated thus:

$$GG_1 = \frac{\sum W}{\sum M_P} \; [2]$$

The total heel likewise is expressed as:

$$H_T = \frac{([TCG - TCB] \times \Delta)}{MCT} \qquad (9)$$

Where TCG: Transverse Centre of Gravity (m)
TCB: Transverse Centre of Buoyancy (m)

If the H_T value is negative, the list is by the portside and where it becomes positive, the list is starboard. However, to achieve zero list the quantity of water needed to be pumped into the list control tank is obtained as:

$$W_H = \frac{GG_1 \times \Delta}{GG_1 - d_T} \qquad (10)$$

Where:

d_T : The center of gravity of the barge in the transverse direction when there is no external load on it less the center of gravity of the barge in the transverse direction when the piles are loaded.

That is, $d_T = 0.00\text{m} — (-1.29\text{m}) = 1.29\text{m}$

The total quantity of water required for both the list and trim correction is given as:

$$W_{TH} = W_T + W_H \qquad (11)$$

2.4 Computer Model

A flowchart showing the sequential flow of the methods followed in arriving at the total quantity of water needed for the correction of heel and trim is shown in Fig. 3. The Java program that flows from the flowchart aided the step by step computation of equations 1 – 11. The program displayed an output result of 1802.84 tonnes which is then distributed to the ballast tanks.

The leveling of the barge with the quay was determined by the excess height, h_1 to correct. Where h_1 is negative, the process stops but positive then the water needed for ballasting can be calculated. This subsequently gave rise to the determination of the water for the correction of trim and heel. The final result is then displayed as W_{TH} which is 1802.84 tonnes.

3. RESULTS AND DISCUSSION

Although tanks 2S, 2P, 4S and 4P are all meant for the ballast purpose however, only tanks 2S and 4S are used. The quantity of ballast needed is 1802.84 tones. Table 4 shows the tanks, percentage utilization and the centre of gravities of the corresponding weights from the keel. The 2.50% represents the water and mud that could not be pumped out and left behind in the tank. It is an allowance that was taken into consideration for any unused tank. Trim and heel are corrected where LCG (X_{CG}) gives 28.49 m and TCG (Y_{CG}) gives 0.12 m.

The capacity (weight) utilization of the tanks on board the barge is presented in Fig. 4. This is done after the water pumped into the tanks for the ballasting purposes has been distributed and it showed from the shape of curve that tanks 2S and 4S all situated at the starboard which are the only tanks used for the ballasting contains the largest quantity of water in terms of weight. And with more of the ballast water contained in tanks 2S and 4S, LCG and TCG become 28.49 m and 0.12 m respectively.

However, [6] was able to achieve LCG =0 and TCG =0. This was accomplished while in applying crane loading, more tanks were used, the total ballast weight was higher and the reference points were taken at the center against this study where the reference points were made from the bow, less number of tanks with less ballast weight.

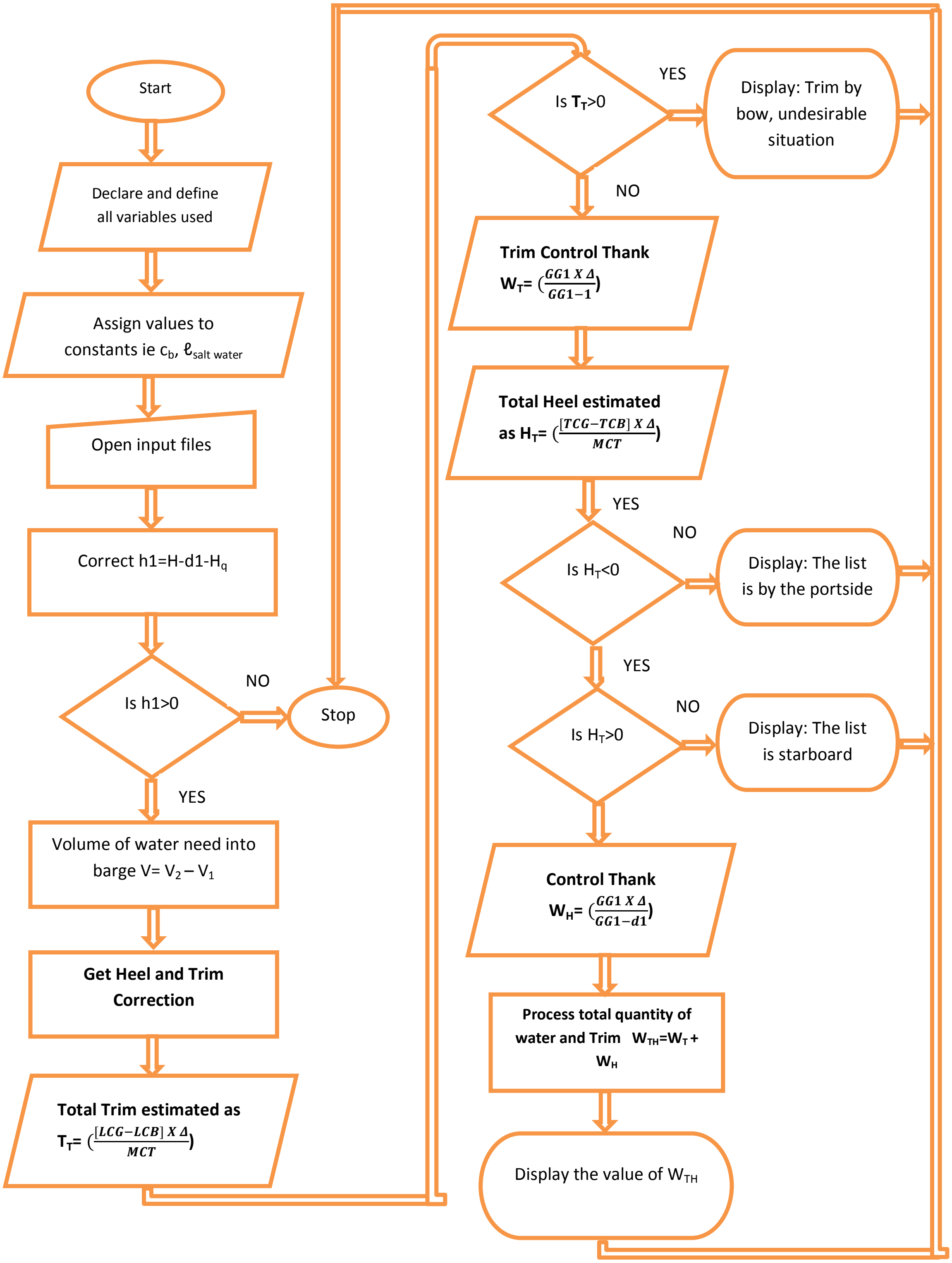

Fig. 3. Flowchart illustrating the computation process of the water needed for the ballasting operation

Table 4. Table of the ballast water distribution to the tanks and their centre of gravities

Barge weight	**Ballast data**								**Weight calculations**		
	Full capacity	**% used**	**Weight**	**KG**	**Wt*KG**	**X_{CG}**	**Y_{CG}**	**Z_{CG}**	**MX**	**MY**	**MZ**
	t	**%**	**t**	**m**	**t*m**	**m**	**m**	**m**	**t*m**	**t*m**	**t*m**
Lightship			905.29	2.74	2480.49	33.53	0.00	2.74	30354.37	0.00	2480.49
Loaded Piles			578.74	5.64	3264.09	30.01	-1.29	5.64	17359.88	-746.23	3262.57
Subtotal			1484.03	3.87	5744.58	32.16	-0.50	3.87	47714.25	-746.23	5743.06
Ballast											
1S	16605	2.50	415.13	1.01	419.28	17.68	5.49	1.01	7339.50	2279.06	419.28
1P	16605	2.50	415.13	1.01	419.28	17.68	-5.49	1.01	7339.50	-2279.06	419.28
2S	16605	5.61	931.66	2.18	2031.02	17.68	5.49	2.18	16471.75	5114.81	2031.02
2P	30996	2.50	774.90	1.89	1464.56	17.68	-5.49	1.89	13700.23	-4254.20	1464.56
3S	28782	2.50	719.55	1.88	1352.75	34.14	5.49	1.88	24565.44	3950.33	1352.75
3P	28782	2.50	719.55	1.88	1352.75	34.14	-5.49	1.88	24565.44	-3950.33	1352.75
4S	28782	3.03	871.17	2.29	1994.66	49.99	5.49	2.29	43549.79	4782.72	1994.66
4P	28782	2.50	719.55	1.88	1352.75	49.99	-5.49	1.88	24565.44	-3950.33	1352.75
5S	16605	2.50	415.13	1.01	419.28	17.68	5.49	1.01	7339.50	2279.06	419.28
5P	16605	2.50	415.13	1.01	419.28	17.68	-5.49	1.01	7339.50	-2279.06	419.28
Subtotal			6396.90	1.75	11225.61	27.63	0.265	1.75	176776.09	1693	11225.61
	Total		7880.66	2.15	16968.67	28.49	0.12	2.15	224490.34	946.77	16968.67

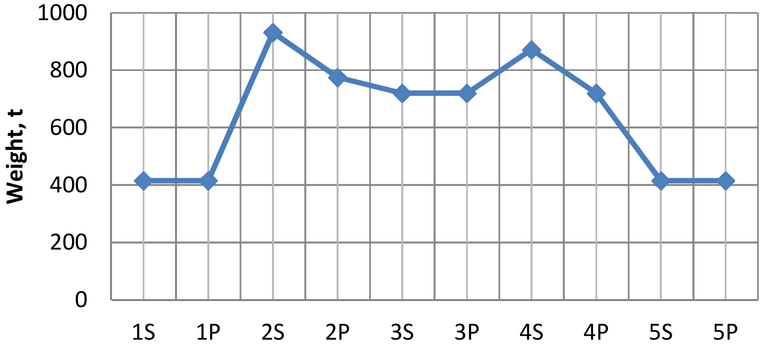

Fig. 4. Weight (water) distribution in tanks

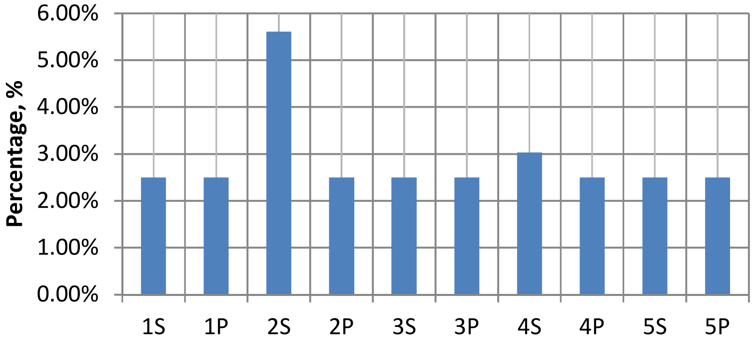

Fig. 5. Weight of water distribution in terms of percentage

Fig. 5 shows the capacity (percentage) utilization of the tanks on board the barge. Again, this is done after the water pumped into the tanks for the ballasting purposes has been distributed. The bars showed that tank 2S correspond to the highest percentage and then followed by tank 4S which again showed they contain the largest quantity of water.

This present work was compared with similar efforts made in similar areas. In [8] consideration was focused on the effects of weight changes on an offshore work barge without giving consideration to what impact ballasting would have on the stability of offshore structures. [13] studied the hull design requirements of FPSO where the stability aspect was not computerized like this present work.

Furthermore, steps have been enunciated through this work on how better stability could be achieved. The introduction of a computer model to work on stability where both ballasting and movement of weight onboard are considered is novel.

4. CONCLUSION

Analyses of the effects of weight changes (both solid objects and liquids) have been shown in this work. These involve the effects of ballasting operation and subsequent distribution of the ballast water into ballast tanks of a barge with the aim of correcting trim and heel. The barge consists of 10 tanks of which four (2S, 2P, 4S and 4P) were used for the ballasting purpose.

1802.84 metric tons of water was calculated and pumped into the barge. The correction of trim and heel was effected by distributing the pumped in-water into the tanks with regards to X_{CG}, Y_{CG}. The results of the study showed that owing to the quantity of water taken for the ballasting, only tanks 2S and 4S were used and trim and heel were taken to be corrected at $X_{CG} = 28.49$, $Y_{CG} = 0.12$ respectively. Computer model was employed to facilitate the steps and calculate the required quantity of ballast water.

5. RECOMMENDATION

From the findings of this work, the recommendation is that prior to the deployment of any offshore structures, proper attention should be given to the loading and offloading operations with regards to the changes on the centre of gravity of the structures.

ACKNOWLEDGEMENTS

I wish to sincerely acknowledge the efforts of Engr. Koukovi E. E. Koumako for his contributions and support in providing the needed materials that aided this work from conception to completion.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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