

# Stability Assessment of Drill Ship Using Probabilistic Damage Stability Analysis

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Drill ship is a ship-shaped structure with a drilling unit at its center and with oil compartments, which is moored and kept in position using anchors. These ships should be capable of working in deep sea for a long time, hence affected by harsh ocean environment. Drill units are said to have greater heave motion, and the height of the derrick influences the vessel's stability. MARPOL Oil Outflow Analysis is performed for damaged crude oil carriers or tankers and Mobile offshore drilling units (MODU) in damaged condition. In the present study, probabilistic analysis is performed on drill ship to understand its stability behavior under damaged condition. Stability assessments are carried out by considering single and multiple damage locations. Oil outflow analysis is carried out for different damage cases of oil tank. Probabilistic damage assessment is done for load cases up to 50 % flooding, to obtain stability charts. These charts will be useful to understand variations in stability parameters under damaged conditions.

## KEY WORDS

- ~ Damage potential diagram
- ~ Stability Chart
- ~ MODU
- ~ MARPOL Oil Outflow Analysis

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## 1. INTRODUCTION

Drill ships are designed for drilling of oil reservoirs to extract oil and natural gas in deep sea. They have drilling platform, derrick, and moon-pools on hull to drill up to a depth of 3,200 m. These vessels are designed for a water depth of 30 to 900 m when the ship movement is allowed for only 5 % of water depth. The transit speed of the vessel is around 10 knots and optimum wind speed is 70 knots in intact condition (Stability booklet, 2006). Non-linear sea states are crucial to be considered during its design as drilling unit has to be aligned perpendicular to oil bore holes in the sea bed. This involves huge effort to keep Mobile Offshore Drilling Units (MODU) stable. Mooring lines, risers, and strings are used to keep the drilling platform stable. Their response and stability parameters are highly critical in these ships. Although current SOLAS 1990 (International Convention for Safety of Life at Sea) agreement guarantees ship safety under damaged condition for passenger ships and dry cargo ships, there is no final and international rules or regulations for determining damage stability on oil carrying vessel. Hence, to evaluate survivability under flooding, regulations for dry cargo ships given by IMO 2008 (International Maritime Organization) are used for damage stability investigations.

Liquid cargo carriers face challenges like liquid property, granularity, fill level, etc. which affect motion response. Vibrations are created due to moving liquid cargo which affects the overall stability of the vessel. Ships movement is then similar to the movement of liquid under the influence of free surface effect. Drill ships have mud carrier tanks, oil tanks and brine tanks which affect its stability under intact and damaged condition.

When damage occurs on a crude oil carrier due to environmental issues, oil outflow occurs and the stability of the

vessel is affected. Extent of flooding and leakage depends on the location of damage, oil fill height, and draft. The oil carrying containers are designed in such a way that the external pressure is lower than internal pressure. This helps to prevent water ingress from the sea, but it promotes oil outflow. If the tank is partially filled, water ingress can also take place. In most cases, the tanks are fully loaded. The present study aims to prepare the stability chart for the damage condition of the drill ship, which will be an effective tool to evaluate the final stability and serviceability of the ship in probable damage cases.

## 2. REVIEW OF PREVIOUS WORKS

To understand the actual scenario of damage stability, researchers started investigating flaws which caused previous accidents, for safety improvement. Shipping industry has reacted after various disasters where a ship lost its watertight integrity. They tried in many ways to improve current regulations like IMO's SOLAS. Researches on damage stability assessment of ship when subjected to ocean environment and its survivability need to be constantly improved as it an unpredictable phenomenon.

Cheng et al (2010) studied the dynamics of spillage during the damaged condition of an oil carrier. Moving Particle Semi-Implicit (MPS) method was adopted using numerical code SSTAB. Coupling between the damaged hull response and internal multiphase flood dynamics was carried out. A two-dimensional small-scale model undergoing sway motion with induced high volume oil leakage was compared with numerical results. The final list angles were obtained numerically for large filling ratio and height. At filling ratio 45 %, a noticeable difference was observed in the final list angle when numerical results were compared. A study about oil outflow from different types of tanks was conducted by Tavakoli et al. (2011). The tanks considered were either below or above waterline during collision and grounding incidents. They verified the performance of the proposed model using CFD simulations and experimental tests. They concluded that the ship with double hull is most efficient and helps reducing oil spill. Begovic et al. (2013) showed variation in motion responses when a ship's hull is damaged, and highlighted scaling issues and effects while modelling. Hashimoto et al. (2014) used moving particle semi-implicit method to simulate flooding of damaged ship for beam wave. The ordinary strip method based on potential flow theory was adopted to check the results. It was confirmed that Boyle's law can qualitatively predict multiphase dynamic effect between air and water during flooding. A new numerical flood simulation tool which allows evaluation of a ship's time dependent damage stability including all stages of flooding was developed by Lorkowski et al. (2014). Lee et al. (2015) performed a set of model tests in intact and damaged ship considering six degrees of freedom in beam seas. When starboard side damage opening faces the sea, heave and roll motion

changes drastically. At the region near damage, free surface effect was strongly coupled with the roll motion of the ship. Manderbacka et al. (2015) experimented to bring out effects of coupling ship motion and flooding in a box-shaped barge model. Flooded water behaved in a different manner in undivided and divided compartments. In divided compartments, flooded water increased roll damping significantly. Onset of flooding suddenly after damage is difficult to be modelled as it is highly nonlinear and varies with different internal layouts of compartments. This can give unpredictable roll response. Acanfora and Luca (2016) conducted experiments on damaged vessels in still water to find roll response in beam waves. Side and bottom damage was investigated, which generated greater roll damping. Moreover, roll period was less for bottom damage case. It is affected by type and position of the damaged compartment. Sway motions were significantly reduced during damage. They also stated that wave frequency fluctuated for different wave height due to nonlinear sea states during different damage scenarios.

In the present study, damage locations were identified, and the probability of failure of the vessel due to compartmental flooding is found out in terms of probability index. Stability charts were developed related to stability parameters. It focuses on damage analysis of oil compartments, which will be helpful in monitoring oil outflow effects on stability.

## 3. THEORETICAL BACKGROUND

The IMO Code specifies a set of vertical center of gravity (VCG) value for different drafts of drill ship. To study intact stability of drill ship, properties like compartmental arrangement, subdivision plan, ship line plan, loading conditions, and hydrostatic characteristics are to be known. To assess damage stability, permeability of rooms and void spaces are considered to be 0.95 and that of machinery rooms 0.85. Downflooding points are to be considered in damage stability assessment. Open spaces are to be considered in intact stability assessment. The codes define three stages of design for drill ships i.e. sailing, drilling, and stand-by condition. The main parameters included in the intact stability criteria are based on limiting metacentric height (GM), equalizing the righting moment and energy to its limiting value.

Damage extent shall be considered horizontally up to 1.5 m and vertical without any limits. Water tight bulkhead should be considered 3 m from the damage location. Longitudinal extend of damage considered should not exceed 3 m. The VCG obtained from the intact stability assessment is considered as initial VCG in damage stability analysis.

The maximum VCG is obtained under loading condition during the operational stage of drill ship. It should satisfy stability and integrity conditions specified in DNV-OS-301. Probabilistic analysis is undertaken to assess the damage stability of drill

ships. To prevent oil pollution occurring due to ship damages, MEPC.117 (52) has provided the outflow parameter  $O_{(M)}$ , which is the total volume of oil cargo in m<sup>3</sup> at 98 % tank filling  $C$ . The ship is loaded up to load line draft  $d_s$  without trim or heel for the calculation of mean oil outflow parameter. The measurement of outflow is affected by tank permeability. It is different for different cargo spaces in a ship. In general cases like cargo tanks, ballast tanks, machinery room, engine room etc. permeability is taken as 0.99. The oil outflow is measured separately for hull side and bottom failure cases. The oil outflow for both cases is combined to get a dimensionless parameter  $OM$  which is represented as:

$$O_M = (0.4 O_{MS} + 0.6 O_{MB}) / C \quad (1)$$

Oil outflow due to side damage is  $O_{MS}$  and oil outflow due to bottom damage is  $O_{MB}$ , both measured in m<sup>3</sup>. The oil outflow for side damage  $O_{MS}$  is given by:

$$O_{MS} = C_3 \sum_i^n P_{S(i)} O_{S(i)} \quad (2)$$

Here, probability  $P_{S(i)}$  of oil tank  $i$  is found and the corresponding oil outflow  $O_{S(i)}$  is measured in m<sup>3</sup> for side damage when filled 98 %. This is performed for  $n$  number of oil tanks. The tank filling  $C_3$  is taken as 0.77 for ships having two adjacent horizontal bulkheads inside cargo tanks and 1.0 for all other ships. Mean outflow for bottom damage is given by:

$$O_{MB(i)} = \sum_i^n P_{B(i)} O_{B(i)} C_{DB(i)} \quad (3)$$

In bottom damage, probability  $P_{B(i)}$  of oil tank  $i$  is found and the corresponding oil outflow  $O_{B(i)}$  is measured in m<sup>3</sup> for side damage when filled 98 %. This is performed for  $n$  number of oil tanks. The factor to account for oil capture is  $C_{DB(i)}$ . In the probabilistic approach, degree of subdivision of a ship is considered sufficient if it meets the requirements of SOLAS criteria and attained survival probability index  $A_i$  is not less than required subdivision index ( $R_i$ ).

$$A_i > R_i \quad (4)$$

Probabilistic damage stability (PDS) approach relies on statistics and involves uncertainty and random variables to describe the behavior of the vessel. Random variables may be mass, velocity, dimension, permeability etc., which might be different for different ships. If two ships have same attained index  $A_i$ , then it is considered safe. The portion of the ship below

water line  $d_s$  is affected by the subdivision length  $LS$  and reserve buoyancy. Required index is calculated based on ship type, and the procedure varies for each ship type. It depends on ship's length, number of persons on board, and rescue boat weight for passenger ships. It solely is a function of ship length in case of cargo ships. Drafts at 100 % loading and 60 % loading condition are represented as  $d_p$  and  $d_l$ . Stability on damage depends on damage location, number of damages between bulkhead, boundary of transverse and longitudinal distance to damage point, etc.

Minimum value of probabilistic stability is found out using parameter  $A_i$ . The probability index  $p_i$  for zone  $i$  is found by not including longitudinal and transverse subdivisions. Horizontal subdivision can generate other flooding scenarios. Producing an attained index  $A_i$  requires three loading conditions:

$$A_i = \sum p_i x_{si} \quad (5)$$

$$A_i = 0.4A_s + 0.4A_p + 0.2A_l \quad (6)$$

Here,  $s, p, l$  are three loading conditions which are multiplied by factors. The  $p_i$  factor depends on the geometry of the ship and its compartmental arrangement. The geometry of each ship deck and initial draft is represented by  $v_i$  factor. It shows that each deck or horizontal subdivision has a probability not to be flooded. Figure 1 shows PDS diagram comprising of single and multiple compartment damage cases for zone 1 to 7. (IMO; 2008) Single damaged zone ( $n=1$ )

$$p_{j,1} = p(x_{1j}, x_{2j}) \quad (7)$$

Two damaged zone ( $n=2$ )

$$p_{j,2} = p(x_{1j}, x_{2j+1}) - p(x_{1j}, x_{2j}) - p(x_{1j+1}, x_{2j+1}) \quad (8)$$

Three or more zones ( $n=3$ )

$$p_{j,n} = p(x_{1j}, x_{2j+n-1}) - p(x_{1j}, x_{2j+n-2}) - p(x_{1j+1}, x_{2j+n-1}) + p(x_{1j+1}, x_{2j+n-2}) \quad (9)$$

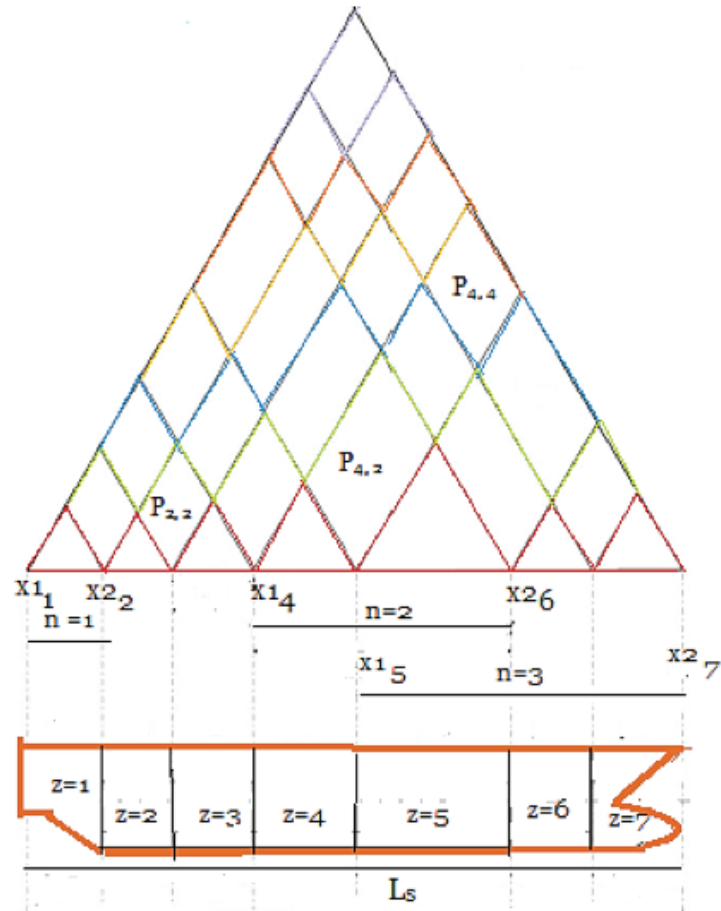


Figure 1.  
Probability chart for damage cases (Explanatory notes SOLAS, 2008).

Highlight of this work is to develop damage stability charts which will be useful to the ship master for predicting a damage with regard to the probability of occurrence of damage as well as to get an idea about how much pollution will be caused to environment through oil spillage because of the damage condition. Oil outflow charts will be helpful in understanding ship survivability after a damage.



Figure 2a.  
Drill ship (Stability booklet, 2006).

## 4. STABILITY ASSESSMENT OF THE DRILL SHIP

### 4.1. Details of the Drill Ship

In the present study, a drill ship (Figure 2a) is used to study the stability characteristics in both intact and damage

conditions. The general arrangement of the ship is shown in Figure 2b and its hull form properties are as shown in Table 1. The drill ship is having tanks and compartments as listed in Table 2. Compartmental arrangements are unsymmetrical. It comprises of double bottom, moon-pool, engine room, forward and aft pump room etc.

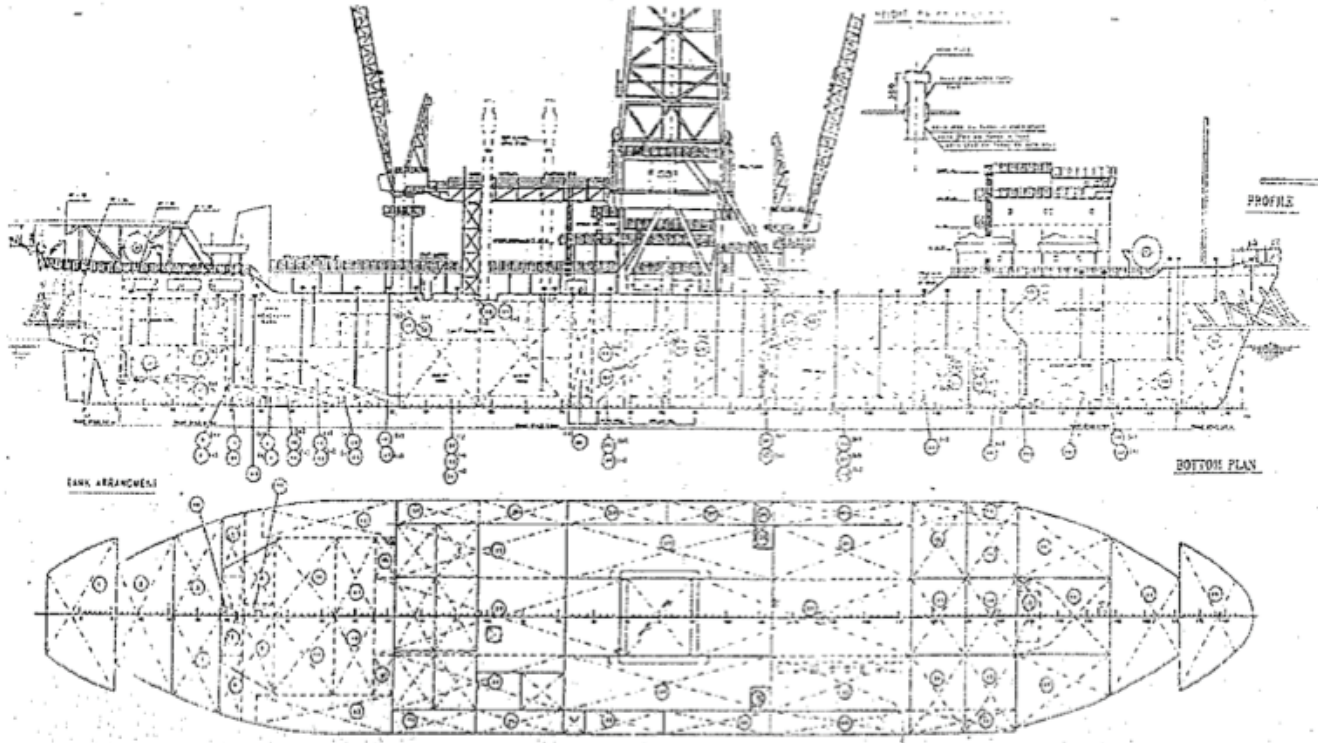


Figure 2b.  
General arrangement of ship (Stability booklet, 2006).

Table 1.

Drill ship hull form properties (Stability booklet, 2006).

Parameters	Value
Length b/w perpendicular (m)	136.80
Block Coefficient	0.7526
Overall Length x Breadth x Moulded depth (m)	145.9 x 24.5 x 11.20
Vessel Type	Drill Ship
Summer DWT (t)	17426
LCG from AP (m)	64.877

**Table 2.**

Drill ship tanks and compartments (Stability booklet, 2006).

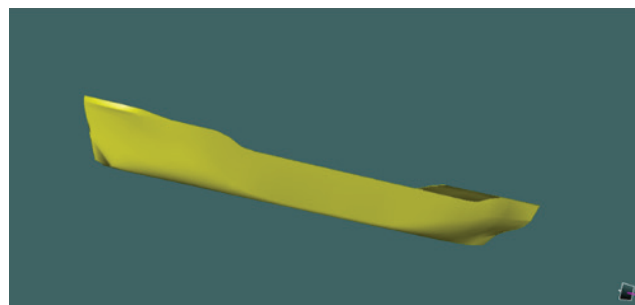
NAME	TYPE	INTACT %	DAMAGE%	DENSITY	FLUID
Aft Thruster port/stb	Compartment	100	100	-	-
Engine Room Port/stb	Compartment	100	100	-	-
Switch Room Port/stb	Compartment	100	100	-	-
Cofferdam port/stb	Compartment	100	100	-	-
Slop tank port/stb	Tank	100	95	0.913	-
Oil 4/ Oil 3/ Oil 2	Tank	100	95	0.8883	Crude
Access port/stb	Compartment	100	100	-	-
Base Oil	Tank	100	95	0.92	Oil
Brine	Tank	100	95	1.025	Sea Water
Aft Pump Room Port/stb	Compartment	100	100	-	-
MoonPool	Compartment	100	100	-	-
Fwd Pump Room Port/stb	Compartment	100	100	-	-
Brine	Tank	100	95	1.025	Sea Water
ROV	Non-Buoyant Vol.	100	100	-	-
Fore Peak	Compartment	100	100	-	-
Double bottom 9/10/11/12	Tank	100	95	1.025	Water
Double bottom 8/7/6/5	Tank	100	95	1.025	Water

An effective way to improve survivability of a vessel is to have a longitudinal bulkhead. Most oil carriers have central cargo tanks without any separating longitudinal bulkhead through the middle. This arrangement can improve vessel survivability under damaged cases.

#### 4.2. Model Details

The ship is modelled as a monohull in Maxsurf modeler (Figure 3), which contains tanks and compartments (Stability booklet, 2006) as shown in Figure 4. The ship has 6 degrees of freedom, three translations and three rotations which include surge, sway, heave as linear motions about x,y,z axis, and roll, pitch, yaw as angular motions respectively. The modeling is done about a reference point by setting out the ship dimensions along the reference frame. The markers and control points together form smooth nurbs which generate the hull surface. The volume and the displacement are set as per the data given in the stability

booklet (Stability booklet, 2006). The longitudinal zone divisions (Figure 5) are applied along length  $L_s$ . It is provided with one central longitudinal and twelve transverse bulkheads, each representing extent of zones, dividing overall length into 9 zones.



**Figure 3.**  
Drill Ship model (source: authors).

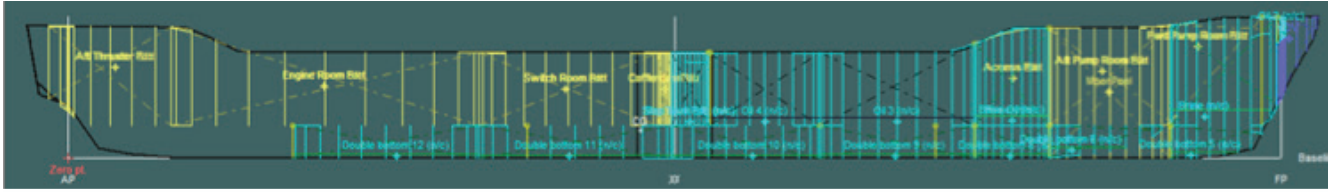


Figure 4.  
Arrangement of tanks and compartments (source: authors).

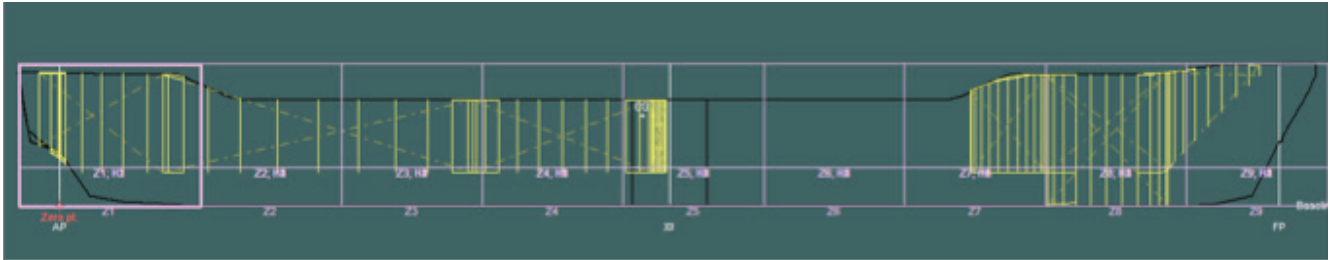


Figure 5.  
Zones for damage stability assessment (source: authors).

Zone 1 is located at the bow of the vessel, close to the forward perpendicular. The analyses are done for single and

multiple compartment flooding. Transverse damage extent is taken as  $B/5$  and  $B/2$  of the ship's beam.

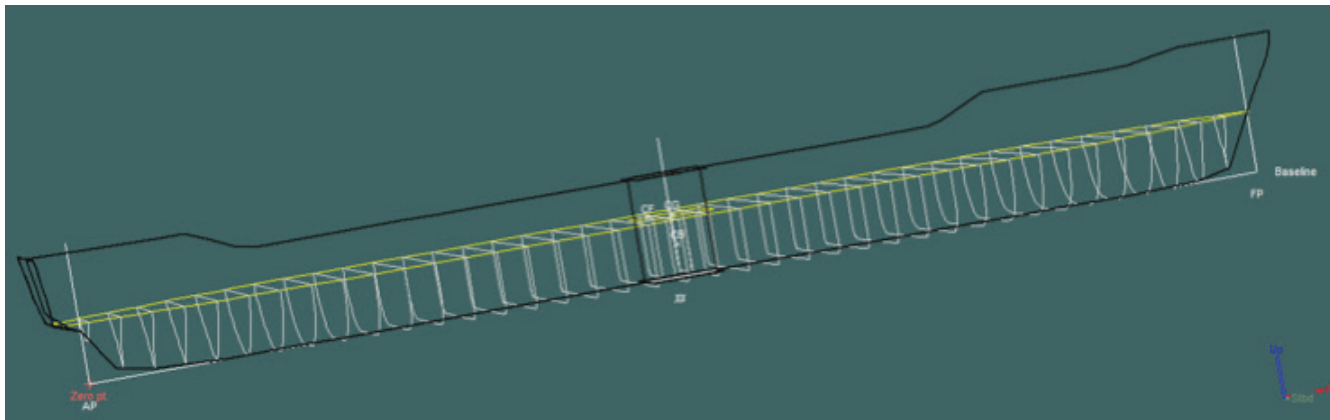


Figure 6.  
Strips generated for motion analysis (source: authors).

The section of the vessel below the waterline is discretized into 43 strips to perform the motion analysis (Figure 6). The strips are two-dimensional planes, for which response equations are solved. Response coefficients of each strip is then integrated throughout the ship to obtain response amplitude operator (RAO). Input parameters include the speed of the ship, wave height and the direction of wave encounter.

### 4.3. Motion Response Analysis

Sea keeping analysis is done based on strip theory using Maxsurf, where heave, pitch, and roll responses are evaluated. The analysis is done to obtain response amplitude operator (RAO) for small wave height, and the fluid is considered inviscid and irrotational. Encountering frequency varies from 0.2 to 2 rad/s.

Encountering wave is considered in head and beam directions for linear wave height. In the operating condition, wave height is considered as 4.25 m for the analysis (Stability booklet, 2006). The response obtained is shown in Table 3. Maxsurf result is

compared with those in the stability booklet (Stability booklet, 2006), which is done using an analysis tool ORCAFLEX. Heave and roll responses in beam sea, and pitch in head sea conditions are shown in Figure 7 (a,b,c).

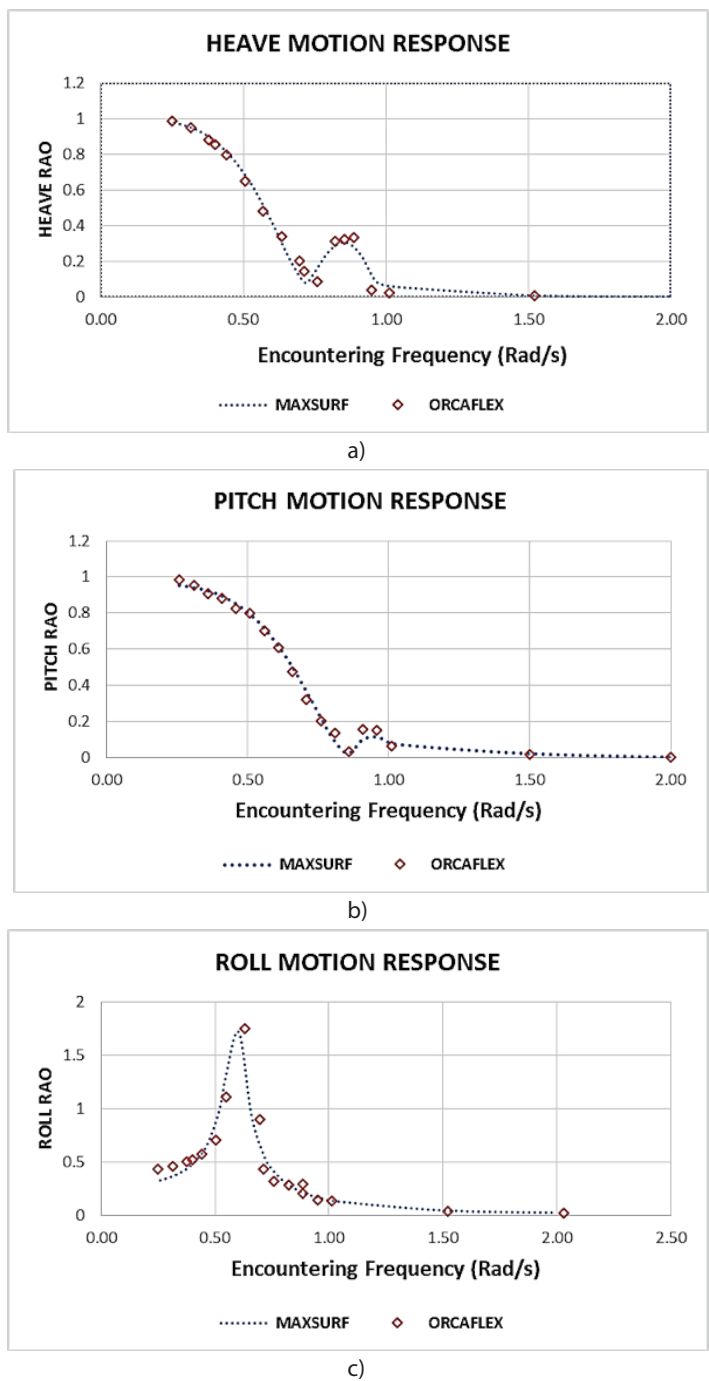


Figure 7.

Response of drill ship (a) beam-heave (b) head-pitch(c) beam-roll (source: authors).



**Table 3.**

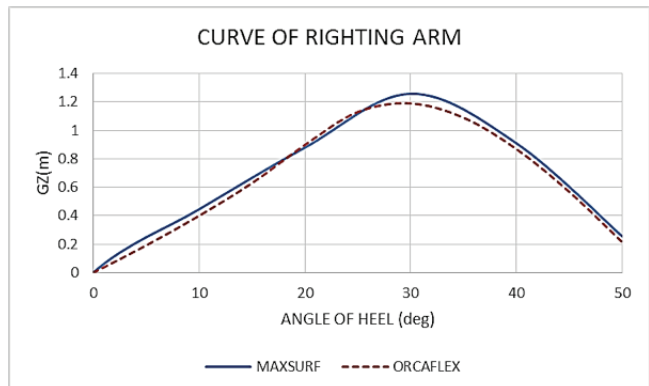
Motion response RAO (Source: author).

FREQUENCY	MAXSURF (source: author)			ORCAFLEX (Stability booklet, 2006)		
	HEAVE	ROLL	PITCH	HEAVE	ROLL	PITCH
0.26	0.977	0.330	0.954	0.985	0.433	0.982
0.31	0.952	0.368	0.942	0.950	0.462	0.955
0.36	0.923	0.410	0.927	0.883	0.505	0.905
0.41	0.872	0.483	0.901	0.853	0.525	0.881
0.46	0.774	0.659	0.848	0.799	0.574	0.823
0.51	0.652	0.999	0.779	0.650	0.708	0.799
0.56	0.579	1.317	0.736	0.481	1.114	0.699
0.61	0.409	1.720	0.630	0.390	1.748	0.610
0.66	0.221	0.936	0.500	0.199	0.902	0.473
0.71	0.082	0.552	0.348	0.079	0.432	0.201
0.76	0.123	0.449	0.268	0.096	0.318	0.200
0.81	0.254	0.321	0.111	0.299	0.295	0.133
0.86	0.307	0.245	0.022	0.32	0.212	0.034
0.91	0.240	0.195	0.100	0.232	0.290	0.155
0.96	0.086	0.161	0.112	0.076	0.142	0.150
1.01	0.059	0.135	0.073	0.023	0.134	0.065
1.50	0.009	0.048	0.020	0.006	0.040	0.018
2.00	0.002	0.026	0.000	0.002	0.022	0.000

Roll resonant peak is obtained at a maximum of 1.72 for a frequency of 0.61 rad/s. A second peak is observed in heave response in beam sea and pitch response in head sea at an encountering frequency of 0.91 rad/sec. Motion response analysis predicted similar behavior as given by ORCAFLEX; hence, the designed model may be used for damage stability and oil outflow analysis.

#### 4.4. Hydrostatic Stability Properties

At fully loaded condition, the vessel displacement is 17,426 t and the corrected distance between keel and center of gravity (KG) including free surface effect is 9.04 m. The heel angle corresponding GZ value is obtained by performing the hydrostatic analysis. GZ value (Table 4) obtained in Maxsurf is compared with ORCAFLEX, as shown in Figure 8. On performing stability analysis, the vessel’s hydrostatic properties were obtained.



**Figure 8.** Hydrostatic stability curve of Sagar Vijay (source: authors).

**Table 4.**

Righting arm obtained in stability analysis (Source: author).

HEEL	RIGHTING ARM, GZ (m)	
	MAXSURF	ORCAFLEX(Stability booklet, 2006)
0	0	0
10	0.445	0.4
20	0.879	0.898
30	1.258	1.19
40	0.91	0.869
50	0.255	0.215

**Table 5.**

Hydrostatic properties (Source: author).

PROPERTIES	VALUE	UNIT
Maximum draft	6.72	m
Vertical center of gravity	12.54	m
Longitudinal center of gravity from aft perpendicular	64.877	m
Transverse center of gravity	0.253	m
Maximum heel angle	30°	-
Maximum GZ value	1.2	m

On validating the model, based on hydrostatic and hydrodynamic properties, the probabilistic damage stability analysis is performed.

#### 4.5. Probabilistic Damage Stability Assessment

The damage stability analysis is carried out for all tanks at the periphery of the vessel and also for those double bottom tanks exposed to water. It is necessary to know the serviceability of the vessel after a damage condition, which is dependent on draft as well as displacements of the ship. To study variations in

the stability due to ship damage-induced flooding, nine load cases have been created. Load cases considered are intended and defined for the proper functioning of the vessel, which are as given in Table 6.

The probability of flooding was found for tanks and compartments, and those lower than 0.01% were neglected. A total of 10 major damage configurations were considered in oil compartments. Damage cases and its probability of getting flooded are listed in Table 7. The compartment like oil 3, oil 2, oil 4, and double-bottom tanks 12, 11,10,9,8,7,6, as listed in Table 2, were damaged to obtain the probability index.

**Table 6.**

Load case definitions (Stability booklet, 2006).

Load case	Displacement (t)	Draft (m)
Load case 1	8,651	4.167
Load case 2	9,645	4.223
Load case 3	9,788	4.503
Load case 4	10,503	4.780
Load case 5	11,217	5.055
Load case 6	11,931	5.327
Load case 7	12,646	5.397
Load case 8	13,360	5.889

The probabilistic damage stability plot for single and multiple flooded compartments is as shown in Figure 9. It is a triangular plot with the lowest row of triangles showing the effect of damage opening in zone 1. The second row of parallelograms shows damage in zones 2, 3 and 4 when flooded simultaneously, which is the combination of multiple compartmental damages.

The probability factor or p-factor for different damage cases is assessed in terms of Attained index. The color coding helps to define sections of the ship which are highly susceptible to occurrence of damage. Longitudinal Subdivision L<sub>s</sub> has a limitation of how the zones are defined to maximize the Attained Index A<sub>i</sub>. The p-factor varies when damage length changes. The Damage Potential Diagram (DPD) can help the designer in finding out damage zones, which have the largest potential for the attained index.

DPD compares the maximum attained index for a selected number of zones to the total attained index for all the zones. The first set represents 'A<sub>i</sub>' at the deepest subdivision draft or summer load line, the second set represents 'A<sub>i</sub>' at a partial subdivision draft, and the third set represents 'A<sub>i</sub>' at zero loading draft condition.

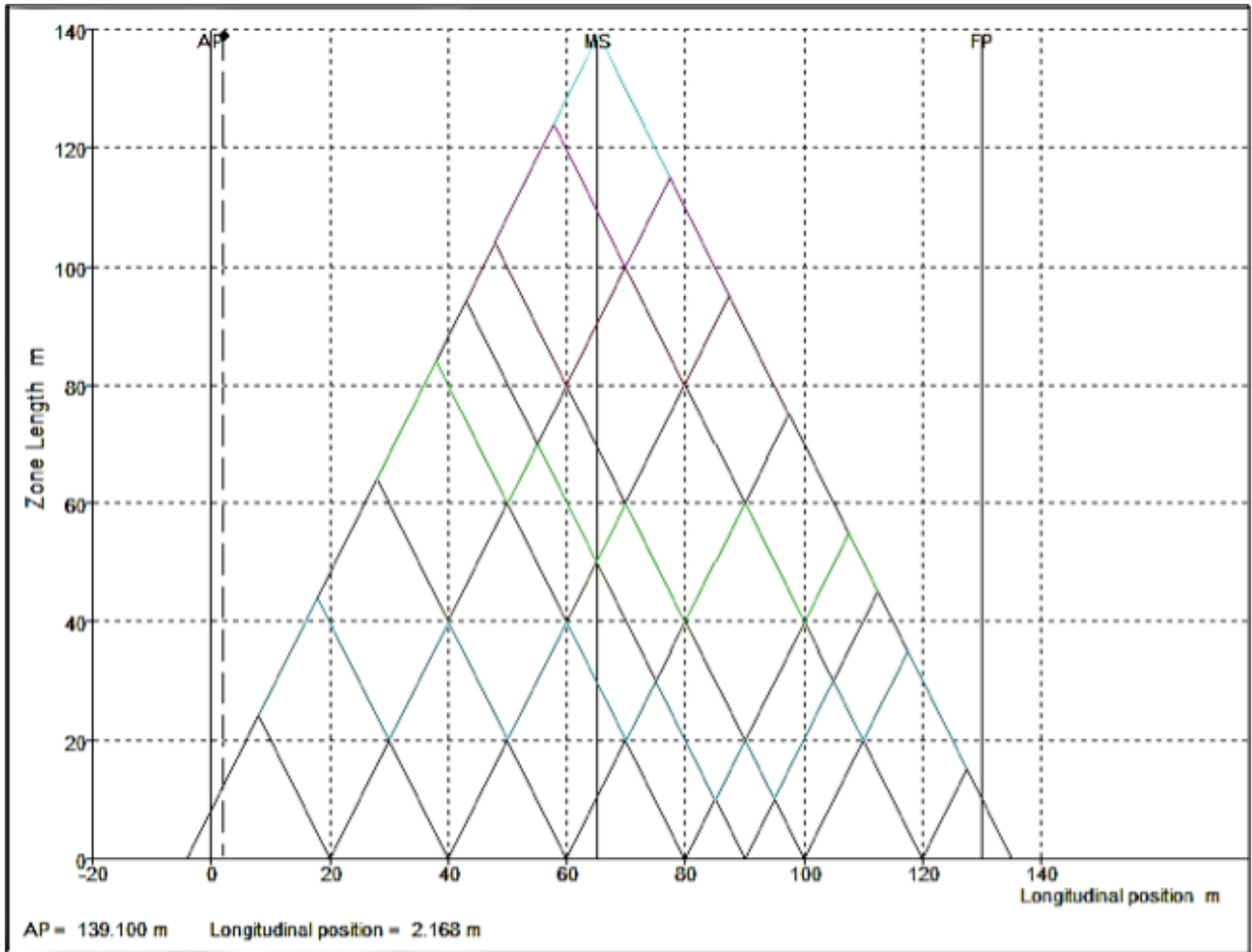
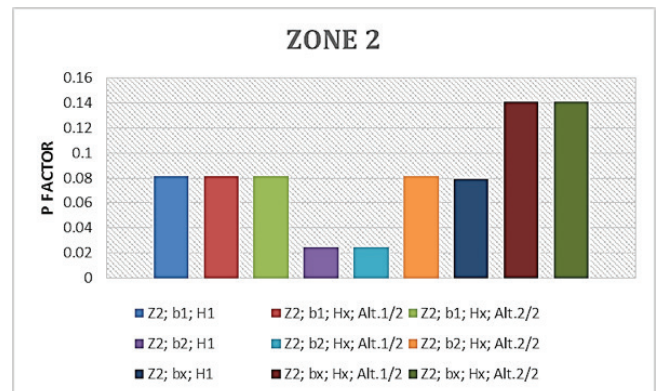
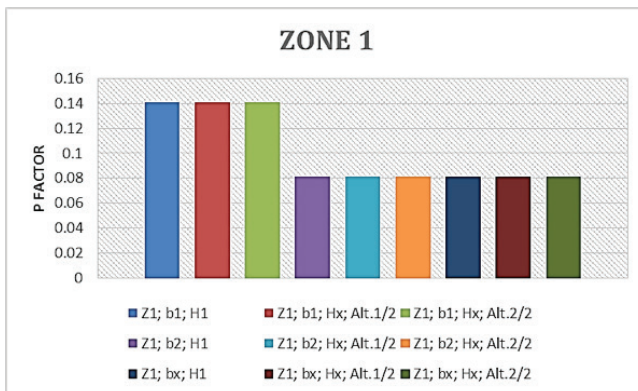


Figure 9. Probabilistic damage stability plot (source: authors).



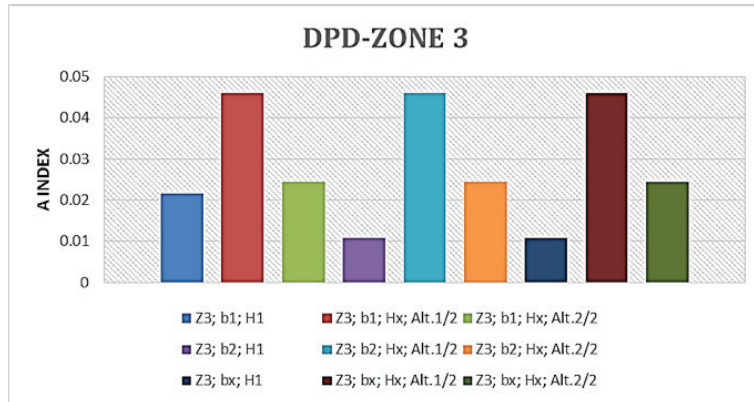
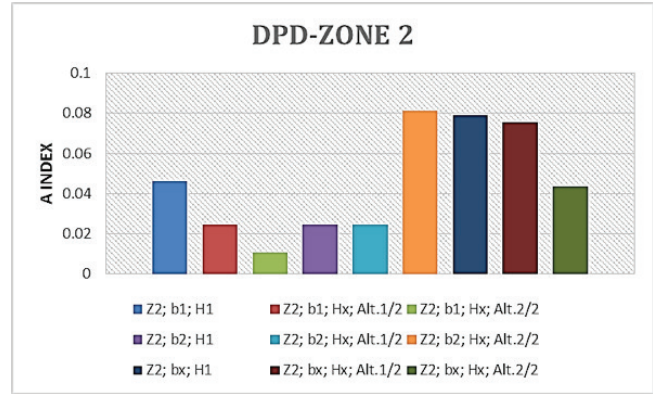
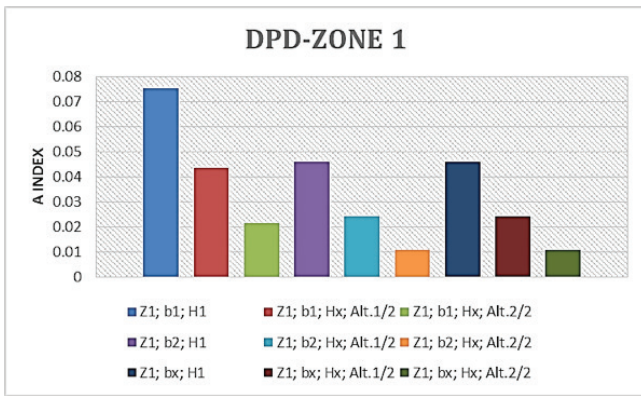
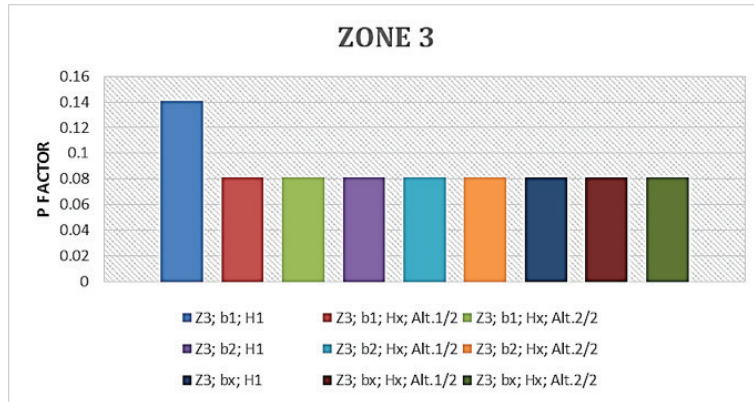
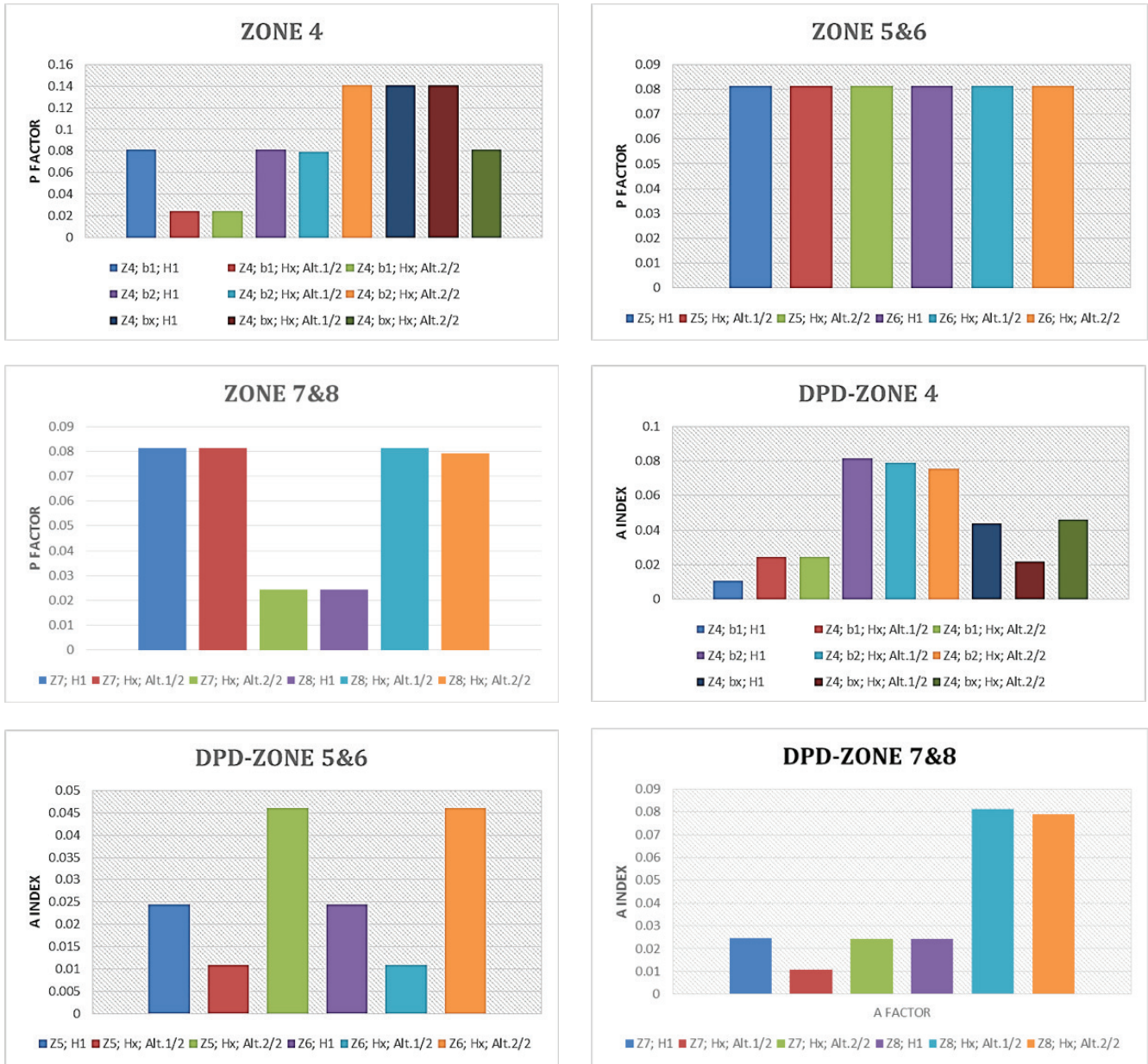


Figure 10. P-factor and Damage Potential Diagram for Zones 1 to 3 (source: authors).

The effects of damage on attained index in different zones are plotted in Figures 10,11 . In case of the drill ship in fully loaded condition, the attained index is 0.53782, which is greater than the

Required Index 0.5046. Hence, the criteria for damage stability are fulfilled according to MSC 216-82.



**Figure 11.** P-factor and Damage Potential Diagram for Zones 4 to 8 (source: authors).

### 5. MARPOL OIL OUTFLOW ANALYSIS

Slop tanks are used to store oily water mixture from cargo tank washing. There are two slop tanks, six double bottom tanks, nine oil and brine carrying tanks inside the vessel (Table

7). Marpol oil outflow analysis is done based on Regulation 12 A and Regulation 23 considering single and multiple combination of oil and brine tanks. The volume of oil outflow is measured and is shown in Figure 12(a-b). Further stability charts related to the same were developed.

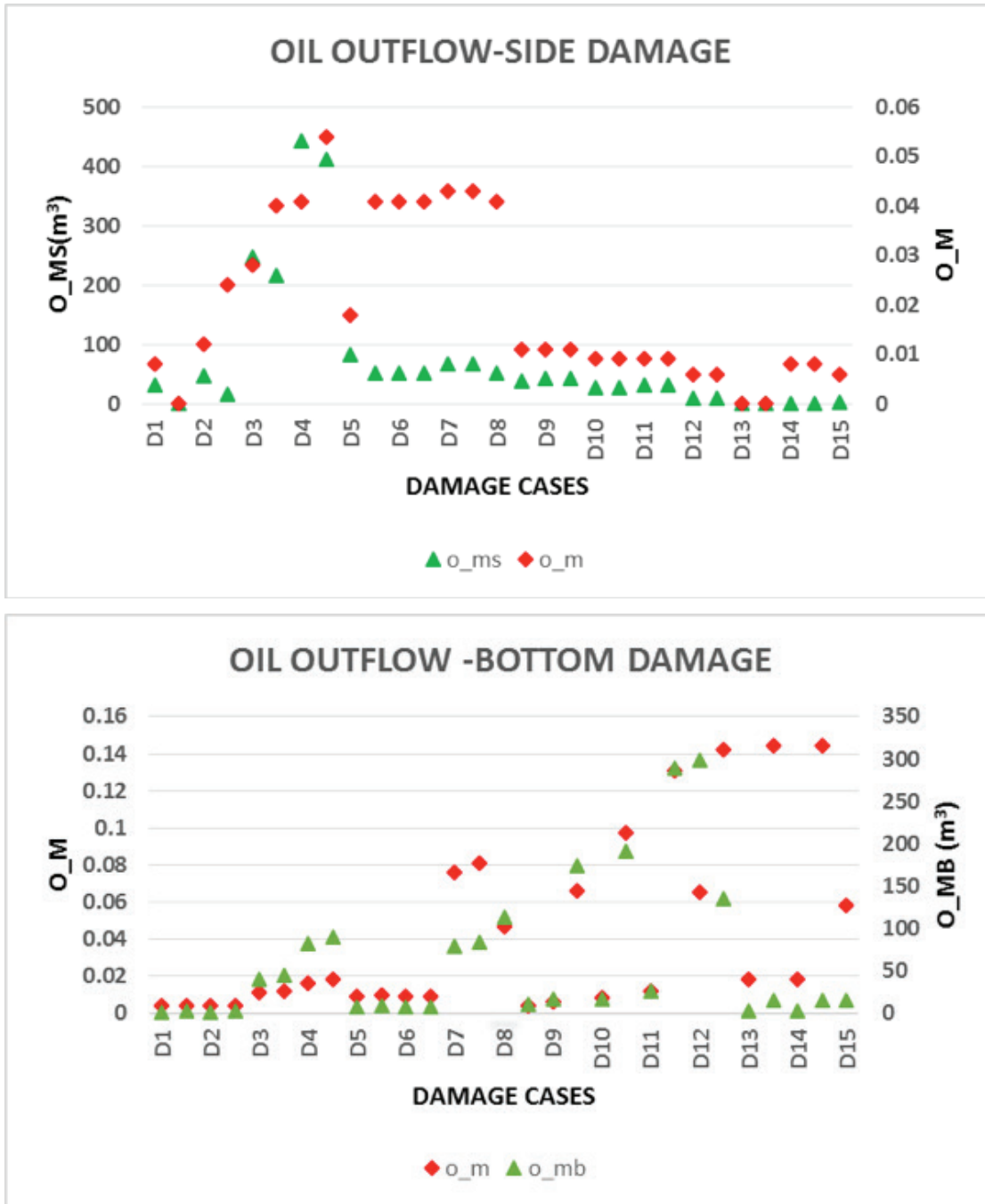


Figure 12. Oil outflow of (a) Side damage (b) Bottom damage (source: authors).

It is found from Figure 12 that mean outflow is the maximum in damage cases D3 to D8 for side damages while in the case of bottom damage, the maximum oil outflow takes place in cases D7 to D15. It is seen that damage of double bottom tanks has less

influence on oil outflow. This means that when bottom damages occur, even if double bottom tanks undergo flooding, the vessel can be stabilized. In side damage condition, oil and brine outflow begins abruptly and it becomes difficult to stabilize the vessel.

**Table 7.**

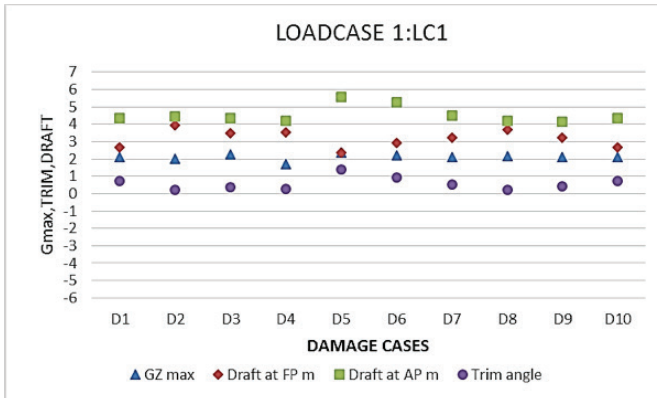
Damage cases (source: authors).

DAMAGE CASE	TANKS	1-BD	o_mb	o_m	2-SD	o_ms	o_m
D1	slop tank port	pass	1.495	0.004	pass	31.181	0.008
		pass	1.742	0.004	pass	0	0
D2	slop tank stb	pass	1.495	0.004	pass	46.154	0.012
		pass	1.742	0.004	fail	14.973	0.024
D3	oil4	pass	40.518	0.011	fail	246.814	0.028
		pass	44.985	0.012	fail	215.633	0.04
D4	oil 3	fail	82.212	0.016	fail	442.507	0.041
		pass	89.096	0.018	fail	411.326	0.054
D5	base oil	fail	7.136	0.009	fail	82.932	0.018
		pass	7.978	0.01	fail	51.751	0.041
D6	brine	pass	7.136	0.009	fail	51.916	0.041
		pass	7.136	0.009	fail	51.916	0.041
D7	brine	fail	78.36	0.076	fail	66.736	0.043
		fail	83.48	0.081	fail	66.736	0.043
D8	db12	pass	113.607	0.047	fail	51.916	0.041
		pass	10.848	0.004	pass	38.995	0.011
D9	db11	pass	16.284	0.006	pass	42.892	0.011
		pass	173.817	0.066	pass	42.892	0.011
D10	db10	pass	16.652	0.008	pass	27.121	0.009
		pass	191.249	0.097	pass	27.121	0.009
D11	db9	pass	26.033	0.012	pass	31.181	0.009
		fail	289.142	0.131	pass	31.181	0.009
D12	db8	pass	299.214	0.065	pass	8.808	0.006
		pass	134.518	0.142	pass	8.808	0.006
D13	db7	pass	1.792	0.018	pass	0	0
		fail	14.328	0.144	pass	0	0
D14	db6	fail	1.792	0.018	pass	1.153	0.008
		fail	14.328	0.144	pass	1.153	0.008
D15	db5	fail	15.623	0.058	pass	2.324	0.006

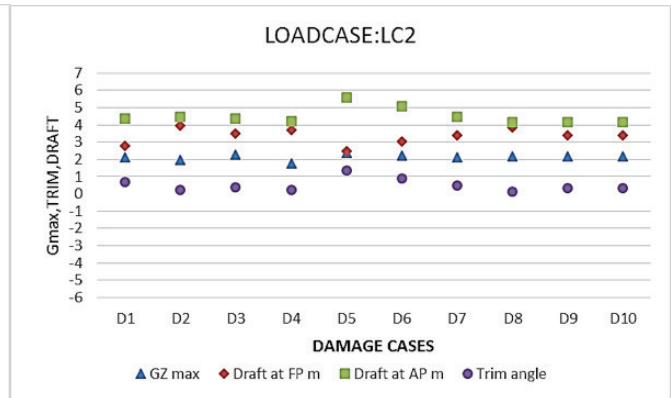
## 6. STABILITY CHARTS

Variation of GZmax of the model in damage cases for different load cases can define the behavior of the ship. As GZmax tends to zero, the righting moment to restore the rolling vessel is reduced, hence the instability. A set of results can be shown by studying draft, trim, and GZmax at the same time. Figure 13 (a)-(h) shows the variation of draft, trim, and GZmax according to damage case for each load case. These plots help to analyze the

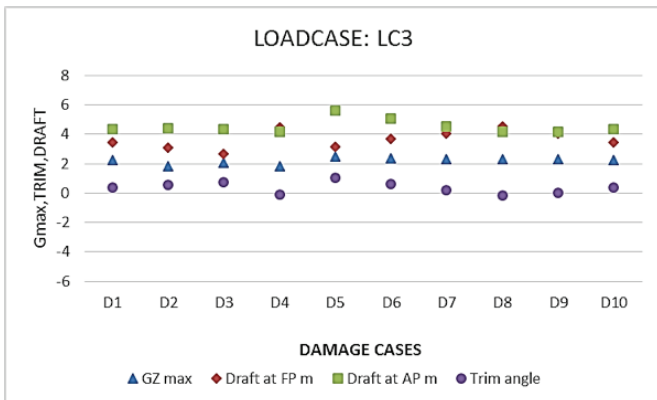
survivability of the vessel under a probable damage, according to loading of the vessel. A sudden shift of trim from positive to negative is seen in load case 4 to 8. A shift in the center of gravity is also observed due to the flooding of cargo tanks from 0 % to 40 %. Positive trim indicates that the vessel is trimmed by the stern, i.e. the draft at the stern is greater than the draft at the bow. As the load increases, the vessel is gradually trimmed by the bow for all damage cases as well as in intact condition. As the trim increases due to flooding, the vessel's serviceability is reduced.



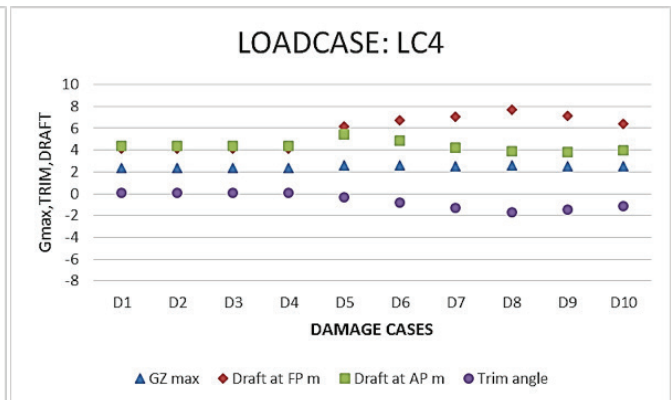
a)



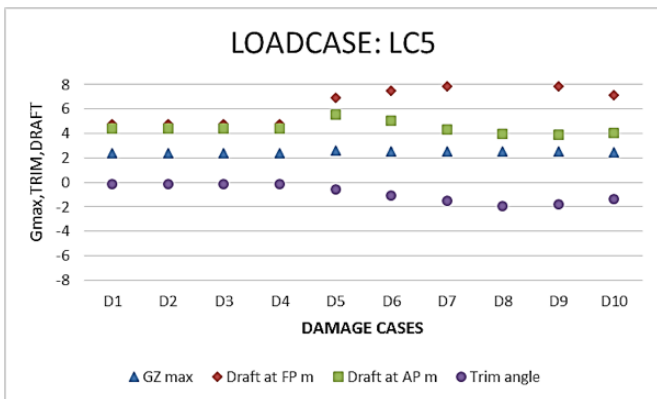
b)



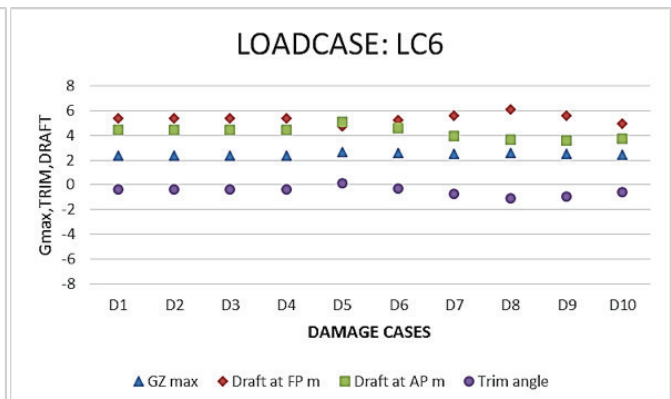
c)



d)



e)



f)



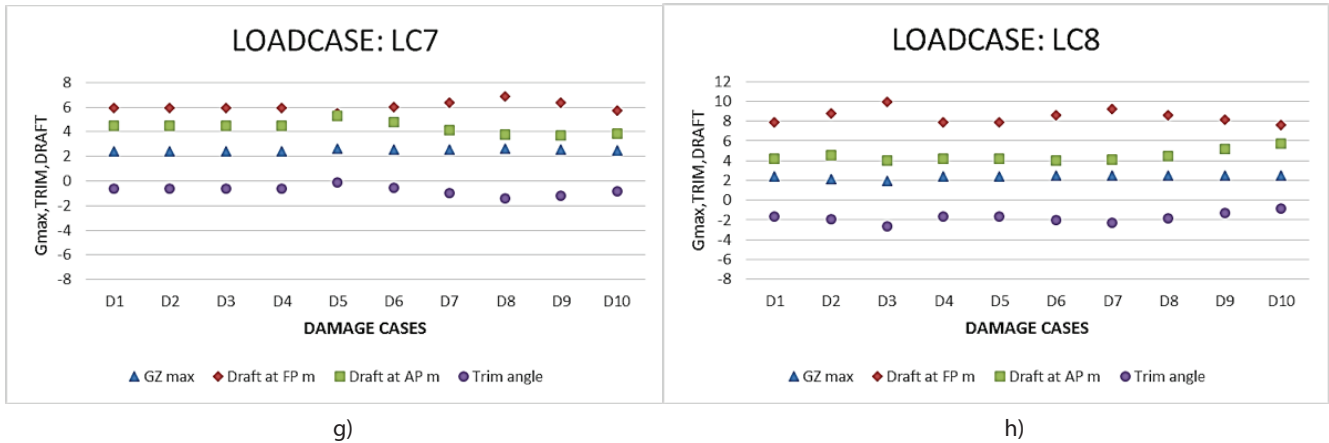


Figure 13. (a-h) Stability charts w.r.t. GZmax, trim, draft (source: authors).

## 7. CONCLUSIONS

The probabilistic damage stability analysis was done to predict the effect of tanks and compartmental arrangement on stability. The damage potential diagram showed the safety of the vessel in terms of the attained index. Oil outflow determines the stability of the vessel under damage condition. By analyzing mean oil outflow volume, we could determine stability variation based on GZ, draft and trim corresponding to the related load case and damage case. The following conclusions were obtained from the oil outflow analysis and probabilistic damage stability analysis:

1) Compartments in the trimming side are found to have greater influence on the attained index. The Damage Potential Diagram shows that the least p-factor value obtained is 0.02 and the maximum is 0.14. It is constant in zones 5 and 6. The Attained Index was obtained to a minimum of 0.01 and maximum of 0.08. There is no variation in p-factor for zones 1,3,5,6. Hence the probability of flooding is less predictable in the rest of the zones. When the Attained Index is high, there is less probability for the vessel to lose stability.

2) The maximum oil outflow under side damage condition is between 200 to 300 m<sup>3</sup>, while in case of bottom damages, it is between 300 to 400 m<sup>3</sup>. This shows that the double bottom tanks can reduce oil outflow and can stabilize the vessel. Damage cases D3 to D7 are oil and brine carrying tanks, hence side damages show greater effect on the stability variation of the vessel. In bottom damage cases, double bottom tanks D10 to D15 are greatly affected. It is clear that the double bottom tanks help to balance stability during bottom damage cases. Therefore, to improve the safety of the vessel, double bottom tanks are to be designed accurately.

3) Stability charts show a shift of trim from the positive to negative value up to 40 %. This is due to water ingress into the vessel due to damage. It was found in all the damage cases that trim occurs by the bow of the ship, while a positive trim value indicates trim by stern. As trim takes negative values, the draft of the ship in the forward end increases. The effect of load case and damage case is critical in stability analysis. In all the load cases and damage cases, GZ value balanced around a value of 2 m. The maximum trim value of 2 m is obtained, which is a limiting trim value. Beyond that value the vessel loses its stability. This shows that a slightest change in the trim can vary stability drastically.

Chances to reduce the consequences after a probable damage scenario will increase if we can predict the stability of the vessel for a set of probable damage cases. Damage stability charts and oil outflow charts will be helpful to evaluate the severity of damage and for a quick response and decision making in an early stage of flooding to represent the survivability of the vessel.

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