RISK EVALUATION IN FLOATING OFFSHORE STRUCTURES

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ABSTRACT

During a vessel's useful life it faces various changes that lead to uncertainties in determining the displacement and center of gravity. Besides upgrading work, the very operation of the platform with constant ballast and oil loading and unloading or the use of maintenance equipment can generates uncertainties related to the displacement and the center of gravity. These, therefore, are the parameters that present uncertainties inherent to the vessel's operations, taking this into account, one example of uncertainties application on the displacement and the transversal and vertical positions of the center of gravity will be presented, in the analysis of the static stability of a converted fpso tanker another question raised in this work is the deterministic treatment of certain criteria for the parameters that depends on random factors, such as the wind, currents and waves. This paper will present a probabilistic approach for the calculation of the roll angle according to resolution imo a562 (environment criteria), the two chosen criteria for this analysis were resolutions imo a167 (general criteria) and a 562 (weather criterion).

Keywords: *FPSO Stability, Probabilistic Stability, FPSO Safety*

1. INTRODUCTION

The application of probabilistic concepts is known in various technological areas with respect to safety systems, processes, people, environment and company image which apply high technology in industries where risk evaluation is an inherent part of the decision-taking process.

An important paper on the application of probabilistic concepts in the shipbuilding industry is the work of St. Denis and Pierson [Ref. 2], when the concepts were applied to the analysis of a ship's behavior at sea.

An understanding of the existence of randomized characteristic factors that influence the intact and damage static stability evaluation was, however, more recent. The deterministic approach continues to be applied in the main.

According to Caldwell [Ref. 3], most of the external and internal factors that affect ship safety against capsize present random characteristics and may be treated in a probabilistic way.

Besides the randomized characteristic factors, the other motivation for studying the application probabilistic on the stability evaluation in offshore areas is the fact that new concepts, using different geometry and sea behavior are coming into being. The use of converted ships as floating production units required adaptations for the application of stability criteria. Other concepts that are emerging will need new studies or will need to adapt the already existing stability criteria.

Another important aspect is the uncertainty in the behavior of certain parameters during the useful life of a platform. Both merchant vessels and offshore platforms suffer during their useful life various alterations that lead to uncertainties in determining the displacement and the center of gravity position. Loading and unloading operations can cause at any moment uncertainties concerning the center of gravity position and the unit displacement.

Uncertainties associated with the random variation in the environmental characteristics (wind, waves, and current) also indicate the possibility of treating the problem using probabilistic methods.

An analysis of the problems of floating unit practices, particularly for platforms, leads us to question the procedures and raise points for evaluation.

The first important aspect to be considered is the uncertainty concerning the value of the vertical center of gravity position. During the construction stage (verified with the application of the inclining test) or during the operational life of a drilling unit and/or a production unit, the vertical center of gravity position may no longer be known after a few years of operation. Upgrading work and different modifications may lead to uncontrolled weight being added to the structure, and as a consequence raise doubts as to the vertical center of gravity position. The existing solution to the problem, an inclining test, does not always present a practical and economically recommended solution. Since this aspect may represent a reduction in floating safety, the common practice has been the application of a unit penalty, not allowing any more loads to be allocated to high points. Similar aspects can be analyzed in respect of unit displacement.

The evolution of lighter platforms and the vertical center of gravity during the unit's useful life, organized in a database, is necessary to understand how these variables behave during operations over time. A clear trend that can be observed is the increase in the vertical center of gravity position and displacement. The upgrading work is generally carried out above the main deck, with the platform hull structure rarely being changed. Thus, one can say that this trend toward an elevation of the KG exists because of allocating loads above the main deck. The same is true for the increase of unit displacement.

We also can observe some deterministic values being used in the stability evaluation. The weather criteria apply a deterministic value to roll angle and this may be compared with a random ship response.

2. OBJECTIVE

During their useful life, vessels are subject to various modifications that indicate uncertainties in determining the displacement and the center of gravity. Besides upgrading work, the operation of the platform itself with the constant loading and unloading of ballast and oil or the use of maintenance equipment, can generates at a given moment, uncertainties related to displacement and center of gravity.

Another important question considered is the deterministic treatment of some parameters that depend on random factors, such as wind, current and waves. An analysis using the probabilistic approach was, therefore, carried out on the evaluation of roll angle according to the IMO A562 criteria (weather criteria).

The two criteria selected for uncertainties analysis evaluation of FPSO static stability were resolutions IMO A167 (General Criteria) and IMO A562 (Weather Criterion) . Both are criterion that were initially indicated for tankers ships and today are largely applied to FPSOs together with the existing criteria for the MODU CODE.

The IMO A167 resolution is related only to the calculation of GMt of the GZ curve (righting arm) and the area below the GZ curve. In this case, only the center of gravity and displacement will influence the criteria.

The IMO A562 resolution considers environmental parameters beyond the GZ curve. It is known that in this case, the influence of the wind, displacement and center of gravity can also be studied, but here only the roll angle will be focused on using these criteria. With the uncertainty of the roll angle being isolated, we can evaluate how this parameter influences the criteria if treated in a deterministic or probabilistic form.

3. METHODOLOGY

A mathematical model was developed that has the main hydrostatic characteristics:

KMt_ - Metacentric Height
KMt = BMt + KB
BMt = I / Vol
I = inertia of the water line
Vol = displaced volume
KB = vertical center of buoyancy

It can be observed that the KMt depends on the hull geometry (water line area, center of volume) and on the vessel condition (draft or displacement). In this way, having once assuming an uncertainty of displacement, as a consequence, the value of KMt is also uncertain.

GMt
GMt = KMt – KG
Where:
KMt = Transversal Metacentric height
KG = vertical position of center of gravity

3.1. Cross Curves

The mathematical model developed for the evaluation of static stability with a probabilistic focus was based first on the cross curves of stability (CCS) and for the selected hull using specific software.

$$KN(\Delta,\theta) = yb(\Delta,\theta)\cos(\theta) + zb(\Delta,\theta)\text{sen}(\theta) \quad (1)$$

Where:
Yb = lateral position of center of buoyancy
Zb = vertical position of center of buoyancy
Δ = displacement
θ = heel angle

3.2. Static Stability Curves

The following equation relates the righting arm GZ to the obtained value for the CCS.

$$GZ(\theta) = KN(\Delta,\theta) - KG\text{sen}(\theta) - YG\cos(\theta) \quad (2)$$

KG and YG represent, respectively, the vertical and lateral position of the floating vessel’s center of gravity on the evaluated displacement condition.

3.3. Criteria analysis

The evaluation model of static stability applying probabilistic models is based on a mathematical model, as previously described and on the existence stability criteria. Two IMO criteria used on merchant tanker ships need to be evaluated: IMO A 167 and IMO A 562. These criteria have also been applied to production floating units such as FPSOs and FSOs.

3.4. IMO A 167 – General Criterion

The IMO A 167 criterion proposes comparing the static stability curve for each loading condition with a default curve. The comparison parameters of the curves are followed related. Aspects of the initial stability and restoration capacity for high angles are in this way included as characteristics of the necessary energy to tilt the floating vessel.

The area under the GZ curve between 0º and 30º angles should not be lower than 0.055m*rad.

The area under the GZ curve between 0º and 40º angles, or between 0º and the flooding angle, in the event that this is less than 40º, should not be lower than 0.09m*rad.

The area under CEE between the 30º and 40º angles, or between 30º and the flooding angle, in the event that this is less than 40º, should not be lower than 0.03m*rad.

The righting arm corresponding to the 30º heel angle should not be less than 0.20m.

The maximum righting arm should occur at an angle of heel greater or equal to 25º.

The initial metacentric height (GMo) should not be less than 0.15m.

3.5. IMO A 562 – Weather Criteria

The weather criterion presents a different characteristic than the abovementioned IMO 167, when verifying the capacity of a ship to resist wind combined effects and the roll motion for each analyzed loading condition, according to the following procedure:

The ship is submitted to a constant wind pressure, acting perpendicularly to the center line, which results in a capsize arm (LWL).

From the angle of static equilibrium resulting (θ0) from the LWL action, it is known that the ship heels because of the wave action to the opposite board were it was found heeled because of the wind effect, until one equilibrium angle (θ1). The angle of static equilibrium (θ0) should not be higher than the lowest value between 16 or 80% of the sinking angle of the deck.

The ship is submitted to one breath of wind that results in a new capsize arm because of the breath of wind (lw2).

Under these circumstances, the area “b” should be greater or equal to the area “a”, represented in the figure below.

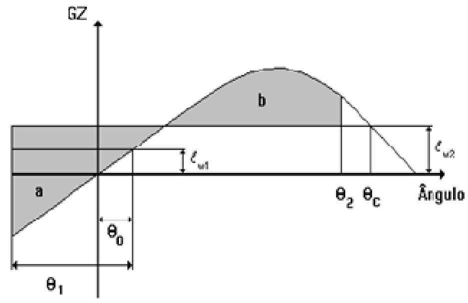


Figure 1. IMO A562 criteria.

θ_o = angle of static equilibrium because of the action of constant wind pressure.

θ_1 = roll angle for the other board side because of wave action.

θ_2 = flooding angle (qf) or 50 or qc, or the smaller one whichever is least.

θ_c = angle of the second intersection between the curve because of the breath of wind (lw2) and the GZ curve.

* The effect of free surface should be considered in each analyzed loading condition.

The capsize arms because of wind action (lw1 and lw2) present constant values for each tilt angle and must be calculated through the following expressions:

$$LW1 = \frac{P.A.Z}{\Delta} \text{ (m)}$$

$$LW2 = 1.5 \text{ } LW1 \text{ (m)}$$

Where:
P = 0.0514 t/m^2;
A = side area projected above the ship’s load line, in sq.m.;
Z = vertical distance between the area A centroid and a point located approximately at half draft, in meters; and
Δ = displacement

The roll angle (θ_1) will be calculated through the following expression:

$$\theta_1 = 109 \text{ x } k \text{ x } X1 \text{ x } X2 \text{ x } \sqrt{r \text{ x } s} \qquad (3)$$

Where:
θ_1 = roll angle, in degrees;

X1 = factor obtained from table 2 (Figure 2);
X2 = factor obtained from table 3 (Figure 2);

k = factor that presents the following values:
k = 1.0 for the ships with rounded bilge, without bilge keel or plate keel
k = 0.7 for ships with chine bilge, k should be obtained in table 3 (Figure 2) for ships with bilge keels and plate keels

$$r = 0.73 + 0.6 \times OG / d \quad (4)$$

OG = distance between the center of gravity and the floating line, in meters (positive if the center of gravity is above the floating line, and negative if it is below).
d = medium molded draft of the ship, in meters.
s = factor obtained from table 4 (Figure 2)
Nb: To use the tables, the following should be observed:
B = ship molded breadth, in meters;
d = medium molded draft, in meters;
CB = block coefficient;
Ak = total bilge keel area, side projection area of the keel plate, or the sum of these areas, in sq.m.;
L = water line length, in meters;
T = roll period, in sec, calculated through the following expression:

$$T = \frac{2 \times C \times B}{\sqrt{GM}} \quad (5)$$

Where:
C = 0.373 + 0.023 (B/d) – 0.043 (L/100);
GM = metacentric height corrected for free surface effect, in meters.

Table 1
Values of factor X1

B/d	X1
≤ 2.4	1.0
2.5	0.98
2.6	0.96
2.7	0.95
2.8	0.93
2.9	0.91
3.0	0.90
3.1	0.88
3.2	0.86
3.3	0.84
3.4	0.82
≥ 3.5	0.80

Table 2
Values of factor X2

CB	X2
≤ 0.45	0.75
0.50	0.82
0.55	0.89
0.60	0.95
0.65	0.97
≥ 0.70	1.0

Table 3
Values of factor k

$\frac{A_k \cdot 100}{L \cdot B}$	k
0	1.0
1.0	0.98
1.5	0.95
2.0	0.88
2.5	0.79
3.0	0.74
.3.5	0.72
≥ 4.0	0.70

Table 4
Values of factor s

T	s
≤ 6	0.100
7	0.098
8	0.093
12	0.065
14	0.053
16	0.044
18	0.038
≥ 20	0.035

Figure 2. Parameters for weather criteria.

3.6. Uncertainties Analysis

The uncertainties of the evaluation are concentrated in the variables: displacement, vertical (KG) and lateral (YG) position of the center of gravity and the roll angle.

The following hypotheses were considered.

a) YG (center of gravity lateral position): This variable may present uncertainties related to its own unit operation with constant loading/unloading. (Concerning the location of loaded item). The YG values can vary both to port side or starboard, both possibilities being considered. The YG variation is symmetrical related to the center line and presents the equal average to the same average as the deterministic value used in the criterion evaluation, in this case zero.

The normal distribution represents very well the YG attributed uncertainty, because this has one average (zero) and its distribution is symmetrical around this average.

b) KG (center of gravity vertical position) and displacement: Both these variables present uncertainties related to the upgrading work on the unit, in addition to its own operations.

One normal distribution will also be used for the variables in question.

This is one particular point that deserves future studies, because to get to know the type of KG behavior or displacement presented during the unit's useful life it is necessary to carry out research to create the necessary data and study the evolution of these parameters.

The upgrading work is mostly carried our at the level of the main deck or above it. So, there is a strong tendency for the vertical position of the center of gravity and the displacement to increase during the vessel's useful life. However, since there was no available data it was not possible to quantify this tendency.

The model initially considers the uncertainties on the vertical (KG) and lateral (YG) position of the center of gravity that are related to the draft and the breadth of the vessel, respectively. An initial value of 5% was considered for the KG and YG values in the expected range and related to the average. For the displacement an initial value of 2% was considered.

The values given to represent the uncertainties of YG, KG and displacement need a deeper investigation and deserve special and specific attention for each floating type, vessel age and other aspects to be considered.

With new data showing a different distribution than that considered in this study, new distributions can be easily incorporated into the probabilistic evaluation method used here.

For each evaluation, it is important to apply every uncertainty hypothesis separately and after verifying the effect of two or three combined hypotheses. The “Monte Carlo” simulation method was applied for evaluating the expected value.

3.7. Roll angle

In the IMO A562 resolution, the roll angle is calculated by a deterministic expression. However, it can be considered as a random variable and also represented by a probabilistic distribution.

The evaluation model was given a normal distribution with an equal media to the deterministic value proposed by the rule. The probabilistic analysis was made using a hypothesis that there exists a 5% probability of the obtained value being out of the variation range of 10% of the deterministic value.

The model performs a simulation for the roll angle. Instead of using the deterministic value calculated through the statistical formula suggested by the rule, the RAO - Response Amplitude Operator was used, obtained through an evaluation of movements based on the Green Function Method to obtain the regular response and application of the linearity principal to the application of the spectrum on the ocean and obtaining the spectrum response.

Given a sea state (period and wave amplitude), we can calculate the sea spectrum. The hypothesis of the platforms being operated in the Campos basin was considered, with a significant wave height of 7.8m and a peak wave period of 15.4s (centenary wave). The sea spectrum will be calculated according to a range of frequency, considering the Jonswap spectrum.

With the roll RAO, transfer function, squared multiplied by the sea spectrum, the roll spectrum response is calculated.

Vessel Spectrum Response = RAO^2 x sea spectrum

Normal distribution

For the uncertainty simulation associated with the YG, KG variables and displacement, the model proposed herein uses the normal distribution to represent the density and probability function. Nevertheless, studies deserve to be developed based on the collected experimental data to prove the appropriate distribution to the above three variables. For the KG variables and displacement, practice seems to indicate that there is a greater tendency toward an addition of weight and elevation of the center of gravity.

CASE STUDY

With the purpose of exemplifying the application of the proposed model and comparing results, a case study was elaborated for a FSPO–type unit, converted from a tanker ship of conventional geometry. The roll response of the converted FPSO was calculated with the application of the Green Function Method.

The hypothesis of the unit operating in the Campos Basin was considered and the ocean spectrum used, therefore, corresponds to Jonswap. The significant high and the peak period correspond to the centenary wave (Hs= 7.8m and Tp= 15.35s).

Having calculated the spectrum response, considering the centenary wave for the Campos Basin, it was possible to substitute the deterministic value considered in the IMO A562 rule, for the distribution found for the roll angle.

The converted FPSO used in the study presents the following values:

Table 1. Main characteristics - converted FPSO

Lpp	231.00	m
B	26.00	m
D	16.870	m
Tdesign	12.600	m
Displacement	61,406	ton
Cb	0.788	-

3.8. Geometric model

Figure 3 shows the converted FPSO sections.

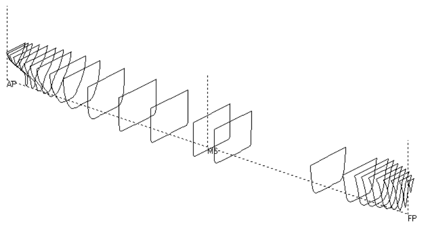


Figure 3. Converted FPSO sections.

Figure 4 presents the static stability curve for the following condition: draft = 12,6 m, displacement = 61400 ton, KG = 9.45 m, YG = 0 m, GM = 1.6m.

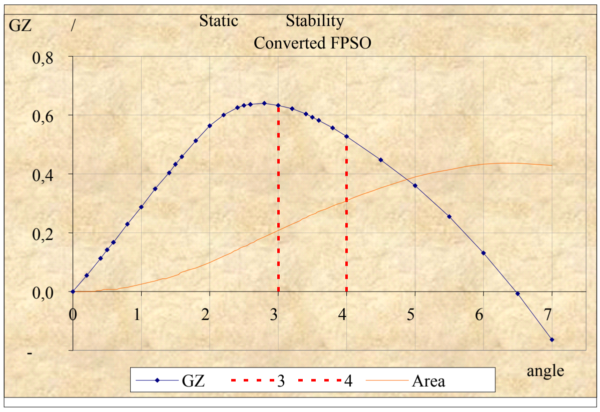


Figure 4. Converted FPSO Static Stability Curve.

3.9. Deterministic analysis of the IMO A 167 criteria

Tables 2, 3, 4 and 5 indicate the required evaluation of the stability of the condition to verify the IMO A 167 criteria.

Table 2. (IMO A 167) - converted FPSO evaluation.

Interval	area	Parameter	Status
0 - 30°	0,2078 m*rad	0,055 m*rad	OK
0 - 40°	0,3106 m*rad	0,09 m*rad	OK
30 - 40°	0,1028 m*rad	0,03 m*rad	OK

* for downfloading angles above 40°

Table 3. (IMO A 167) - converted FPSO GMo evaluation.

Metacentric Height		Parameter	Status
Gmo	1,610 m	0,15 m	OK

Table 4. (IMO A 167) - converted FPSO Maximum GZ.

GZ arm in 30°			Parameter	Status
GZ	0,633	m	GZ >= 0,20	OK
angle	30	º		

Table 5. (IMO A 167) - converted FPSO GZ at 30º evaluation.

Maximum GZ		Parameter	Status
GZ	0,638 m	angle >= 25°	OK
angle	28º		

The results indicate that all the parameters were approved in the deterministic evaluation.

Deterministic analysis of the IMO A 562 criteria

The IMO 562 criteria were also evaluated for the same load condition. Table 6 presents the area ration ratio calculation.

Table 6. Area ration (IMO A 562) - converted FPSO.

Areas	Area ration
area A = 0.160 m*rad	1.638
area B = 0.262 m*rad	

As can be observed, the area ration (B/A) is 1.638 with the criteria being approved.

Probabilistic analysis of the IMO A 167 criterion

Table 7 and the graphics shown in figures 5, 6 and 7 present the uncertainties in the center of gravity and displacement that were considered. Each one of these variables was considered separately and after a correlation was made between them.

Table 7. Uncertainties in KG, YG and Displacement.
Figure 5. KG distribution.

Center of Gravity						
		variable (m)	Average	Probability	z	σ
KG	5% x Draft =	0,630	9,45	5%	1.645	0,3830
YG	5% da meia boca =	0,650	0	5%	1.645	0,3951
Displacement						
		variable (t)	Average	Probability	z	σ
Disp.	2% x Disp. =	1.228	61.406	5%	1.645	747

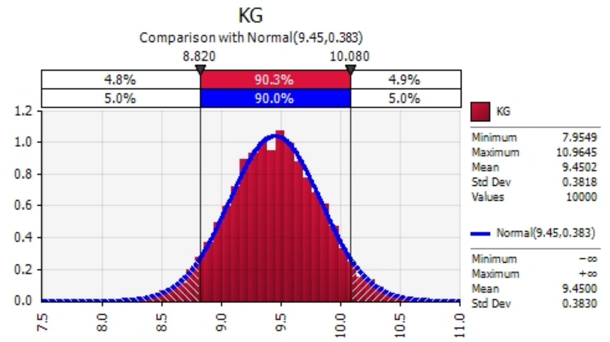
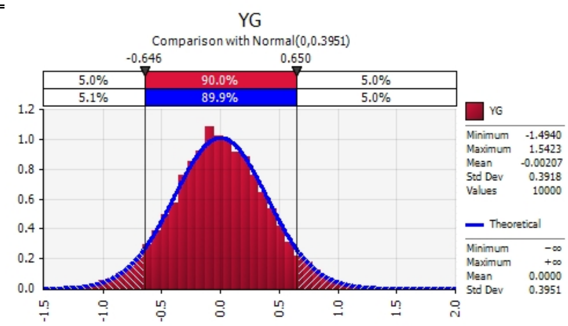
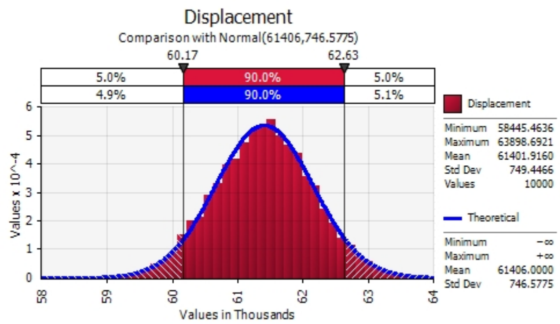


Figure 6. YG distribution.
Figure 7. Displacement distribution.





Tables 8, 9 and 10 present the results according to the IMO 167 criterion, for the isolated uncertainties of the variables KG, YG and displacement.

Considering the uncertainty of KG, the angle of maximum GZ has an approximate 24% probability of being greater than 25°, above the value recommended by the rule.

Table 8. KG (9.45; 0.383).

Table 9 below shows that the isolated YG

INPUT: KG (μ=9,45 ; σ=0,383)					
Name	Min	Mean	Max	p1	x1
Area: 0° - 30°	0,01449	0,20801	0,41147	0,14%	0,055
Area: 0° - 40°	-0,02691	0,31103	0,66632	0,70%	0,09
Area: 30° - 40°	-0,04140	0,10302	0,25485	2,73%	0,03
GZ (30°)	-0,08871	0,63359	1,39296	1,19%	0,2
Angle of Maximum GZ	20	27,8528	50	24,39%	25
GMt	0,16724	1,61183	3,13058	0,00%	0,15

uncertainty causes great impact in the areas below the GZ curve and the value of the righting arm at 30°. These parameters have considerable probabilities of being below the limit recommended by the rule. The angle where the maximum GZ occurs was also quite influenced, although it didn't present concerning related to the rule criterion.

Table 9. YG (0.00; 0.3951) IMO A167.

INPUT: YG (μ=0,00 ; σ=0,3951)					
Name	Min	Mean	Max	p1	x1
Area: 0° - 30°	-0,66852	0,05024	0,20775	43,82%	0,055
Area: 0° - 40°	-0,81593	0,10809	0,31059	38,32%	0,09
Area: 30° - 40°	-0,14741	0,05785	0,10283	19,87%	0,03
GZ (30°)	-0,88524	0,35979	0,63265	20,58%	0,2
Angle of Maximum GZ	28	29,1006	60	0,00%	25
GMt	1,61	1,61	1,61	0,00%	0,15

The uncertainty considered for the displacement caused less impact than the KG and YG uncertainties, as can be seen in Table 10.

Table 10. Displacement (61406; 747) _ IMO A167.

INPUT: Displacement (μ=61406 ; σ=746,5775)					
Name	Min	Mean	Max	p1	x1
Area: 0° - 30°	0,20275	0,20767	0,21014	0,00%	0,055
Area: 0° - 40°	0,28575	0,31044	0,33038	0,00%	0,09
Area: 30° - 40°	0,08300	0,10277	0,12023	0,00%	0,03
GZ (30°)	0,55217	0,63249	0,70676	0,00%	0,2
Angle of Maximum GZ	24,00000	27,34700	30,00000	1,59%	25
GMt	1,50222	1,61119	1,74405	0,00%	0,15

Tables 11, 12 and 13 present the result for the IMO A167 criterion, with combinations of two variables with uncertainty: KG, YG and Displacement.

When KG and YG uncertainty were considered, the probabilities obtained were very high, with the exception of GMt

Table 11. KG (9.45; 0.38) + YG (0; 0.40) IMO A167.

INPUT: KG (μ=9,45 ; σ=0,383), YG (μ=0,00 ; σ=0,3951)					
Name	Min	Mean	Max	p1	x1
Area: 0° - 30°	-0,61845	0,05217	0,36017	45,34%	0,055
Area: 0° - 40°	-0,73444	0,11123	0,58322	40,66%	0,09
Area: 30° - 40°	-0,16579	0,05906	0,22305	26,99%	0,03
GZ (30°)	-0,89023	0,36598	1,22962	25,91%	0,2
Angle of Maximum GZ	20,00000	29,77000	65,00000	14,16%	25
GMt	0,13638	1,62058	2,94319	0,02%	0,15

Combining KG and displacement uncertainties, the most critical result was presented at an angle where the maximum GZ occurs, with a 25% probability of criterion failure. It should be noted that when considering the same uncertainties isolated for KG and displacement, in both cases, the maximum GZ angle also appeared as the most critical parameter.

Table 12. KG (9.45; 0.38) + Displacement (61406; 746) _ IMO A167.

INPUT: KG (μ=9,45 ; σ=0,383), Displacement (μ=61406 ; σ=746,5775)					
Name	Min	Mean	Max	p1	x1
Area: 0° - 30°	0,01681	0,20726	0,39811	0,11%	0,055
Area: 0° - 40°	-0,02849	0,30980	0,64648	0,61%	0,09
Area: 30° - 40°	-0,04531	0,10254	0,24838	2,74%	0,03
GZ (30°)	-0,10315	0,63127	1,35770	1,08%	0,2
Angle of Maximum GZ	20,00000	27,85150	45,00000	25,41%	25
GMt	0,24023	1,60745	3,03363	0,00%	0,15

When considering the uncertainties for YG and displacement at the same time, the criteria related to the area below the GZ curve and the righting arm at 30° presented probabilities of criterion failure between 19% and 43%.

Table 13. YG (0; 0.40) + Displacement (61406;746) _ IMO A167.

INPUT: YG (μ=0,00 ; σ=0,3951), Displacement (μ=61406 ; σ=746,5775)					
Name	Min	Mean	Max	p1	x1
Area: 0° - 30°	-0,55931	0,05258	0,20918	43,05%	0,055
Area: 0° - 40°	-0,67193	0,11117	0,32335	37,77%	0,09
Area: 30° - 40°	-0,11262	0,05859	0,11625	19,46%	0,03
GZ (30°)	-0,68097	0,36431	0,68860	20,43%	0,2
Angle of Maximum GZ	24,00000	29,07580	55,00000	0,33%	25
GMt	1,46461	1,61045	1,73472	0,00%	0,15

Table 14 presents the results for the IMO A167 criterion with the combination of three variables with uncertainty, KG, YG and displacement.

Table 14. KG (9,45;0.38) + YG (0;0.40) + Displacement (61406;746,5775)_IMO A167.

INPUT: KG (μ=9,45 ; σ=0,383), YG (μ=0,00 ; σ=0,3951), Displacement (μ=61406 ; σ=746,5775)					
Name	Min	Mean	Max	p1	x1
Area: 0° - 30°	-0,63367	0,04842	0,37890	46,21%	0,055
Area: 0° - 40°	-0,77959	0,10580	0,62162	42,09%	0,09
Area: 30° - 40°	-0,17171	0,05738	0,24272	28,72%	0,03
GZ (30°)	-0,93780	0,35702	1,32403	27,26%	0,2
Angle of Maximum GZ	20,00000	29,73220	65,00000	16,05%	25
GMt	0,08810	1,61097	3,05369	0,01%	0,15

Analyzing the result above, one can notice a big influence of YG variation on the criteria related to the areas above the GZ curve and the righting arm at 30º.

3.10. Probabilistic analysis of the IMO A 562 criterion

The graphic in figure 8 represents the converted FPSO roll motion RAO for several angles of azimuth. Only the results related to the 90° angle will be considered in this work. While the graphic in figure 9 shows the response spectrum for the roll motion.

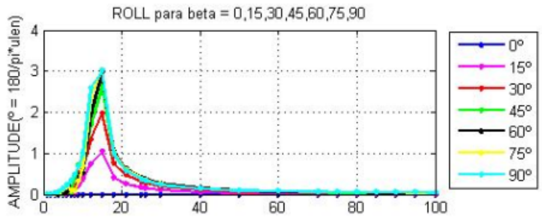


Figure 8. Converted FPSO roll RAO.

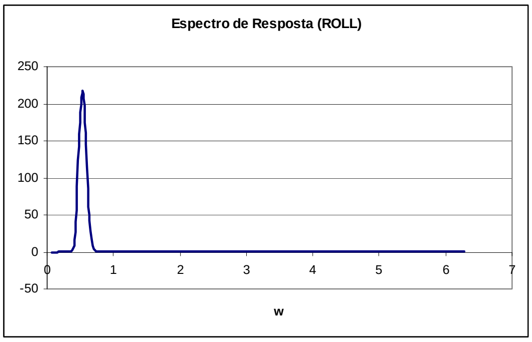


Figure 9. Converted FPSO Roll Response spectrum.

Table 15 and the graphic in figure 10 present the uncertainty considered in the roll angle with normal distribution. The average considered is equal to the value presented in the deterministic analysis (24.63°).

It should be noted that the probability to exceed the considered variation (an average of around10%) is 5%. This is the same as saying that in 90% of occurrences, values within the estimated variation range are found.

Table 15. Roll distribution (Average 24.6°).

Roll Angle				
10% of Deterministic Value = 2.46	Average	Probability	Z	Standard Deviation
	24.6	5%	1.64	1.497

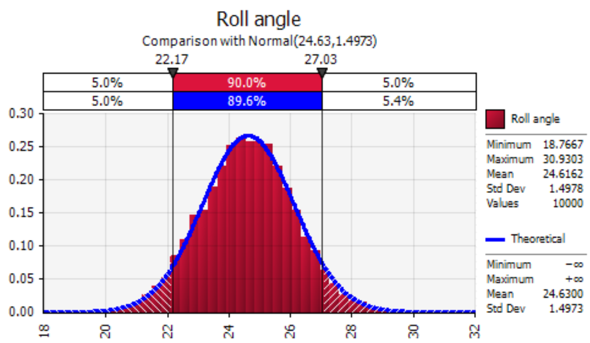


Figure 10. Roll distribution (Average 24.6°).

In table 16, one can notice that even with the considered distribution in the roll angle the probability of areas ration to be less than 1 is null.

Table 16. Roll Angle (24.6; 1.497).

Roll Angle (μ=24,63 ; σ=1,4973),					
Name	Min	Mean	Max	p1	x1
area A	0,10077	0,16004	0,23159		
area B	0,26191	0,26191	0,26191		
Areas Ratio	1,13093	1,65719	2,59900	0,00%	1,000

In spite of the failure probability of this criterion being null, the variation of the roll angle affected significantly the areas ration, as can be seen in the table above.

Another possibility of distribution was considered in this study of the roll angle: the response spectrum was calculated by the Wamit program, the significant roll amplitude was estimated and the mean normal distribution was replaced by this value.

Table 17 and Figure 11 present the characteristics of a new distribution given to the roll angle:

Table 17. Roll distribution (Average 10.5º).

Roll Angle (2)						
Roll Angle (2)		variable	Average	Probability	z	σ
	10% x deterministic =	1,05	10,51	5%	1,645	0,6389

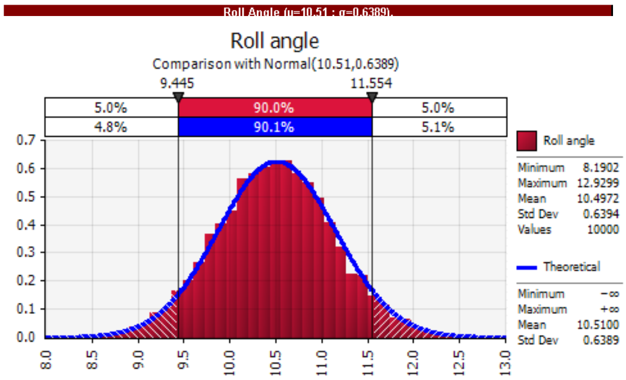


Figure 11. Roll distribution (Average 10,51º).

It should be noted in table 18 that this variation of roll angle did not generate failure probability in the criterion of the areas ration. However, once again, one can notice that this variation is quite influential on the areas ration.

Table 18. Roll Angle (10.51; 0.639).

Roll Angle (μ=10,51 ; σ=0,6389),					
Name	Min	Mean	Max	p1	x1
area A	0,02011	0,03186	0,04648		
area B	0,26191	0,26191	0,26191		
Areas Ratio	5,63531	8,32903	13,02503	0,00%	1,000

The results above indicate the importance of studying the probabilistic approach for variables of random characteristics, such as the roll angle. For the cases presented here, the results showed null failure probability for the criterion, even with the distributions considered. However, it is worth stressing that, when a distribution closer to what is real was considered, with the average being calculated in function of the wave spectrum of the Campos Basin and the converted FPSO RAO, the areas ration increased significantly. This comparison shows that, depending on the ocean and the vessel, the consideration made by the rule can be too severe.

The following graphic in figure 12 presents the two values considered for the average roll angle. One can notice that when considering the value calculated by the rule expression, the A area of the IMO A 562 criterion is greater than the same area for the roll angle calculated on the basis of the response spectrum.

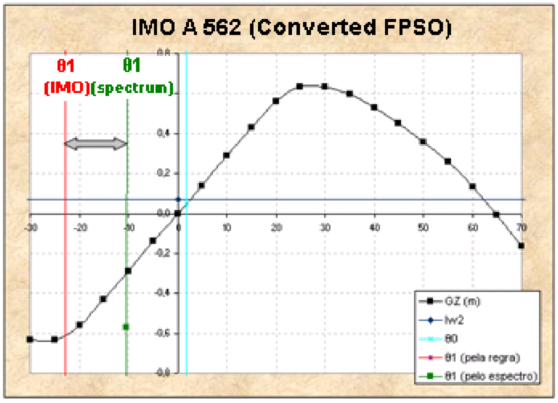


Figure 12. Roll angle variation.

4. SENSITIVITY ANALYSIS

The sensitivity analysis was carried out for all the parameters of the IMO A167 criterion, considering the same variations already presented for the KG, YG and displacement variables.

The parameters related to the areas below the GZ curve and the righting arm at the 30º angle are more affected by the YG variable. The KG variable influences less, although it is still significant. And the displacement presented little influence. The graphic shown in Figure 13 presents the result of the analysis for the area between 0° and 30°.

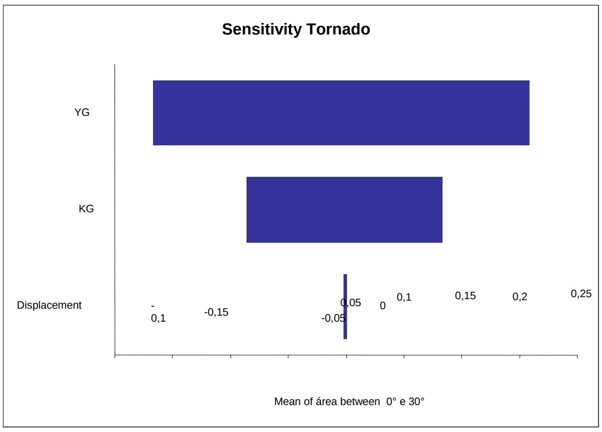


Figure 13. Sensitivity Analysis - Area between 0° and 30°.

The maximum GZ angle is mainly affected by the KG variable. The YG and displacement variables showed less influence under this parameter, as can be seen in Figure 14:

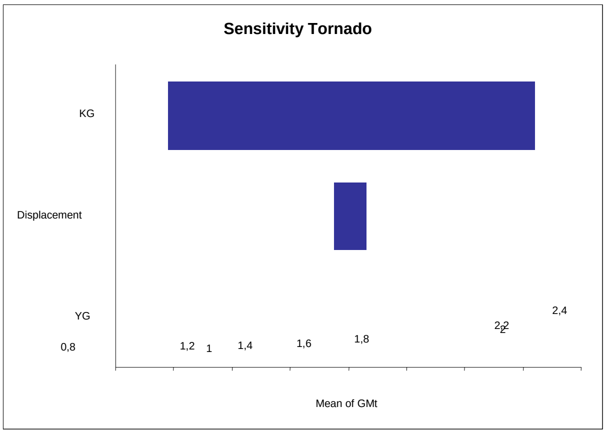


Figure 14. Sensitivity Analysis - Angle of Maximum GZ.

The GMt calculation depends only on KG and KMt, the later being the displacement function. As expected, in the sensitivity analysis of the GMt parameter, the YG variable did not have any influence. Between the KG variables and displacement, the greatest influence was the vertical position of the center of gravity.

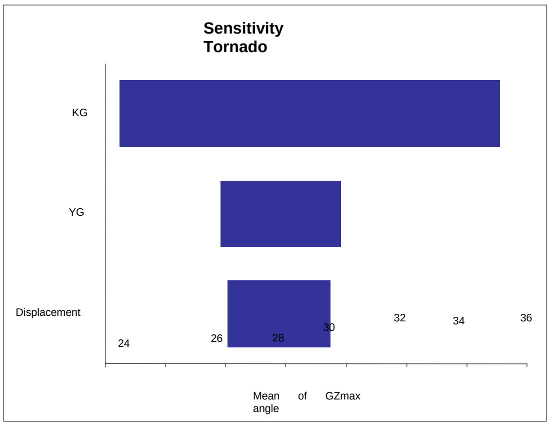


Figure 15. Sensitivity Analysis – GMt.

5. CONCLUSIONS

The study presented allows a more detailed analysis of the application of the stability criteria existing today for merchant ships and which can be applied to that have been presented on floating production systems. Certain conclusions can be made:

1 – The proposed method indicates a possibility for the treatment of uncertainties in the evaluation of intact static stability of floating systems with the use of the criteria existing today.

2 – It is important to evaluate the risk associated when considering certain deterministic parameters in the application of the criteria. Operational practice has shown that the vertical position of the gravity center as its own displacement have undergone important variations during the useful life of drilling and oil production units.

4 - On the application, including the randomness of the roll motion, considering a more elaborate calculation of the average value and the frequency distribution, we can use the same criterion and consider the effects of uncertainties associated with the wave spectrum.

5 – Studies are still needed so as to evaluate better the variations in the displacement and the position of the center of gravity. The elaboration and the access to a data bank of the behavior of these characteristics during the useful life of a vessel can indicate one distribution and parameters more appropriate than the ones used here.

6. ACKNOWLEDGMENTS

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