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Offshore Inclining Test

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ABSTRACT

The stability test that includes the Lightweight Survey and the Inclining Experiment is the traditional way to determine the light ship and the centre of gravity of a vessel. It is normally conducted in sheltered waters in calm weather conditions and usually requires the vessel to be taken out of service to prepare for and to conduct the test. The motivation to this work began with the application of semisubmersible units (SS) in the oil and gas production activity. These units are planned and installed for long term operation, typically 25 years. Throughout their operational life a SS unit usually requires modifications, basically due to the natural reservoir changes or due to safety or regulatory issues that lead to changes in lightweight. The option of demobilizing a Floating Production System (FPS) to calm waters to execute the Inclining Experiment is neither economical nor technically feasible, due to the impacts to the mooring system, risers system and reservoir management plus the associated costs to tow the unit close to coastal areas. Bearing in mind this scenario, an alternative method to carry out the test with the unit in operation offshore with wind, waves and current and under the influence of the mooring lines and risers could be applied as previously proposed. This paper addresses the main technical issues to be overcome in order to validate and produce reliable results in these new conditions.

Keywords: *inclining test, IMO MODU Code, Centre of Gravity*

1. INTRODUCTION

The stability test that includes the Lightweight Survey and the Inclining Experiment is the traditional way to determine the light ship and the centre of gravity of a vessel. The stability test is required for most vessels upon their completion and is the worldwide recommended and approved method to determine the light vessel characteristics and the Centre of Gravity coordinates. It is normally conducted in sheltered waters in calm weather conditions and usually requires the vessel to be taken out of service to prepare for and conduct the test [1], [2].

The motivation to this work began with the application of semisubmersible units (SS) in the production activity. These units are planned and installed for long term operation, typically 25 years. Throughout their operational life a SS unit requires modifications, basically due to the natural reservoir changes or due to safety or regulatory issues. These changes lead to adjustments in the process plant, typically with the introduction of new equipment to carry out the new processing activities. Safety and legal requirements can also pose the necessity of additional equipment and its structural support.

Once the weight control procedures may not be effective the regulatory bodies and classification societies impose the execution of a new Inclining Test every time the summation of the weight changes surpasses a certain limit.

The option of demobilizing a FPS to calm waters is neither economical nor technically feasible, due to the impacts to the mooring system, risers system and reservoir management plus the associated costs to tow the unit close to the coast. Therefore, instead of the Inclining Test, the classification societies opt to apply penalties to the units, prescribing VCG values above the ones calculated in the weight control reports. Bearing in mind this scenario, this paper evaluates an alternative method to carry out the Inclining Test with the unit in operation offshore, with wind, waves and current and under the influence of the mooring lines and risers, as described in previous studies addressing the same problem [3], [4], [5], [6] and [7].

In order to validate the method an inclining test of a moored semi-submersible with risers and under the action of waves has been carried out in Laboceano ocean basin. The results were analysed and discussed and the error margins were also determined and compared with the traditional approach. After this stage the procedure was applied to a full scale unit of the Petrobras fleet. Ballast transfer was executed to incline the unit and the wave induced motions recorded through a MRU (Motion Recording Unit) equipment. The mooring and risers were carefully modelled in numerical simulation programs and included in the VCG determination. After these two phases, the paper presents the main conclusions and validation of this alternative procedure using only proven measuring equipment and numerical methods to calculate the Centre of Gravity coordinates.

2. SEMISUBMERSIBLE UNIT

Figure 1 – Typical SS production unit

The hull selected to perform the model test is a typical semi-submersible platform. The main characteristics of this unit are shown below:

Table 1 – Platform Main Dimensions

Particular	Value
Length Over All (m)	116.0
Beam (m)	72.0
Depth Main Deck (m)	41.6
Pontoon Width	13.5
Deck length	77.0
Deck width	63.3
Draft (m)	23.47
Displacement (t)	33562

3. MODEL TESTS

3.1 Description

The model tests were conducted at LABOCEANO’s ocean basin from UFRJ in Brazil from August to September 2013 with a typical SS to evaluate the proposed procedures to carry out the inclining tests offshore [8].

The main objective of the tests was to evaluate a procedure to perform inclining tests with a moored SS with risers installed at site in the presence of waves and wind mean load. The results from the inclining tests would then be compared with model dry calibration and with still water conventional tests.

A SS hull was constructed at scale of 1:50 and due to basin dimensions limitations, and in order to keep a simplified test, a truncated and simplified mooring and risers system was designed to mimic the influence of such systems on the platform behaviour. The measurements included platform motions, line tensions, local wave heights and waves run-up at four columns.

The structure was firstly tested free floating and then the mooring and risers system was installed. The moored structure was then tested in still water (different draft of free floating condition), and finally wave tests were performed. A set of regular and irregular waves were simulated, and inclining tests in waves were performed using weights in different positions at the deck. A test matrix was defined in a way that the inclining tests in waves could be compared to static inclining tests so that the mean equilibrium angles could be compared. Also, the main parameter to be measured – the vertical centre of gravity, should be well known for both cases. This last requirement was fulfilled by measuring the KG of the instrumented and ballasted model on dry condition before and after the tests.

The environmental conditions chosen for the tests included both regular and irregular waves, with different heights and periods, and two directions (waves from stern and quarter stern).

For the procedure itself, the model deck was prepared with high precision machining so that the weight used to impose the known inclining moment would be precisely positioned at required distances to minimize uncertainty on the results.

On the instrumentation side, a high accuracy visual tracking system was used to measure the model 6 DOF motions, in order to obtain high quality measurements in waves. As additional measurements, the relative wave heights were also measured at four columns, in order to simulate the measured draft at draft marks. Mooring lines and risers dynamic tensions were also measured, and so were the wave heights at certain points at the basin. The water depth in full scale is 600 m.

3.2 Model Calibration

Figure 2 illustrates the model used in Laboceano basin:

Figure 2 – SS Model in Laboceano Basin

The results at dry "LEVE" condition obtained are summarized below:

Table 2 – Platform Mass Data

	Model Scale		Prototype scale	
Mass	233.450	kg	30091.329	ton
XG	0	mm	0	
YG	0	mm	0	m
ZG	428	mm	21.4	m
IXX	8.90E+07	kg.mm2	2.87E+07	ton.m2
IYY	8.86E+07	kg.mm2	2.86E+07	ton.m2
IZZ	1.05E+08	kg.mm2	3.38E+07	ton.m2

The mass of the model considers the inclining weight (2.32 kg in model scale), positioned at the center of the deck X=0mm, Y=0mm, Z=871mm. The weight and center of gravity coordinates of “LEVE” or LIGHT condition without inclining test mass are shown below as these values will be used later in the proposed procedures to determine the KG.

Table 3 – Mass measured in Dry Conditions

	Prototype scale (light without inclining test mass)	
Mass	29836.11	ton
XG	0	m
YG	0	m
ZG	21.182	m

3.3 Mooring and Riser System Design

A mooring system was designed and constructed using eight (8) lines. Also, six (6) risers representing groups were designed and constructed to simulate the influence of such lines.

Figure 3 – Mooring and Risers Model

3.4 Environmental Conditions

Both regular (4) and irregular (4) waves have been tested using the JONSWAP spectrum.

Table 4 – Model Test Wave Data

WAVEFILE	SPEC	HEIGTH (m)	PERIOD (s)	DIR
W01_10101	-	1.0	8.0	180
W01_102010	-	1.5	8.0	180
W01_10301	REG	2.0	9.0	180
W01_20100	REG	1.5	8.0	225
W02_10102	JS	1.0	8.0	180
W02_10201	JS	1.5	8.0	180
W02_10304	JS	2.0	9.0	180
W02_20100	JS	1.5	8.0	225

3.5 Test Matrix

All tests were grouped into five (5) batteries. The following groups describe the naming convention.

GROUP PT100 – PRE-TESTS - "LEVE" CONDITION, FREE FLOATING: Model freely floating (no mooring, no risers) was tested for equilibrium and inclining test measurements.

GROUP PT120 – PRE-TESTS - "LEVE" CONDITION, MOORED W RISERS: Model moored with risers installed

GROUP T120 – "LEVE" CONDITION, MOORED W RISERS: Same as Group PT120

In all groups the Inclining Weight was placed in 8 different positions from Starboard to Portside in order to incline the platform.

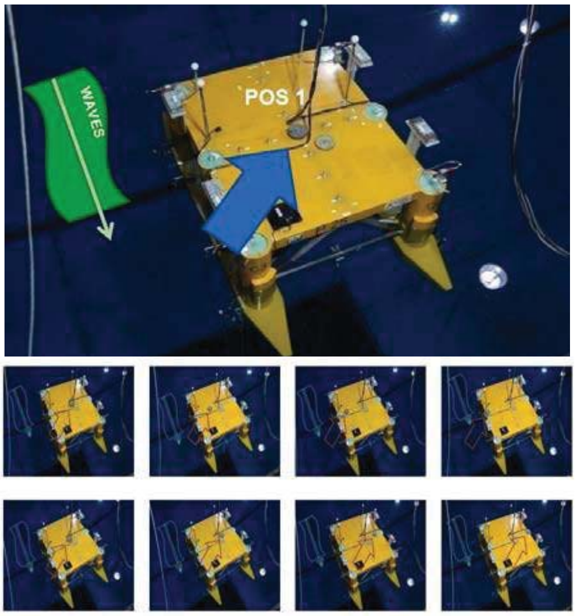

Figure 4 – Test Weight Positions

3.6 Model Test Results

As a sample of the model test results the irregular waves roll motion time trace, mean values and standard deviation for all groups and for the 8 Test Weight positions are shown in Figures 5, 6 and 7:

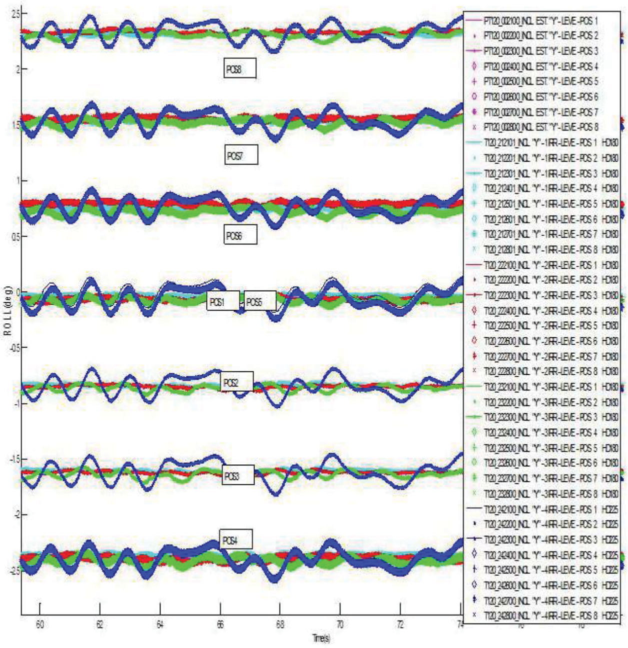

Figure 5 Time traces of roll motion for all irregular waves and test weight positions

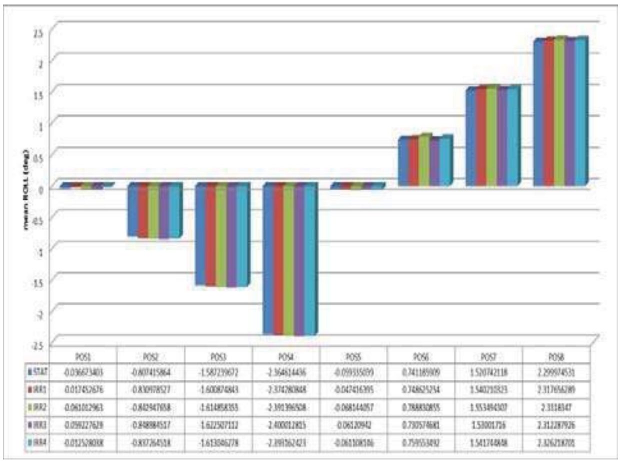

Figure 6 Mean Roll angle for all irregular waves and test weight positions

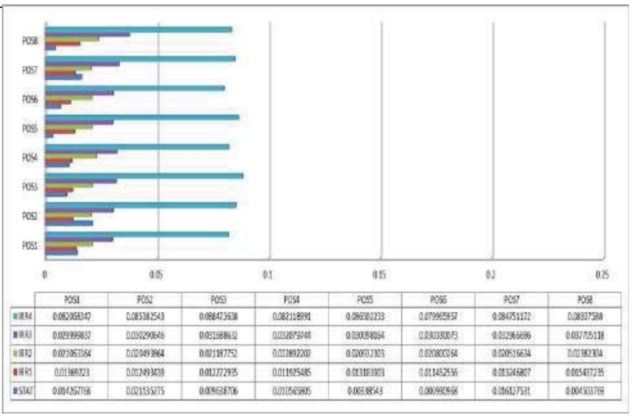

Figure 7 – Standard Deviation of Roll angle for all irregular waves and test weight positions

4. KG CALCULATION PROCEDURE

In order to determine the KG based on the model test results, two approaches were selected:

1- Uncoupled Direct Method procedure

2- Coupled Iterative Method

Both procedures will use the data generated in the model scale inclining experiment carried out at LabOceano. However to use the model test data it is first necessary to generate numerical models and to calibrated them to obtain the same behaviour as the physical models employed in LabOceano. Two models will be required: the hydrostatic one and the mooring and risers.

4.1 Numerical Hydrostatic Model

The hydrostatic data model was prepared using the in-house hydrostatic and stability program SSTAB, as can be seen below:

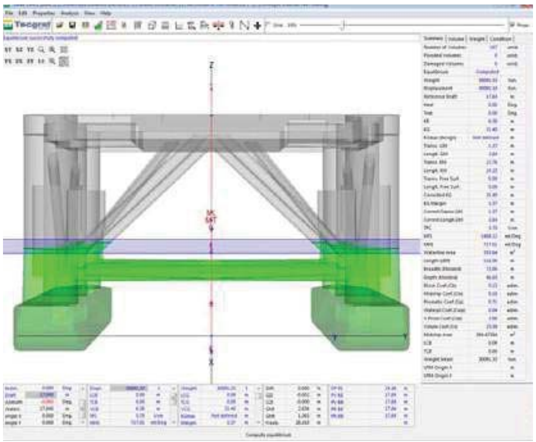

Figure 8 – SSTAB Numerical Model

Table 5 – Test Conditions

#	Cond.	Displac. (t)	Heel (Deg.)	Trim (Deg.)	Draft (m)	KG (m)	KMt (m)	GMt (m)
1	LIGHT	30087.46	0.0	0.0	17.85	21.40	22.76	1.32
2	LIGHT M-R LOADS	34029.00	0.0	0.0	24.87	19.66	22.29	2.63
3	LIGHT M-R CAT	34028.98	0.0	0.0	24.87	19.66	22.29	2.63

LIGHT condition refers to the platform model, plus ballasts, plus the inclining weight, plus the required instrumentation.

LIGHT M-R LOADS: This condition is the same as the LIGHT condition plus the addition of the vertical component of the mooring and risers tensions as point loads.

LIGHT M-R CAT: This condition adds the mooring and risers tensions calculated using a catenary model included in the SSTAB program.

With this model one can calculate the displacement and KM in the mean draft obtained in the model test.

4.2 Mooring and Riser Model

The mooring and risers system was modelled in DYNASIM program using eight (8) mooring lines and six (6) riser representative groups. The mooring lines in DYNASIM were modelled as close as possible to the LabOceano configuration, using segments of steel wire, steel chains, floaters and stainless steel springs.

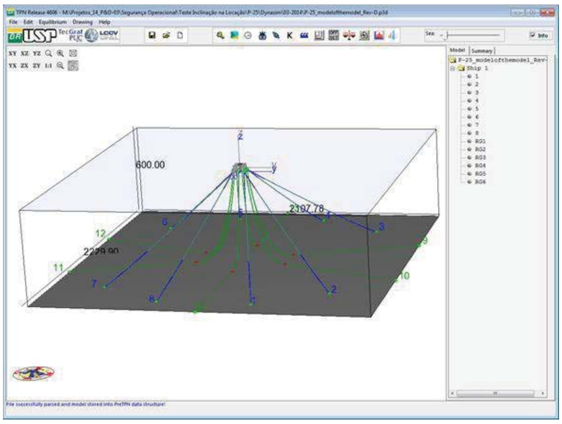

Figure 9 – M&R Numerical Model

As all segments but the springs were highly stiff, all the stiffness was considered to be characterized by the springs. However the main requirement of the numerical model was to match the total stiffness obtained in the pull-out tests PT-120-101000 and PT-120-102000 and the Frame tests with force plate.

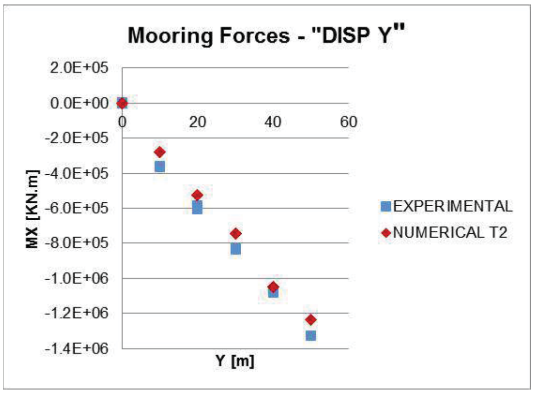

Figure 10 – Restoring Force Calibration

4.3 Uncoupled Direct Method Procedure

A final derivation of GM was performed based on Hydrostatic data and Mooring lines and Risers Moments calculated from Calibrated numerical model. So, for each mean position achieved for the model during wave tests, the Mooring lines and risers moments were subtracted to allow GM and KG calculations, using the following equation:

$$GM = \frac{w.d.\cos(\theta) - Mmris}{Disp.\sin(\theta)} \qquad 1$$

where:

w - Inclining weight

d - Inclining distance

θ - Inclining angle

Disp - Displacement

Mmris - Total moment for mooring lines and risers calculated for achieved equilibrium position, i.e., mean position for each test.
The KG was then calculated by:

$$KG = KM \quad GM \qquad 2$$

The results of KG were then obtained for each test using the conventional expressions [1] and [2]. Implicit in this approach is that it is only valid for small inclination angles due to the change in KM for larger angles.

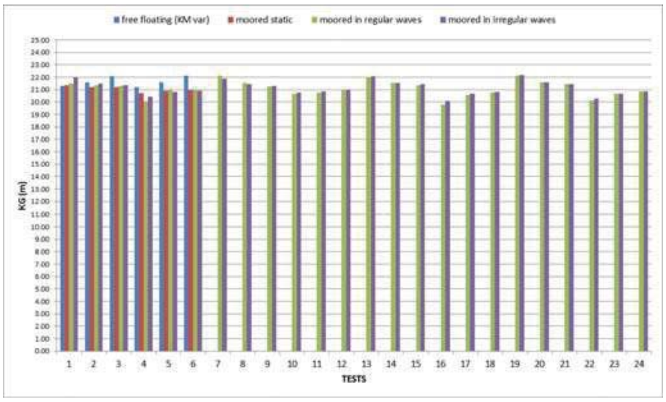

Figure 11 – Uncoupled Procedure Results

KG calculated values are presented in pink lines for free floating test results, brown lines moored static w/o wave results, green lines moored regular waves results (1 REG, 2 REG, 3 REG and 4 REG) and blue lines moored irregular waves results (1 IRR, 2 IRR, 3 IRR and 4 IRR).

4.4 Coupled Iterative Method Procedure

In this item a numerical procedure to determine the KG using the in-house programs SSTAB, for hydrostatic and stability calculations, and DYNASIM for mooring analysis is described. This procedure is based in an iterative search calculation where KG values are input and the equilibrium of the platform is calculated and checked with the model test mean values of heel and trim. When the calculated heel equates the model test heel result the associated KG is the target KG. The procedure is repeated for the 6 positions and the mean KG will be the resultant KG of the platform.

This procedure is fully based in the SSTAB equilibrium algorithm, which does not use any hypothesis of small angle or fixed Metacenter, but determines the coordinate of the Center of Gravity that reproduces the model heel, trim and draft. Therefore the inclining moment is imposed through the change of position of the inclining weight and the platform attains the equilibrium that is dependent of hydrostatic properties and the mooring and risers moments in the inclined position. The forces and moments due to the lines are determined through a catenary model included in the search for equilibrium.

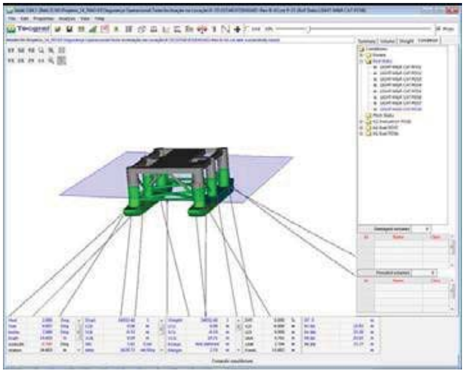

Figure 12 – SSTAB Program

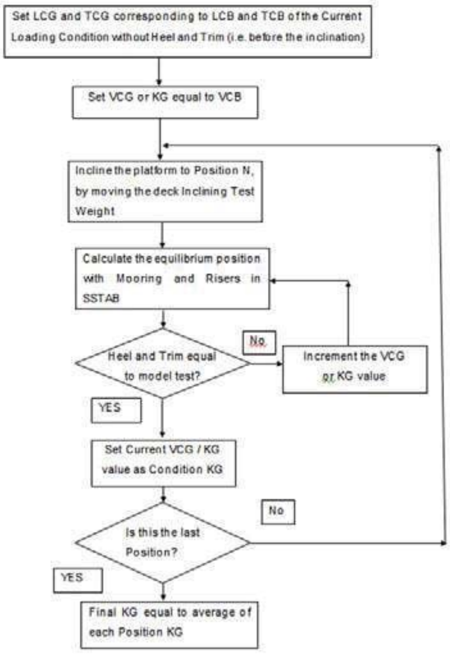

Figure 13 Iterative Coupled procedure

The X and Y displacements can also be considered and input to SSTAB with the objective of including the effect of the offset caused by waves, current and wind in the forces/moments induced by the mooring and risers systems.

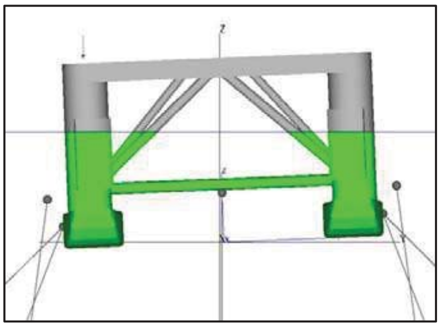

Figure 14 – SSTAB Program mixing hydrostatic and lines static calculations

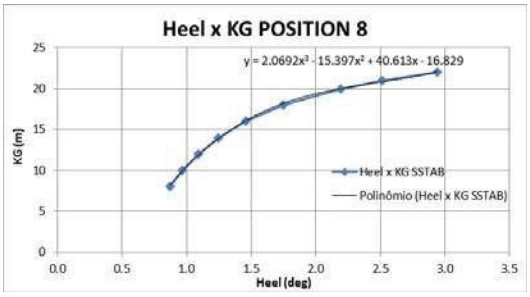

Figure 15 – SSTAB Program based iterative equilibrium calculations mixing hydrostatic and lines static calculations

4.5 Results for Model Test Verification

A KG analysis was performed by using calibrated numerical models leading to the following results:

Table 6 – Test KG results

	KG	Mean m	% Diff to ref	% Diff to free floating
	reference value	**21.40**	-	-
Conv. Method	free floating small angle	**21.01**	-	-
	free floating all angles	**20.73**	-	-
Uncoupled Direct Method	free floating	**20.87**	**-2.48%**	**-0.67%**
	moored static	**21.06**	**-1.61%**	**0.22%**
	moored in regular waves	**21.10**	**-1.42%**	**0.41%**
	moored in irregularwaves	**21.16**	**-1.12%**	**0.72%**
Coupled Iteractive Method	SSTAB free floating static	**21.02**	**-1.78%**	**0.05%**
	SSTAB moored static	**20.70**	**-3.27%**	**-1.48%**
	SSTAB irregular wave 3	**20.73**	**-3.13%**	**-1.33%**

Comparing the differences to the free floating condition small angles value (KG = 21.01 m), that represents the conventional procedure currently accepted KG determination practice with the other calculation methods, that include different approaches, we can verify an error from -1.96% to 1.65%, that is reasonable considering all the uncertainties involved by the inclining tests.

It can be observed that even the conventional inshore inclining test procedure works with some tolerance ranges, once it is difficult to define precisely some variables, like hull displacement, external weights and variable loads in the platform, draft and angle measurements, etc. Though, the sensitivity analysis performed in this report showed that the error are within an adequate margin of tolerance.

We conclude that this increase in the error is acceptable and within the tolerances of the current practice of inclining tests as performed by the industry and certified by regulatory institutions, therefore we consider that the inclining test can be performed offshore with the effects of mooring lines and risers and waves consistently taken into account.

5. APPLICATION OF THE OFFSHORE INCLINING TEST PROCEDURE TO AN ACTUAL UNIT

The objective of this item is to apply the procedure to execute the Inclining Experiment offshore in the location as described in the previous items, without removing the unit or stopping the production. This procedure has been approved in principle by ABS.

The proposed procedures have been applied initially in model scale in order to check their feasibility. In this way a model test has been carried out at LabOceano aiming at producing data that has been used to execute all the steps required for the offshore inclining experiment. LabOceano has issued a report [12] and also time series results of all tests in MATLAB format.

As the feasibility of the Model Scale Inclining Experiment has been confirmed and approved in principle, these tests were then performed in a typical semisubmersible unit in order to determine the lightweight and Centre of Gravity with the modifications carried out since the last Stability Experiment, executed in sheltered waters after the construction.

Based on the results of the full test with the SS unit, reported in this document, an official test will be carried out aiming at obtaining the approval of the classification societies and regulatory bodies in order to update the KG of the units in operation after eventual lightweight modifications carried out in the last years. Therefore the penalties imposed could be lifted in a safe and correct way enabling the execution of the required improvements within the safety standards.

The test has been carried out on the 6th of June 2014 from 13:00 to 16:00 (Brasilia Time Zone) or 16:00 to 19:00 (GMT). The ballast was transferred between tanks S05WBT and S11WBT. There was no admission or discharge of ballast to the sea. In this way only the trim was changed.

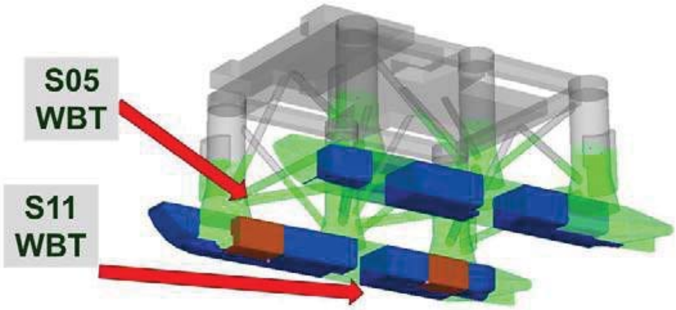

Figure 16 – Tanks used in the experimental test

The following manoeuvers have been executed:

Table 7 Ballast Manoeuvers

	Manoeuvers Time	Ballast transfer	Nominal Trim
POS01	Reference 13:00	Parallel Draft	0
POS02	1 13:20	11BE==>5BE	2.5
POS03	2 13:49	5BE==>11BE	2
POS04	3 14:04	5BE==>11BE	1.5
POS05	4 14:24	5BE==>11BE	1
POS06	5 14:48	5BE==>11BE	0.5
POS07	6 15:07	5BE==>11BE	0
POS08	7 15:31	5BE==>11BE	-0.5
POS09	8 15:56	5BE==>11BE	-1
POS10	9 16:16	5BE==>11BE	-1.5
POS11	10 16:38	5BE==>11BE	-2
POS12	11 17:02	5BE==>11BE	-2.5
POS13	12 17:23	11BE==>5BE	0

During the test the consumption of fresh water and of fuel oil was reduced to a minimum, however it is not possible to eliminate it completely in a producing unit. Therefore the alternative was to carefully register the level of these tanks in order to take this reduction into account.

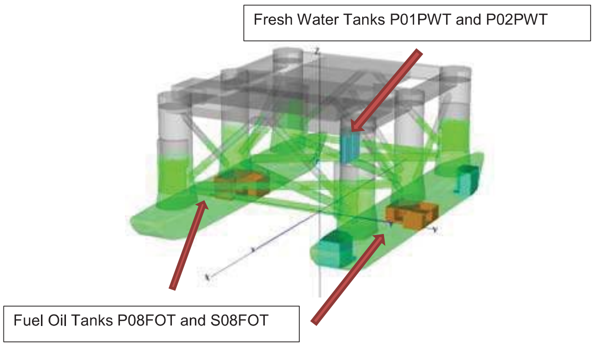

Figure 17 – Tanks with consumption during the test

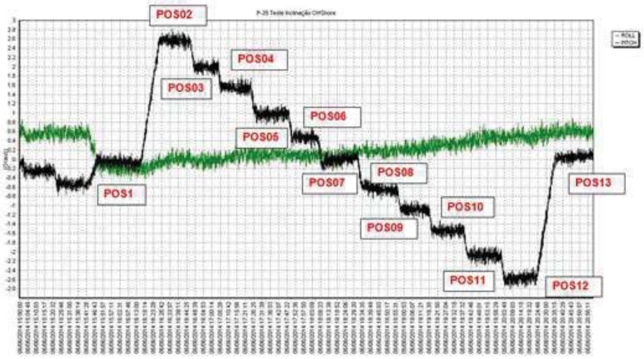

Figure 18 – Heel and Trim Positions

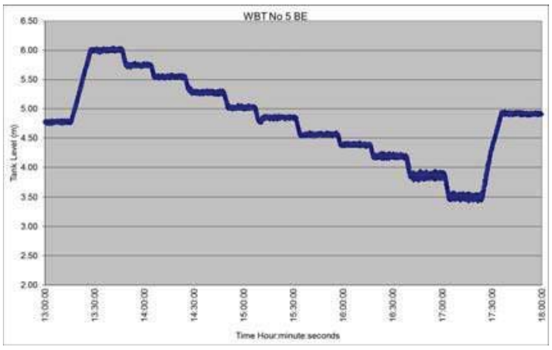

Figure 19 – WBT 5 Tank Ballast Transfers

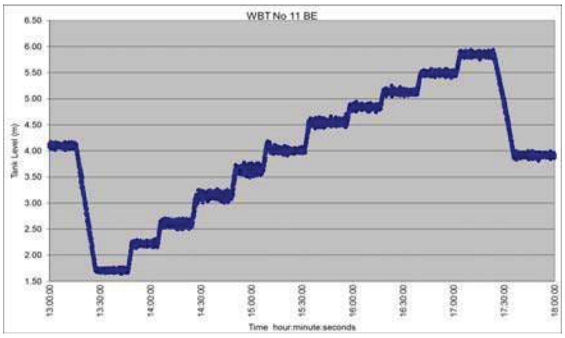

Figure 20 WBT 11 Ballast Transfers

Due to the non-linearities inherent to this method the more general approach of the Coupled Iterative Method has been applied to determine the KG.

5.1 Numerical Hydrostatic Data

The hydrostatic data model was adjusted using the in-house hydrostatic and stability program SSTAB, as can be seen in Figure 21. The SSTAB program has a special feature characterized by the inclusion of a catenary model within the equilibrium calculations taking into account the non-linear behaviour of the mooring and risers system.

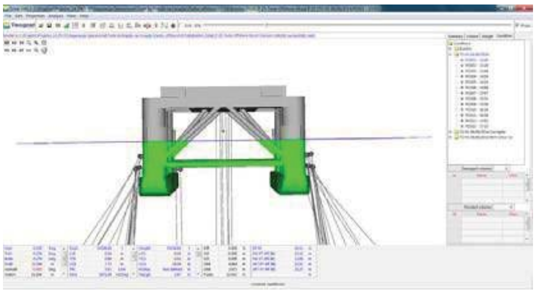

Figure 21 – Initial Position

Table 8 – Initial Position Condition

#	Condition.	Displac. (t)	Heel (Deg.)	Trim (Deg.)	Draft (m)
1	POS01 - 13:00	33350	-0.21	-0.07	23.31

Table 9 – Target Draft, Heel and Trim for All Positions

	Draft Origin (m)	Required Heel Test (deg)	Required Trim Test (deg)
POS01 - 13:00	23.31	-0.21	-0.07
POS02 - 13:20	23.30	-0.02	2.56
POS03 - 13:49	23.30	-0.04	1.99
POS04 - 14:04	23.31	0.05	1.55
POS05 - 14:24	23.30	0.1	0.97
POS06 - 14:48	23.29	0.07	0.48
POS07 - 15:07	23.29	0.06	0
POS08 - 15:31	23.28	0.18	-0.63
POS09 - 15:56	23.28	0.22	-1.09
POS10 - 16:16	23.28	0.32	-1.54
POS11 - 16:38	23.27	0.44	-2.07
POS12 - 17:02	23.25	0.49	-2.58
POS13 - 17:23	23.26	0.61	0.04
Averages	23.29		

5.2 Mooring and Riser Model

The mooring and risers systems were modelled in DYNASIM program with 12 mooring lines and 36 risers.

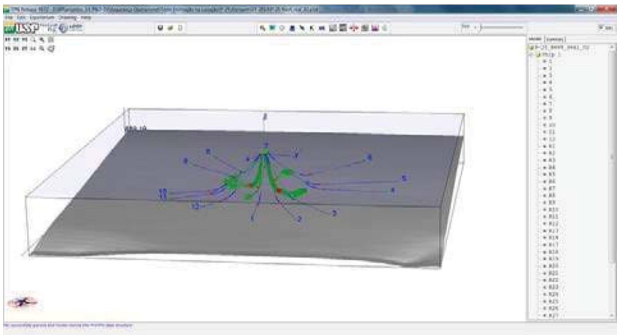

Figure 22 – M&R model as inspected in the field

The mooring lines in DYNASIM were modelled as the AS-LAID configuration [15], using segments of steel wire and steel chains. This model is imported in SSTAB program.

Table 10 – Mooring Line Composition

	Bottom Chain (m)	Interm. Wire Rope (m)	Chain Connection (m)	Top Chain (m)
1	950	600	10	148
2	1120	600	10	143
3	1135	600	10	202
4	1380	600	10	152
5	1510	600	10	137
6	1410	600	10	130
7	1220	600	10	105
8	1220	600	10	160
9	1130	600	10	160
10	965	600	10	145
11	950	600	10	165
12	840	600	10	173

Table 11 – Mooring Line Properties

	Diam (mm)	MBL (kN)	EA (kN)	Weight in Air (kN/m)	Weight in Water (kN/m)
R3_Stud_Chain	0.084	5550	5.84E+05	1.516	1.315
EIPS_Steel_WireRope	0.096	5740	5.04E+05	0.38	0.315
R4_Stud_Chain	0.078	6295	5.17E+05	1.34	1.17
R4_Stud_Chain	0.078	6295	5.17E+05	1.34	1.17

5.3 KG Calculation – Coupled Iterative Method Procedure

In this item a numerical procedure to determine the KG using the in-house program SSTAB, for hydrostatic and stability calculations, that includes the catenary model imported from DYNASIM program for mooring analysis is described. This procedure is based in an iterative search calculation where KG values are input and the equilibrium of the platform is calculated and checked with the measured offshore test mean values of heel and trim. When the calculated trim equates the measured trim results the current KG is the target KG. The procedure is repeated for the 13 positions and the mean KG will be the resultant KG of the platform.

This procedure is fully based in the SSTAB equilibrium algorithm, which does not use any hypothesis of small angle or fixed Metacentre, but determines the coordinate of the Centre of Gravity that reproduces the model heel, trim and draft. Therefore the inclining moment is imposed through the change of the ballast level in the test tanks (5SB and 11SB) and the platform attains the equilibrium that is dependent of hydrostatic properties and the mooring and risers moments in the inclined position. The forces and moments due to the lines are determined through a catenary model included in the search for equilibrium. The X and Y displacements can also be considered and input to SSTAB with the objective of including the effect of the offset caused by waves, current and wind in the forces/moments induced by the mooring and risers systems.

In order to determine the overall KG of the condition, all weight items, but liquid cargos in tanks, have been added to the so called Calibration item. The Calibration item is initially comprised by all items described below based on estimates of the current loading condition.

Table 12 – All Weight Items Summation

Item	Weight (t)	LCG (m)	TCG (m)	VCG (m)
Calibration Item (All weight items Except variable loads)	20093.94	-2.46	1.14	28.41

The Calibration item obtained above is a reference once the actual weight value and X and Y coordinates of the centre of gravity´s item has been obtained to attain the equilibrium with the Heel and Trim measured in POSITION01. Four KG calculations have been carried out: One without considering the displacement of the unit in the X and Y directions (offset) due to the environmental actions, other one considering this displacement, another removing the catenary model of the mooring and risers, thus considering them as fixed vertical loads and the last one modelling the tanks cargoes as fixed loads.

5.4 KG Calculation Without Offset Consideration

Table 13 show the weight items considered to assemble the Loading Condition. The Calibration Item comprises, as described above, the Lightweight, consumables, crew, etc. The remaining weight items of the platform are the liquid contained in the tanks, which have been measured through the PI control system and the mooring and risers systems, which are included in the model based on the As-Laid system.

Table 13 – Condition Weight Items

Weight Class	Weight (t)	% of Total	LCG	TCG	VCG
Calibracao	19953.89	59.83	-2.52	1.17	0.00
Mooring Lines	1020.13	3.06	1.03	0.34	16.80
Risers	924.18	2.77	-9.12	2.65	21.06
Ballast_Tanks	8974.40	26.91	3.87	-3.92	3.89
Fresh_Water	1015.32	3.04	17.80	28.08	7.95
Drill Water	323.88	0.97	39.16	-26.22	2.21
Fuel_Oil	1138.21	3.41	-4.35	-7.38	3.10
Total Weight	33350.01	100.00	0.09	0.08	2.51

The procedure described in Figure 13 is applied for the 13 positions beginning with POSITION01. As the trim angle is 0 it is not possible to iterate to determine the KG, this is only possible when the trim is different from 0. The procedure is applied for the remaining 13 positions.

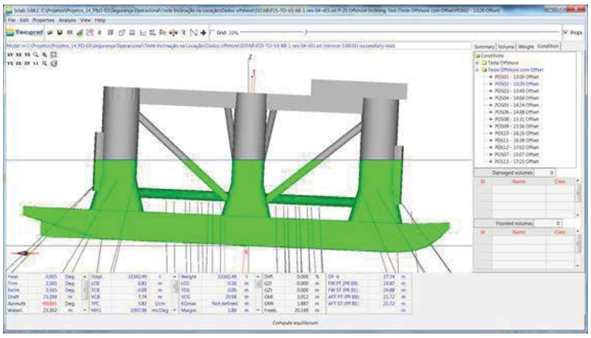

Figure 23 – SSTAB model with lines as catenaries in Position 02 (POS02)

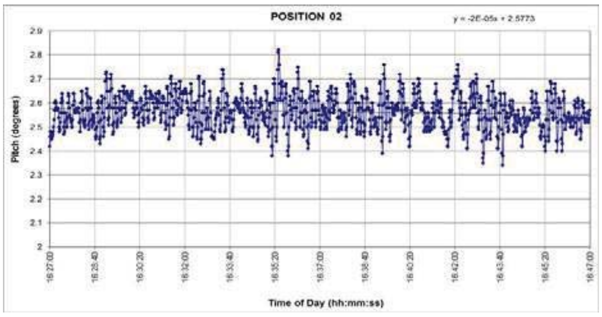

Figure 24 – Trim angle measurement POS02

Table 14 – VCG Coord. Calculated for Inclining Test Positions without Offset

	Displ (t)	Draft Origin (m)	Resultant Heel SSTAB (deg)	Resultant Trim SSTAB (deg)	LCG (m)	TCG (m)	VCG (m)
POS01 - 13:00	33350.01	23.31	-0.21	-0.07	0.056	0.08	
POS02 - 13:20	33343.87	23.3	0	2.57	0.29	0	20.63
POS03 - 13:49	33350.6	23.31	0.13	2	0.24	0	20.7
POS04 - 14:04	33349.96	23.31	0.13	1.56	0.2	0	20.87
POS05 - 14:24	33349.07	23.31	0.15	0.97	0.15	0	21.22
POS06 - 14:48	33350.13	23.31	0.59	0.38	0.1	-0.01	22.44
POS07 - 15:07	33347.34	23.31	0.02	-0.05	0.06	0	
POS08 - 15:31	33344.79	23.3	0.05	-0.65	0	0	18.31
POS09 - 15:56	33349.3	23.31	0.13	-1.12	-0.04	-0.01	19.14
POS10 - 16:16	33347.07	23.31	0.12	-1.54	-0.08	-0.01	19.38
POS11 - 16:38	33343.79	23.3	0.11	-2.1	-0.13	-0.01	19.56
POS12 - 17:02	33342.9	23.3	0.13	-2.61	-0.17	-0.01	19.65
POS13 - 17:23	33342.09	23.3	0.02	-0.04	0.06	-0.01	
Averages	33346.99	23.31			0.06	0.00	20.19

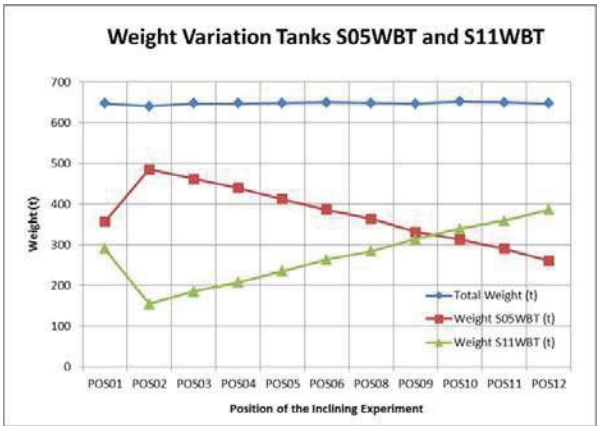

Figure 25 – Balance of ballast between tanks during transfers

5.5 KG Calculation With Offset Consideration

In this chapter the results considering the offset measured through the SMO (Offshore Monitoring System) system are presented. The offsets are calculated based on the GPS data stored in the SMO system from Petrobras.

Table 15 – Offsets X and Y in relation to the Neutral position during the Inclining Test

	Offset X (m)	Offset Y (m)
POS01 - 13:00	3.15	-1.98
POS02 - 13:20	3.49	-1.66
POS03 - 13:49	3.09	-1.71
POS04 - 14:04	2.80	-1.37
POS05 - 14:24	2.80	-1.16
POS06 - 14:48	2.89	-0.70
POS07 - 15:07	2.55	-0.92
POS08 - 15:31	2.64	-0.38
POS09 - 15:56	2.07	-0.43
POS10 - 16:16	1.90	-0.28
POS11 - 16:38	1.69	0.07
POS12 - 17:02	1.53	0.31
POS13 - 17:23	2.17	-0.27

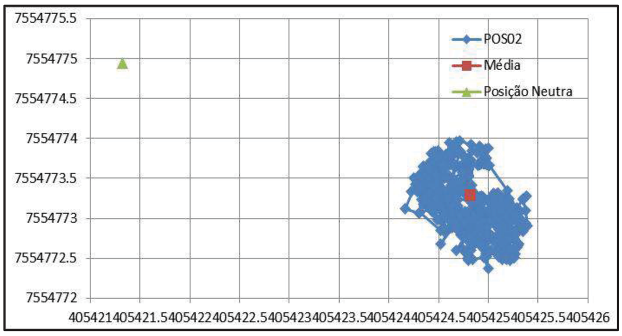

Figure 26 – Planar displacements measured by GPS during Position02 inclination

Table 16 – Calculation of Offsets in relation to the Neutral Position

	Neutral Position without environmental loads	
	East (m)	North (m)
Neutral Position	405421.32	7554774.95
Average of POSITION02	405424.81	7554773.29
Offset	3.49	-1.66

Table 17 – Weight Items for POS02

Summary of Loading Condition for POS02 - 13:20 Offset					
Weight Class	Weight	% of Total	LCG	TCG	VCG
Calibracao	19963.26	59.86	-2.45	1.03	30.04
Mooring Lines	1016.44	3.05	0.03	0.50	16.80
Risers	925.64	2.78	-9.25	2.69	21.12
Ballast_Tanks	8967.29	26.89	4.77	-3.92	3.93
Fresh_Water	1015.56	3.05	17.83	28.08	7.95
Drill Water	323.88	0.97	39.29	-26.25	2.21
Fuel_Oil	1138.21	3.41	-4.24	-7.40	3.10
Total Weight	33350.28	100.00	0.34	0.00	20.51

Table 18 – VCG Coord. Calculated for Inclining Test Positions with Offset

	Displ (t)	Draft Origin (m)	Resultant Heel SSTAB (deg)	Resultant Trim SSTAB (deg)	LCG (m)	TCG (m)	VCG (m)
POS01 - 13:00	33350.51	23.31	-0.21	-0.07	0.01	0.08	
POS02 - 13:20	33350.28	23.31	0	2.57	0.34	0	20.51
POS03 - 13:49	33351.76	23.32	0.17	2	0.3	-0.01	20.41
POS04 - 14:04	33351.1	23.31	0.22	1.55	0.26	-0.01	20.46
POS05 - 14:24	33350.44	23.31	0.09	0.97	0.21	-0.01	20.53
POS06 - 14:48	33351.37	23.32	0.62	0.49	0.16	-0.01	21.3
POS07 - 15:07	33346.55	23.31	-0.17	-0.03	0.06	-0.01	
POS08 - 15:31	33351.23	23.32	0.27	-0.64	0.03	-0.02	19.98
POS09 - 15:56	33349.22	23.31	0.4	-1.1	-0.02	-0.02	20.22
POS10 - 16:16	33346.1	23.31	0.46	-1.55	-0.01	-0.02	20.35
POS11 - 16:38	33344.14	23.3	0.46	-2.08	-0.06	-0.02	20.28
POS12 - 17:02	33347.94	23.31	0.26	-2.59	-0.11	-0.01	19.93
POS13 - 17:23	33343.17	23.3	-0.15	0	0.06	-0.01	
Averages	33348.75	23.31			0.09	-0.01	20.40

5.6 KG Calculation with the Mooring and Risers Modelled as Constant Vertical Weights

This item presents the calculation of the KG for the Calibration Item and for the overall KG of the condition for each Position considering the mooring and riser loads as constant vertical loads applied in the respective fairleads or connection points. It should be noted that this approach is the recommended way by the rules and regulations to take into account the mooring and risers loads. In this type of method the horizontal component (Th) of the mooring loads is not considered and also the variation due to the change in position of the connection points is also not included in the calculations. Only the vertical component (Tv) as a constant load is considered.

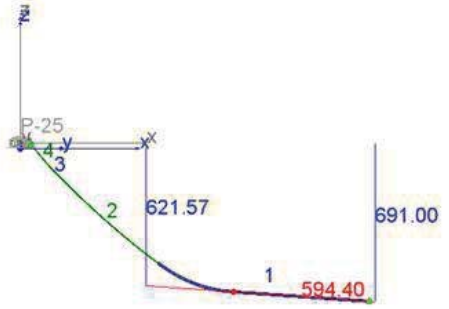

Figure 27 – Mooring Line Catenary

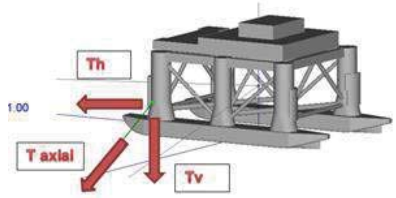

Figure 28 – Mooring line tension components

Table 19 – Vertical Component of Tension

	Vertical Constant Load (t)	X(m)	Y(m)	Z(m)
L1	88.85	39.5	35	16.8
L2	90.07	35.2	36	16.8
L3	86.47	30.6	34.8	16.8
L4	83.69	-30.6	34.8	16.8
L5	83.58	-35.2	36	16.8
L6	82.48	-39.5	35	16.8
L7	81.65	-39.5	-35	16.8
L8	86.83	-35.2	-36	16.8
L9	77.39	-30.6	-34.8	16.8
L10	79.37	30.6	-34.8	16.8
L11	91.55	35.2	-36	16.8
L12	88.20	39.5	-35	16.8

Table 20 – VCG Coord. Calculated for Inclining Test Positions without Offset and with Constant Vertical Tension

	Displ (t)	Draft Origin (m)	Resultant Heel SSTAB (deg)	Resultant Trim SSTAB (deg)	LCG (m)	TCG (m)	VCG (m)
POS01 - 13:00	33350.01	23.31	-0.23	0.01	0.056	0.08	
POS02 - 13:20	33342.52	23.3	-0.02	2.58	0.33	0	18.92
POS03 - 13:49	33349.72	23.31	0.07	2	0.28	0	18.76
POS04 - 14:04	33349.26	23.31	0.06	1.56	0.24	0	18.67
POS05 - 14:24	33348.61	23.31	0.06	0.97	0.19	0	18.34
POS06 - 14:48	33349.9	23.31	0.08	0.49	0.14	-0.01	18.37
POS07 - 15:07	33347.32	23.31	0.01	0.03			
POS08 - 15:31	33345	23.3	0.07	-0.63	0.03	0	19.92
POS09 - 15:56	33349.71	23.31	0.17	-1.09	-0.01	-0.01	19.62
POS10 - 16:16	33347.66	23.31	0.14	-1.56	-0.05	-0.01	19.56
POS11 - 16:38	33344.59	23.3	0.1	-2.08	-0.1	-0.01	19.34
POS12 - 17:02	33343.91	23.3	0.13	-2.58	-0.15	-0.01	19.27
POS13 - 17:23	33342.09	23.3	0.02	0.04			
Averages	33346.95	23.31			0.09	0.00	19.08

5.7 KG Calculation with the Mooring and Risers Modelled as Constant Vertical Weights and with Liquid Cargoes as Solid Weights

In this item the objective is to consider the liquid cargo as a fixed item, without variation due to the inclination of the platform. This is the usual way to perform the hydrostatic calculations, without including the effect of the change in the coordinates of the center of gravity of the liquid cargo inside the tank. The SSTAB program automatically calculates the change in the liquid form of the cargo due to the inclination and the consequent moment that is produced by this change. Usually this effect is taken into account by the correction of the free surface effect by the elevation of the vertical coordinate of the tank center of gravity. The purpose of this item is to investigate the free surface correction in tanks with shapes different from the parallel walls assumption used to determine the increase in the vertical coordinate of the overall KG of the condition. In this way the liquid cargo was considered as fixed and the free surface correction would have to be applied and a comparison with the option with the liquid cargo equilibrium within the tank is performed.

The tanks used to incline the platform, as already mentioned are the tanks S05WBT and S11WBT. The shape of the tanks are the same and as the inclinations are around the Y axis (trim), the resultant shapes of the water line can be seen below.

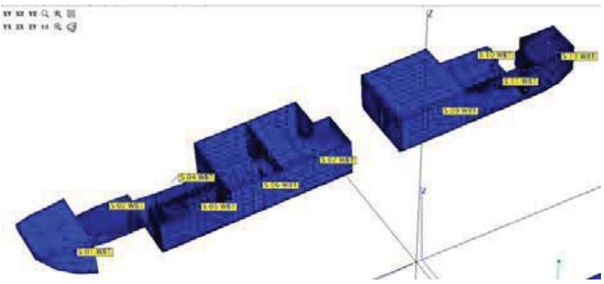

Figure 29 – Pontoon Ballast Tanks Level

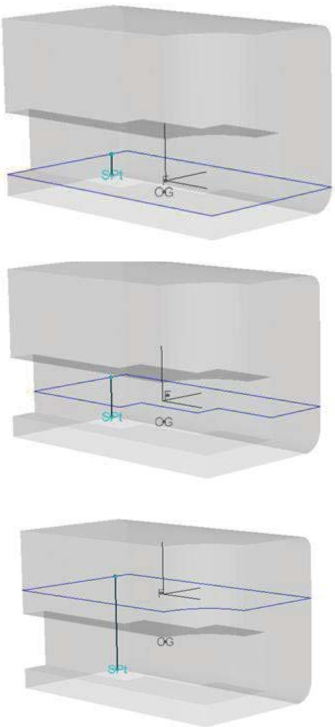

Figure 30 – Three ballast levels of Tank S05WBT showing the complex shape (Level 1, 2 and 5 m)

Table 21 – VCG Coord. Calculated for Inclining Test Positions without Offset with Constant Vertical Tension and with Ballast Tanks as Solid Weights

	Displ (t)	Draft Origin (m)	Resultant Heel SSTAB (deg)	Resultant Trim SSTAB (deg)	LCG	TCG	VCG
					(m)	(m)	(m)
POS01 - 13:00	33350.01	23.31	-0.23	0.01	0.056	0.08	
POS02 - 13:20	33343.14	23.3	-0.06	2.57	0.31	0	19.33
POS03 - 13:49	33350.48	23.31	-0.01	1.99	0.27	0	19.24
POS04 - 14:04	33350.54	23.31	-0.01	1.55	0.23	0	19.14
POS05 - 14:24	33350.61	23.31	-0.01	0.97	0.18	0	18.76
POS06 - 14:48	33352.64	23.32	0.01	0.48	0.13	0	18.44
POS07 - 15:07							
POS08 - 15:31	33344.69	23.3	0.05	-0.63	0.04	0	20.48
POS09 - 15:56	33349.27	23.31	0.15	-1.09	0	-0.01	20.19
POS10 - 16:16	33346.99	23.31	0.12	-1.54	-0.03	0	20.06
POS11 - 16:38	33343.63	23.3	0.08	-2.07	-0.08	0	19.85
POS12 - 17:02	33342.66	23.3	0.08	-2.58	-0.13	0	19.76
POS13 - 17:23							
Averages	33347.70	23.31			0.09	0.01	19.53

5.8 Preliminary Verification of Results of the Experimental Offshore Inclining Test

Based on the results obtained above one can verify on Table 22 the estimated KG of the Calibration Item (including all items except the tanks and lines) and the overall condition KG of the typical SS Unit following the 4 different approaches:

Table 22 – Final KG

Option	Liquids Cargoes	Mooring & Riser	Offset	KG Calibrated Item(m)	KG Solid All Items(m)	GMT (m)
1	Fluid	Catenary	Yes	29.89	20.4	2.05
2	Fluid	Catenary	No	29.54	20.19	2.26
3	Fluid	Constant	No	27.68	19.08	3.37
4	Solid	Constant	No	28.43	19.53	2.92

In Table 22 one can see clearly the effect of the Mooring and Risers in the calculation of the KG and hence in the stability. In Option 2 the KG was calculated considering the exact effect of the mooring and risers calculated with the catenary formulation, therefore increasing the Condition KG, whereas in Option 3 this effect was not considered resulting in a smaller KG (19.08 m). In this way the current approach of not considering the mooring and riser contribution results in a difference of 1.11 m in the Condition KG, i.e. with the mooring and riser contribution considered correctly the platform would have a KG of 20.19 m. The conclusion is that the effect of mooring and risers is beneficial for the stability introducing a restoring moment that is not considered in the conventional analysis including the effect of tension as constant weights.

Another aspect that should be considered is the influence of the moment induced by the liquids inside the tanks. In this particular case the comparison of Option 3 and Option 4 leads to a KG increase of 0.45 m. The use of the conventional free surface correction (calculated as Transversal FS = 0.24 m and Longitudinal Free Surface = 0.335) is smaller than 0.45, showing an inadequate correction of the effect of the inclination of the liquids due to the complex shape of the tanks.

The final KG of the test condition considering the effect of the mooring and risers and the offset is 20.4 m and the KG of all items except the mooring and risers and liquid cargoes is 29.89 m. That leads to a GMT of 2.05 m and a GML of 4.04 m. Without considering the exact catenary effects and the correct effect of the liquids inclination inside complex tanks the Condition KG would be 19.53 m and the Calibration Item KG would be 28.43 m. The latter values are the ones that are used to verify the IMO and Classification Societies rules.

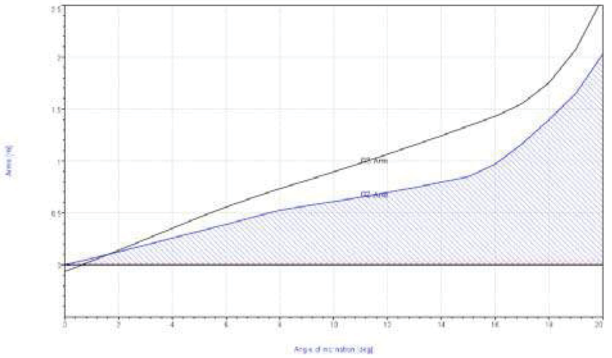

Figure 31 – GZ Curve with Mooring Lines defined as Catenary Model (black) and with Fixed Weights (blue)

Figure 31 shows the GZ curve for inclination around the Y axis (trim) for the SS with the same KG for the Calibration Item (29.89 m) and the Condition of POS01, showing the influence of the Mooring and Risers modelled as catenaries increasing the GZ.

6. CONCLUSIONS

It has been shown, firstly in model test scale and secondly in full scale, that an offshore inclining test is a feasible procedure.

The IMO Rules and Regulations were developed aiming at ships and mobile offshore units, without taking into account permanent offshore moored units that remain in the field for 25 to 30 years. In this way alternative procedures and regulations shall be implemented in order to consider the special nature of this type of unit.

The offshore test is a sound and robust way to assess and to guarantee the safety of offshore units throughout their operational lives. All procedures are based on proven measurement devices and engineering methodologies.

The mooring and risers effect is beneficial for the stability, introducing an additional restoring moment that is not considered in the current calculations of stability.

7. ACKNOWLEDMENTS

We acknowledge the great contribution of the TECGRAF Institute from PUC-Rio Pontifical Catholic University of Rio de Janeiro) in the development of the programs MG, SSTAB and DYNASIM.

8. REFERENCES

ASTM International, 2004, “Standard Guide for Conducting a Stability Test (Lightweight Survey and Inclining Experiment) to Determine the Light Ship Displacement and Centers of Gravity of a Vessel”

International Maritime Organization IMO, 1989, “Code for The Construction And Equipment Of Mobile Offshore Drilling Units 1989 (Modu Code - 89)”.

Bradley, M.S. and MacFarlane C.J. Inclining Tests in Service, 1986, “Advances in Underwater Technology”

MOSIS System MacFarlane C.J. Internet Description

Brown D.T. and Witz J.A. RINA, 1996,

"Estimation of Vessel Stability at Sea Using Roll Motion Records"

Nogueira, S., 2009, "Development of a Inclining Test Procedure Applicable to Semi Floating Production Units Moored on Location", OMAE2009-79184, Honolulu, Hawaii, USA, 31 may – 5 June.

Nogueira, S., 2010, "Sistemática para Executar Teste de Inclinação em Unidades Semissubmersíveis de Produção Operando na Locação" in Portuguese, Dissertação de Mestrado (MSc Dissertation), COPPE/UFRJ

LABOCEANO COPPE/UFRJ, 2013, "Model Tests for Verification of Inclining Tests Offshore Procedure" Draft Report - 006_12_RELPRJ03_01A 2013