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Benchmark Model Tests on the DeepStar Theme Structures FPSO, SPAR and TLP

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Abstract

In the framework of the studies on the DeepStar Theme Structures for deepwater in the Gulf of Mexico, contractors and research institutes have carried out series of pre-model test computations. The DeepStar Theme Structures are a turret moored FPSO, a classic SPAR and a standard TLP. The Theme Structures were exposed to hurricane and loop-current condition. The scatter was significant in the pre-model test computational results. In order to compare the computed results with results of model tests, a series of benchmark model tests were carried out. Based on the model tests results post-model test validation analysis and guidelines for ultra deepwater model tests and coupled analysis for deepwater structures were carried out.

In this paper, the sequence of the DeepStar Theme Structure developments will be given briefly and the philosophy behind and the performance of the benchmark model tests will be presented.

Introduction

In the framework of the DeepStar Theme Structures studies for deep water in the Gulf of Mexico, contractors and research institutes carried out series of pre-model test computations. The computations were carried out based on the technical specifications for the Theme Structures and weather conditions. The structures were exposed to hurricane and loop-current condition. The FPSO and Spar were installed in 3,000, 6,000 and 10,000 ft of water depth, while the TLP was installed in 3,000 and 6,000 ft. Comparing the pre-model test computation results of the same structures as carried out by different participants, the scatter was significant. In order to compare the computed results with results of model tests, a series of benchmark model tests were carried out.

The motivation for the selected model scale and the description of the model basin facility is given. The description is given of the model manufacturing including mooring lines and risers. Further, the calibration of hurricane and loop-current environmental conditions is presented. A hurricane and a loop-current current profile had to be adjusted to match the specifications. In addition, the associated turbulences were measured in the basin. The results are presented. Concerning the waves, attention was given to not only the wave spectra but also to the wave group spectra. The Theme Structures were exposed to an API wind spectra. The procedure to adjust the wind spectra is described.

The test set-up, instrumentation, data reduction and the program of the benchmark model tests will be presented.

Finally some conclusions are drawn.

Since the results of the benchmark model test program will be used for post-model test computations (model-the-model), the performance and the reporting of the model test set-up must be as accurate as possible.

In the same framework of the DeepStar Theme Structures project, guidelines for model testing in ultra deepwater and guidelines for coupled analysis of deepwater floating structures are established.

This paper documenting the benchmark model tests is the first in a series of papers covering the DeepStar Theme Structures project. The other papers deal with prediction of the responses of the Theme Structures (model test vs. analysis), and development of guidelines for model test in ultra deepwater and for coupled analysis of deepwater systems.

Review of the DeepStar Theme Structures Studies

The DeepStar Theme Structures (CTR 4401A)

The Theme Structures, as studied for the Gulf of Mexico, were a turret moored FPSO, a classic SPAR and a standard TLP. The FPSO and the SPAR were designed for 3,000, 6000 and 10,000 ft water depth. The TLP was designed for a water depth of 3,000 and 6,000 ft. The specifications for the FPSO, SPAR and TLP are briefly described below.

FPSO

The FPSO was designed for a production level of 120,000 bpd and a storage capacity of 1,440,000 bbls. The particulars of the vessel are given in [1]. To prevent green water, the bow was raised as is shown in Figure 1. Note that for simplicity, no process equipment was added to the tanker.

The FPSO riser system included 4 liquid production risers, 4 gas production risers, 4 water injection risers, 4 gas injection risers and 1 gas export risers. Umbilicals were neglected in both the computations and model tests. For both the computations and model tests, the number of risers was restricted to 13; therefore, the water and gas injection risers were paired.

The mooring systems for the different water depths were:

-WD-3,000 ft: Chain-steel semi-taut-4*3 legs
-WD-6,000 ft: Polyester-taut-4*3 legs
-WD-6,000 ft: Steel-spring buoy-4*3 legs
-WD-10,000 ft: Polyester-taut-4*3 legs

The positions of the risers and the mooring lines for a water depth of 3,000 ft are given in the Figures 2, 3 and 4. For the particulars of the risers and mooring system, see [2], [6] and [15].

Spar

The classic Spar was designed for a production level of 55,000 bpd of oil and 72 mmscfd of gas.

The main particulars of the Spar were:

Displacement (net buoyancy)	m.ton	53.600
Displacement including entrapped water	m.ton	220.740
Diameter	ft	122
Length	ft	705
Draft	ft	650
Hard tank depth	ft	220
Well bay dimensions (25 slots)	ft	58*58
Fairlead location (above base level)	ft	300

The spar platform and risers were the same for 3,000, 6,000 and 10,000 ft water depth. The risers consist of 19 production risers, 2 water injection risers, 1 oil export riser and 1 gas export riser (see Figure 5).

The mooring systems for the different water depths were:

-WD-3,000 ft: Steel semi-taut-14 legs equally spaced
-WD-6,000 ft: Polyester-taut-14 legs equally spaced
-WD-10,000 ft: Polyester-taut-14 legs- equally spaced.

For the layout of the mooring, see Figures 6 and 7, and for more details, see [4] and [18].

TLP

In 3,000 ft water depth, the TLP included 1 drilling riser and 7 production risers, while for 6000 ft there were 11 production risers plus one drilling riser.

The main particulars of the TLP are:

water depth	ft	3000	6000
Draft	ft	80,0	103,0
Displacement	m.tons	32775	53392
Diameter column (OD)	ft	54,0	64,0
Column span (c/c)	ft	200,0	200,0
Column freeboard	ft	67,0	72,0
Pontoon height	ft	24,0	28,0
Pontoon width	ft	27,0	32,0
Total Weight	m.tons	24157	35454

The particulars of the tendons are:

		3000 ft	6000 ft
Number of tendons		8	12
Outer diameter	inch	32	44
Wall thickness	inch	1,3	1,85
Young's modulus	ksi	30000	30000
Pre-tension @ top	m.ton	879	1124
Length	ft	2928	5907
Tendon weight wet	m.ton	91,29	420,66

The layout of the tested TLP in 6000 ft is given in Figure 8 and 9. For more details, see [5] and [19].

The weather conditions

The Theme Structures were exposed to the hurricane and loop-current weather conditions. The specified weather conditions are summarized in the table below. The specified current profiles are presented in Figure 10.

	Hurricane	Loop-current
waves		
Hs	12,19 m	6,1 m
Tp	14 sec	11 sec
Jonswap	γ=2,5	γ=2
Direction	180^0 (E)	90^0 (S)
Wind		
1-hour mean	41,12 m/s	22,35 m/s
wind spectrum	API	API
Direction	210^0 (EEN)	90^0 (S)
Current		
Direction	150^0 (EES)	0^0 (W)

The pre-model test computations (CTR 4401B)

The pre-model test computations were carried out by the contractors and research institutes for the specified Theme Structures, weather conditions and water depths. The pre-model test study was carried out in 1999. The study is documented in [3]. Because of the scatter found in the results, a benchmark test program was established.

The benchmark model test program (CTR 4501A)

The prime objective of the benchmark model tests was to simulate the specifications as accurately as possible. These specifications imply the modelling of the Theme Structures including the complete mooring and riser systems without using any truncations, and the accurate simulation of the hurricane and loop-current weather conditions.

The benchmark test program was carried out in November 2000. The full description of the program is given below.

The post-model test computations and further developments (CTR 5401B)

After the model tests, the post-model test analysis were carried out. In this study, both the model-the-model computations and sensitivity analysis were carried out. Finally, guidelines for ultra deepwater model tests and coupled analysis for deepwater structures were established [10, 11].

The total work is reviewed in this series of papers. The series comprises this paper and other OTC papers as given below.

1) Paper # 16583-Prediction of Spar responses –Model tests vs. Analysis [4]
2) Paper # 16584-Prediction of TLP Responses – Model tests vs. Analysis [5]
3) Paper # 16585-Prediction of FPSO responses-Model Tests vs. Analysis [6]
4) Paper # 16586-Model-the-Model: Validating Analysis Models for Deepwater Structures with Model Tests [7]
5) Paper # 16587-Model testing for Ultra deep water [8]
6) Paper # 16588-Guidelines on coupled Analysis of Deepwater Floating Systems [9]

The following concerns the benchmark model tests. The model basin, choice of model scale, test preparations, instrumentation and test program are presented.

Description of the model basin and chosen model scale

The model tests were carried out in the Offshore Basin of MARIN. The basin measures 44,35 m * 35,6 m and has a movable floor, which is used to adjust the water depth. The top view of the basin is given in Figure 11. The maximum water depth measures 10.5 m at model scale. In Figure 12, the cross section over the basin is shown. The basin also has a deep pit, with a maximum water depth of 30 m and diameter of 5 m. When the pit is not used, a hatch covers it. Inside the pit is a movable "spider" floor, consisting of 8 equally spaced legs as shown in Figure 13. Each leg has an air powered cylinder clamp. The spider can be lowered in a controlled way keeping the spider in a horizontal plane. At the desired level, the 8 air powered cylinder clamps are activated and the spider platform is rigidly clamped inside the pit.

The current generation system consists of 6 separate layers, each equipped with its own pump system. Current can be generated over the full depth of 10.5 m. This current generation system enables the adjustment of vertical current profiles. The maximum values of the current velocities that can be generated over the vertical is given in Figure 10. In the same figure, the required hurricane and loop-current profiles are indicated.

Irregular waves are generated by a system of approximately 200 oscillating flaps of 0.4 m each. Each of these wave flaps is controlled individually with full control over stroke and period. This wave generation system can generate long-crested irregular seas, irregular seas with directional spreading and combinations of irregular waves and swell. In generating irregular long crested waves, "infinity" number of wave components is generated. Wave absorbing beaches are used opposite to the wave generators. The wave generators themselves have an active reflection compensation option.

Wind is generated by a large number of wind fans mounted on a battery. The position of the battery is remotely controlled at any position in the basin.

The chosen model scale depends on the following conditions:

-The maximum depth of the model basin. The minimum depth as applied for the Theme Structures studies was 3000 ft corresponding with 914,4 m.

-The width of the model basin. For instance, the largest spread of the mooring system in the horizontal plane was formed by the FPSO and amounts for a water depth of 3000 ft to 1764,46 m. According to the specification, truncation was not allowed.

-To meet the specified height of the maximum waves and periods of the wave spectra, the current speed distribution and the 1-hour mean wind speed and wind spectrum.

-Considerations on scale effects on the slender members.

Concerning the depth, an optimum model scale amounts to 1:87. This means that the mooring line spread at model scale is 20.28 m, which is shown in the Figures 3 and 4. In the hurricane set-up, the mooring could laid-out without any truncation. In the case of the loop-current test set-up, some truncation was applied to the lines over the short side of the basin. Computations show that the mooring lines were not lifted off the seabed over the truncated portion of the line. Such a truncation is allowed since it has no physical effects on the system.

For the TLP, a water depth of 6,000 ft was chosen, since the tendons and risers could be installed in the pit (see Figure 9).

For the adjustment/calibration of the environment, the required data in the specifications could be met.

To judge the scale effect on the slender members like the steel wires, risers and tendons at model scale, the criteria is given to the Reynolds number and the associated drag resistance.

For the hurricane and loop-current current speeds, the Reynolds numbers of the slender members for both prototype and model are reviewed in Table 1. From the results, it can be observed that the Reynolds number for steel wire and chain for the FPSO and for the Spar in the hurricane current will decrease to Re=100 and 150, respectively. Figure 14 gives the effect of the drag for steel wires at small Reynolds numbers [12], while Figure 15 gives the effect of the drag of chains for both large and small Reynolds number [10] and [12]. These results indicate that the scale effects are relatively small. Therefore, a scale of 1: 87 was chosen for all model tests.

Calibration of the environmental conditions

Adjustment of current for Hurricane and Loop-current

The specified current profiles for 3,000 ft water depth are shown in Figure 10. By changing the RPM of each of the six pumps, the vertical current profile can be adjusted by trial and error. The vertical current distribution has been adjusted at the center of the turret of the FPSO, and at the still-water centerline for the Spar and TLP. The adjusted current profile for the hurricane condition is shown in Figure 16, while the profile of the loop-current is presented in Figure 17. The profile has been measured in 2 ways by means of:

-a vertical sweep

-a stationary measurements during a period of 3 hours (the test duration).

To measure the current profile along the vertical, an electro magnetic speed (EMS) probe mounted on a vertical traversing system (TRICAP) was used. By moving the EMS slowly upwards and down wards the in-line current velocities were continuously measured (a vertical sweep). For the steady current measurements, both the inline and the transverse component were measured. The current velocities were recorded and analyzed. The EMS probe is an ellipsoidal probe for high spatial resolution and minimum disturbance. It is able to measure bi-axial current velocities up to 5 m/s. The inaccuracy of the probe is ± 1% of the measured value.

The degree of turbulence and the associated spectra of the turbulence were also determined.

The degree of turbulence is defined as follows:

$$T = \sigma/V$$

in which:

σ=standard deviation of the current in the considered direction
V=mean current velocity in the main direction

The main direction is assumed to be the inline current direction.

The draft of the Spar was 650 ft (198.12 m). In the specified loop-current current profile, the Spar would be exposed for more than the half of its draft to a turbulent shear current. DeepStar participants were concerned that the turbulence would have an unrealistic effect on VIV. Therefore, to study possible VIV motions more properly, a second loop-current profile was used with a homogenous flow over the first 200 meters (see Figure 18). To achieve the current profile the maximum current speed at the surface was decreased from 2,13 m/s to 1,87 m/s. Current turbulence was small for this homogenous current profile.

Current turbulence was measured and analyzed. The current speed registration in-line (x) and transverse direction (y) for the original loop-current is given for the highest measuring point in Figure 19. The associated current turbulence spectra are given in the Figures 20 and 21.

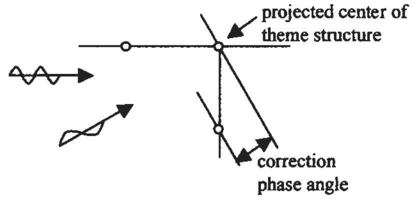
In the table below, the turbulence levels are given for both loop-current profiles.

FPSO	Vx T in %	Vy Tin %
h=12 m	6,6	1,0
h=168 m	15,5	2,5
h=579 m	16,0	2,8
Spar		
h=20.9 m	5,2	1,0
h=109 m	5,4	1,0
h=198 m	7,3	1,1
h=435 m	10,7	2,4

The high turbulence levels at the altitudes h=168 m and h=579 m are associated with the strong shear current. For more details, see [13].

Calibration of Waves for Hurricane and Loop-current

Irregular waves were generated during 3*3 hours full scale. The wave maker program used to generate the irregular wave conditions was such that the wave pattern does not repeat itself over the length of the test duration. Wave probes were installed 3.95 meters (model scale) upstream of the waves and 3.95 meters (model scale) abreast (phase angles) of the "center" probe, as indicated below for the hurricane condition.



The waves were calibrated satisfying the theoretical distribution of the spectral density of the wave frequency components (Jonswap), the theoretical distribution of the wave elevation (Gauss), the theoretical distribution of the crest and troughs (Rayleigh) and the theoretical wave group spectra (Pinkster). The analysis was split into parts of 3 hours (seed #1, seed #2 and seed #3). For more details, see [13].

Calibration of Wind Hurricane and Loop-Current

For both the hurricane and loop-current the simulated wind was a 1-hour mean combined with an API wind spectrum. For the adjustment of the wind force on the FPSO, Spar and TLP, use was made of an underwater 6-component force balance transducer. The schematic drawing of the underwater 6-component force balance transducer is shown in Figure 22.

For the Spar, the procedure was as follows. The movable floor was raised. The 6-component force balance transducer was placed on a rotating table, which was attached to the floor with the vertical axis located at the projected "center" of the structure in rest position in the basin. With the installed 6-component force balance transducer, the floor was lowered to some distance that the transducer was below SWL. The Spar hull consisted of 2 parts, an upper part and a lower part. The upper part including the superstructure was placed on the 6-component force balance transducer. The floor was lowered up to the correct draft of the Spar.

By means of the six-component force balance transducer, the wind loads and moments were measured for the steady 1-hour mean wind speed and the wind spectra.

The measured forces have to correspond with the specified forces. After the 1-hour wind load was adjusted the wind load spectra (Seed #1, #2 and #3) were calibrated. The procedures were carried out for both the wind fans in the hurricane and loop-current condition.

The same procedure was followed for the TLP. In this case, the 6-component force balance transducer was placed in the projected "center" of the TLP at rest in the basin. The total TLP was placed on the 6-component force balance transducer. The moveable floor was lowered to have the correct draft of the TLP. The theoretical and measured wind spectrum force on the TLP in hurricane wind under 180^0 is presented in Figure 23.

For the FPSO the following procedure was applied. The movable floor was lowered so far that the 6-component force balance transducer was completely below water. The FPSO was sailed inside the slot of the transducer. By means of 4 underwater clamps, the tanker was fixed to the transducer. By rotating the 6-component balance around the vertical axis, wind forces can be measured under different angles. In the direction $\psi_{wr}=180^{0}$ in hurricane wind, the center of the turret was in the projected location of the FPSO in rest condition in the basin.

As mentioned earlier, the FPSO did not include process equipment or the associated wind effects. Therefore, the specified forces and moments should comply with OCIMF [14]. However, since the bow shape was significantly changed to prevent green water and no longer matched a standard VLCC, OCIMF would give wrong results. Therefore, the coefficients were measured in the basin. A significant difference was found between the measured and the OCIMF C_X, C_Y and C_N coefficients. The measured coefficients were used for all further computations.

By means of the measured coefficient for $\psi_{wr}=180^0$, the 1-hour mean wind force was computed and adjusted on the model. After the 1-hour average was adjusted, the wind force spectrum was calibrated (seed #1, seed #2 and seed #3).

The wind loads were adjusted with the structures in the projected "center" of the structure in rest position in the basin. Since the structures are moored in relatively deep water, the mean displacement may be several meters further from the position where the wind was adjusted introducing accuracies. To improve the location independency of the structures with regard to the wind loads a double row of wind fans were placed on the battery. In this way, a relatively larger area with approximately homogeneous wind speed was achieved. For more details, see [15], [18] and [19].

Model of the FPSO, SPAR and TLP systems

Models of the FPSO system consisting of the hull (wood), turret (steel and aluminum), chains (chain), steel wires (steel wires) and risers (silicon hose with internal steel wire) were manufactured according the specification for dimensions, weight and stability data. Deviations from the specification were reported.

The model of the Spar consisting of the hull including soft tank, hard tank, and buoyancy can guide frame were made from PVC. The buoyancy cans and keel riser guides were also PVC. The chains, steel wires and risers were modeled in the same way as for the FPSO. Deviations from the specification for dimensions, weights and stability data were reported.

Three sets of strakes were manufactured for the Spar. The strakes had a height of 3.65 m and a pitch ratio of 5. The strakes were nearly over the full draft with an interruption over the mooring line–pulley area.

The TLP model was made of PVC with the tendons of hollow PVC tube. The risers were made in similar way as for the FPSO and Spar. The tendon axial and bending elasticity were modeled as close as possible to the specification. The risers did not include constant force tensioners. Instead, the risers were directly connected to the TLP. Deviations from the specification of dimensions, weights and stability data were reported.

For the FPSO, Spar and TLP risers, the outer diameter, underwater weight and the axial elasticity were modeled as close as possible to the specifications.

For more details, reference is made to [15], [18] and [19].

Model test set-up

The basin has a prescribed current direction. In hurricane and loop-current direction, the orientation with regard to the current was different. As a result, the complete set-up for the FPSO, Spar and TLP had to be changed from hurricane to loop-current condition. For more details, reference is made to [15], [18] and [19].

Instrumentation

The following measurements were carried out:

FPSO	#
DOF	6
relative wave height bow	1
Turret: Fx, Fy, Fz, Mx*), My*)	5
Mooring line force (top)	12
(vertical) Axial riser force (top)	13
Spar	
DOF	6
Relative wave height moonpool	1
Mooring line force (top)	14
Axial riser force	3
Heave motions buoyancy cans	3
TLP	
DOF	6
Accelerations platform	3
Relative wave height-air gap	5
Tendon and risers forces	24
Axial force tendon at base	1

*) Presented at the level of the turntable

High frequency forces in the risers due to VIV or second order sum frequency force oscillations in the tendons of the TLP were expected. For this reason, all signals were sampled at 50 Hz. For more details, reference is made to [15], [18] and [19].

Test program

The test series for the FPSO, Spar and TLP test were carried out during 3 tests of 3 hours each. The wave train and wind spectra for each test used a different random seed for both hurricane and loop-current conditions. Prior to the test in the combined wind, wave and current tests, the following fundamental tests were carried out in both hurricane and loop-current condition (see [15], [18] and [19]):

FPSO

-Surge static load - displacement test (still water)
-Surge and roll decay test (still water)
-Current only test
-Surge decay test in current
-Wind only test (1-hour mean)
-Current + wind test (1-hour mean wind).

Spar

-Surge static load - displacement test (still water)
-Surge, heave and sway decay without strakes (still water)
-Roll and pitch decay without strakes (still water)
-Heave decay of the 3 instrumented risers (still water)
-Loop-current without strakes during 3 hours
-Loop-current with strakes during 3 hours
Further, all tests were carried out with strakes
-Surge, heave and sway decay in current
-Roll and pitch decay in current (only loop-current)

-Wind only test (1-hour mean)
-Current only tests
-Current + wind test (1-hour mean)

TLP

-Surge static load - displacement test (still water)
-Surge and heave decay test (still water)
-Current only test
-Surge decay test in current
-Wind only test (1-hour mean).

Presentation

The results were presented as statistical analysis of the total signal and, for selected signals, the high frequency, wave frequency and low frequency part of the signal. Time-domain plots were presented of the motions of the structure in the horizontal plane. Additionally, response spectra, RAOs and Weibull curves of selected signals were given. The complete set of results is presented in [15], [16], [17], [18], [19], [20], [21] and [22].

Conclusions

The following conclusions can be drawn:

1) The series of tests were carried out with a high accuracy to guarantee quality benchmark tests for the analysis.
2) All deviations from the specifications were extensively reported.
3) To study the low frequency turbulence of the current in the basin, measurements have to be carried out in both x-, and y-directions.

Conclusions regarding results of analyses and comparisons between model test and analytic results can be found in other OTC papers ([4], [5], and [6]).

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	Full Scale			**Model Scale 1:87**		
Component Diameter	**Diam**	**Current V in m/s**		**Diam**	**Current V in m/s**	
	m	**2.13**	**1.07**	**m**	**0.23**	**0.11**
		Prototype Re			**Model Scale Re**	
FPSO						
3.5" wire rope	.089	1.6E+05	8.0E+04	.001	2.0E+02	9.9E+01
3.5" chain	.089	1.6E+05	8.0E+04	.001	2.0E+02	9.9E+01
17.5" production riser	.445	8.0E+05	4.0E+05	.005	9.9E+02	5.0E+02
15.2 " gas production riser	.386	6.9E+05	3.5E+05	.004	8.5E+02	4.3E+02
14.8" water injection riser	.376	6.7E+05	3.4E+05	.004	8.3E+02	4.2E+02
8 " gas injection riser	.203	3.6E+05	1.8E+05	.002	4.5E+02	2.3E+02
13.5" gas export riser	.343	6.1E+05	3.1E+05	.004	7.5E+02	3.8E+02
TLP						
44" tendon	1.118	2.1E+06	1.0E+06	.013	2.5E+03	1.2E+03
21" drilling riser	.533	9.6E+05	4.8E+05	.006	1.2E+03	5.9E+02
14.25" production riser	.280	5.0E+05	2.5E+05	.003	6.2E+02	3.1E+02
Spar						
5.375' wire rope	.137	2.5E+05	1.3E+05	.002	3.1E+02	1.5E+02
5.25" chain	.133	2.4E+05	1.2E+05	.002	3.0E+02	1.5E+02
21" drilling riser	.533	9.6E+05	4.8E+05	.006	1.2E+03	5.9E+02
14.25" production riser	.362	6.4E+05	3.2E+05	.004	7.9E+02	4.0E+02
8.625" water injection riser	.219	3.9E+05	2.0E+05	.003	4.8E+02	2.4E+02
6.625" water injection riser	.168	3.0E+05	1.5E+05	.002	3.7E+02	1.9E+02
16" oil export riser	.406	7.3E+05	3.7E+05	.005	9.0E+02	4.5E+02
16" gas export riser	.406	7.3E+05	3.7E+05	.005	9.0E+02	4.5E+02

Table 1: Scale effects on slender members

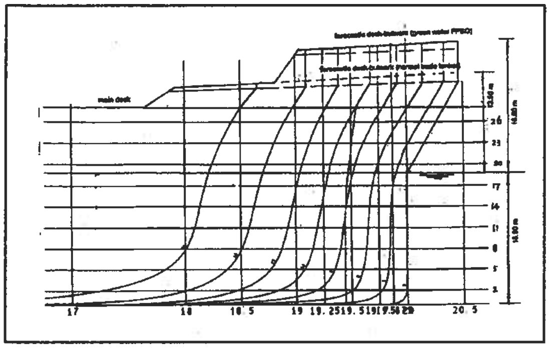


Figure 1: Bow configuration of FPSO

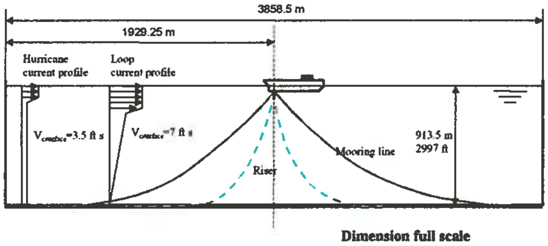


Figure 2: Test set-up FPSO system in basin

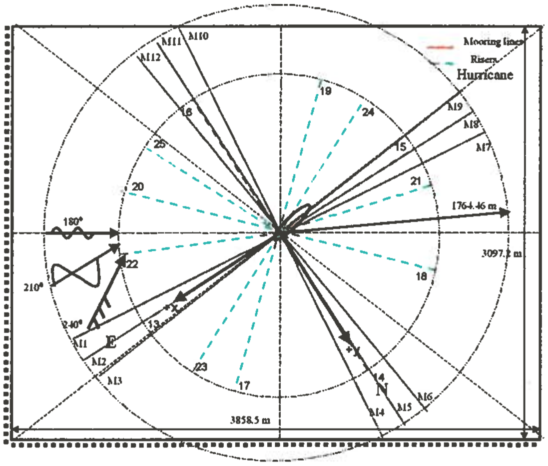


Figure 3: Test set-up of FPSO system in hurricane condition

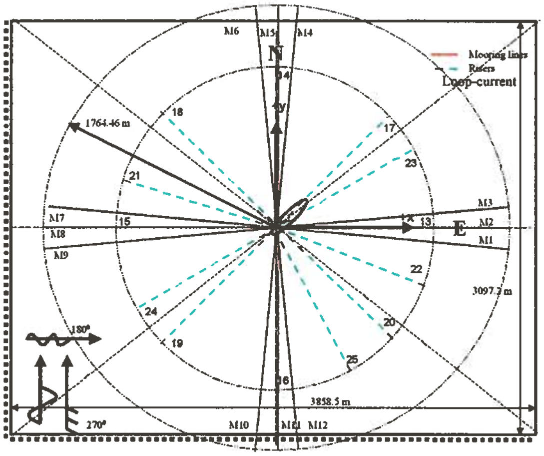
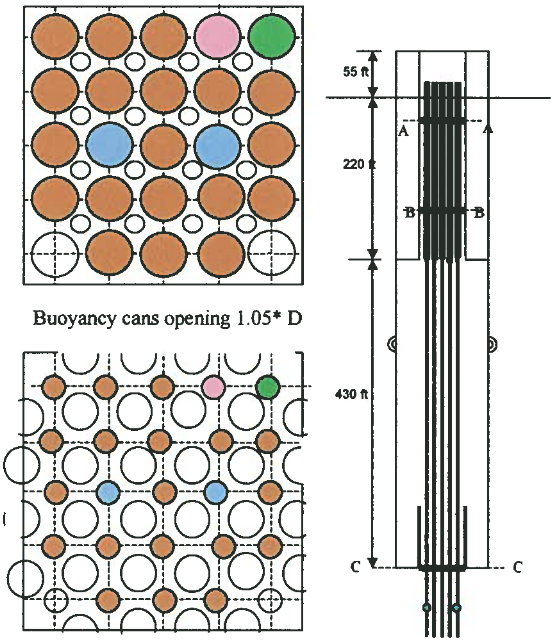


Figure 4: Test set-up of FPSO system in loop-current condition



Buoyancy cans opening 1.05* D

Keel guides opening 1.2* D

Figure 5: Distribution of risers in the Spar

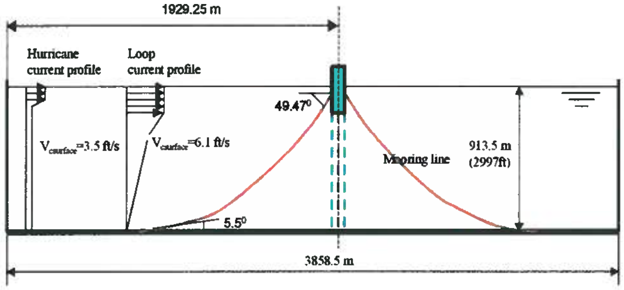


Figure 6: Test set-up of Spar system in basin

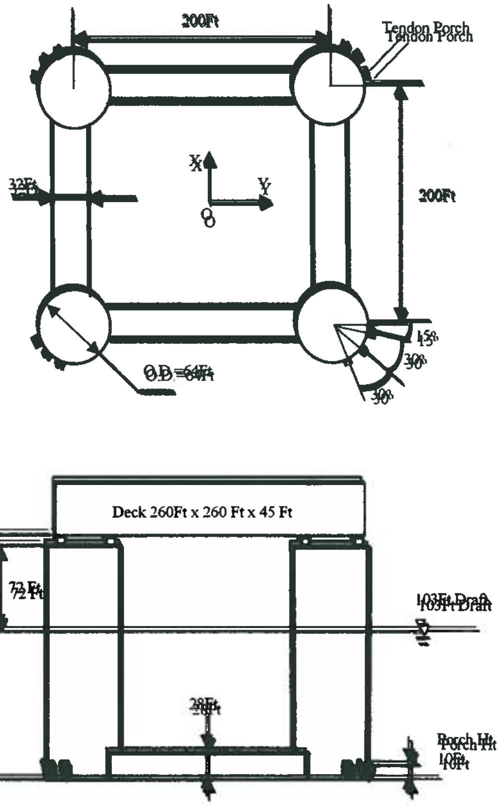


Figure 8: Layout of TLP in 6,000 ft water depth

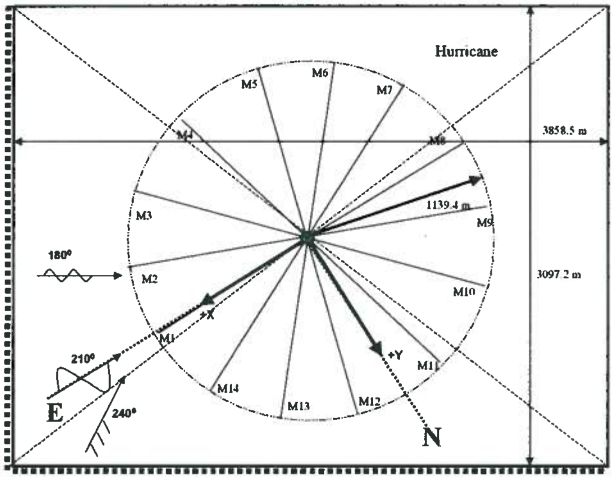


Figure 7: Test set-up of Spar system in hurricane condition

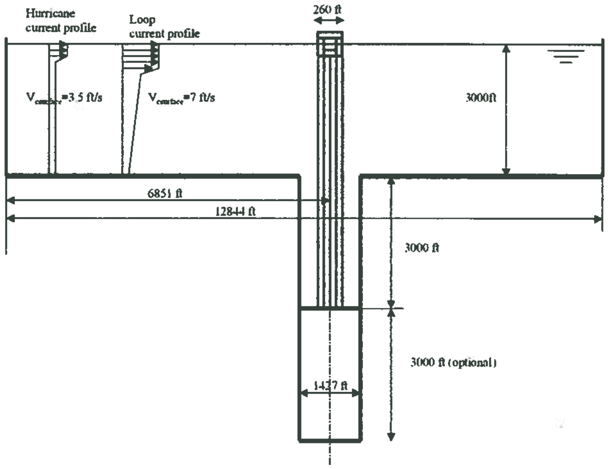


Figure 9: Test set-up of TLP system in basin in 6,000 ft water depth

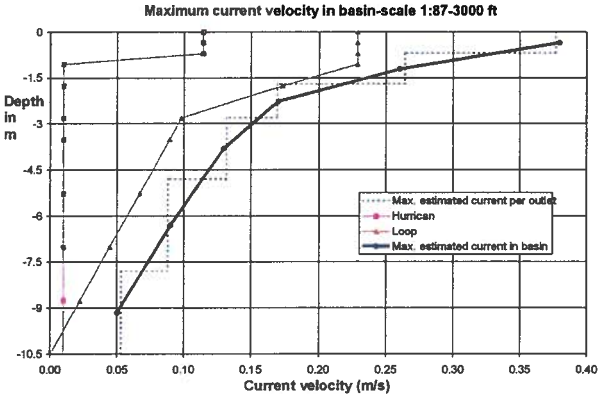


Figure 10: Specified current profiles and maximum estimated current velocities in the basin (model scale for depth and current velocities)

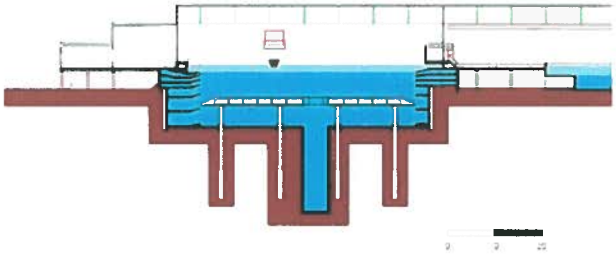


Figure 12: Cross section over the basin

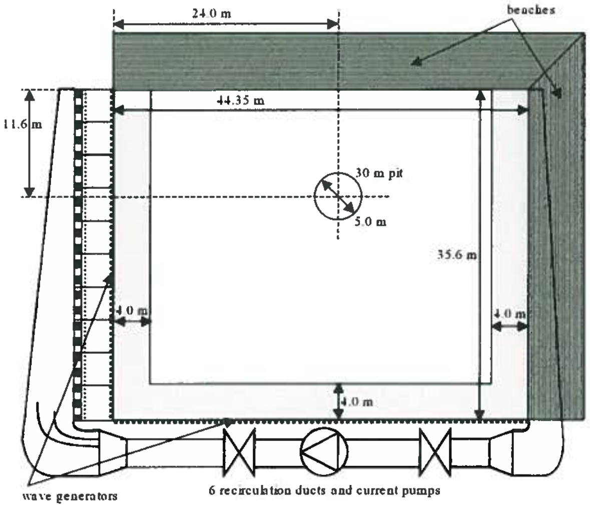


Figure 11: Top view of the basin

Figure 13: Layout of moveable floor in the pit

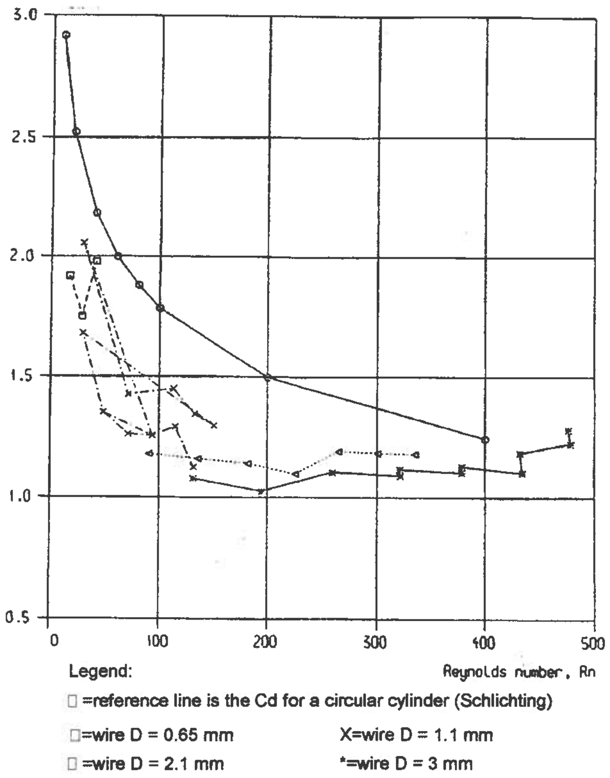


Figure 14: Drag coefficients for steel wires at low Reynolds numbers [12]

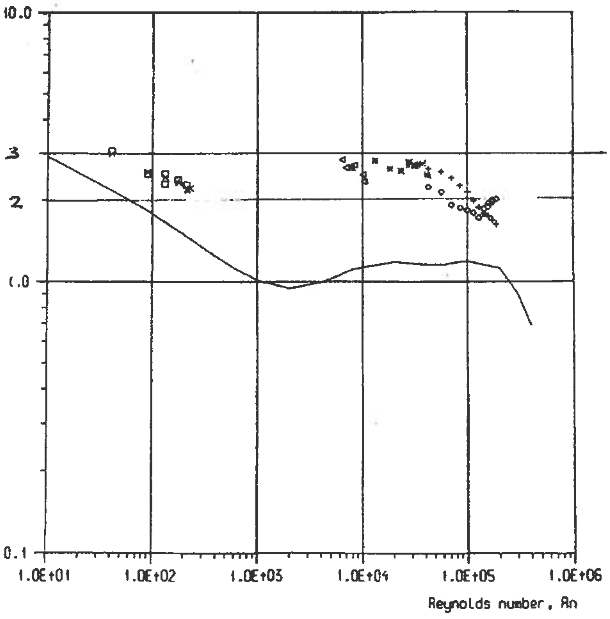


Figure 15: Drag coefficients of chain for model and prototype scale [10] and [12]

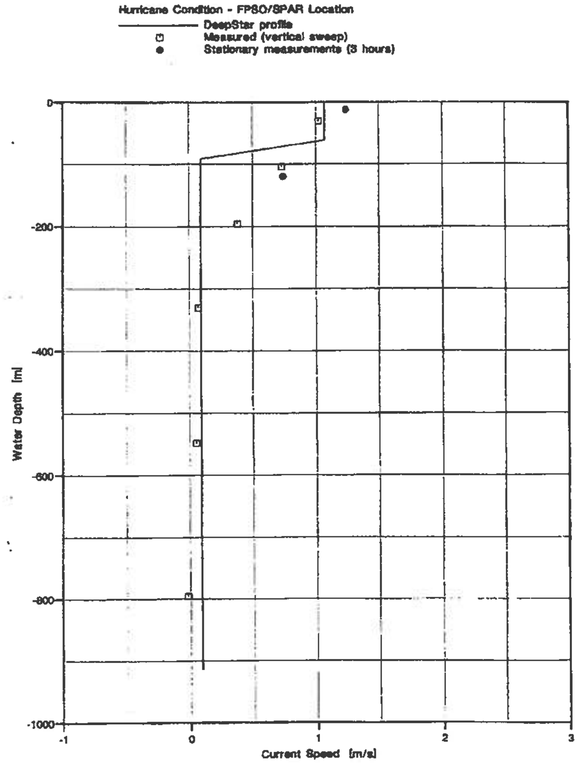


Figure 16: Specified and measured current profile-hurricane

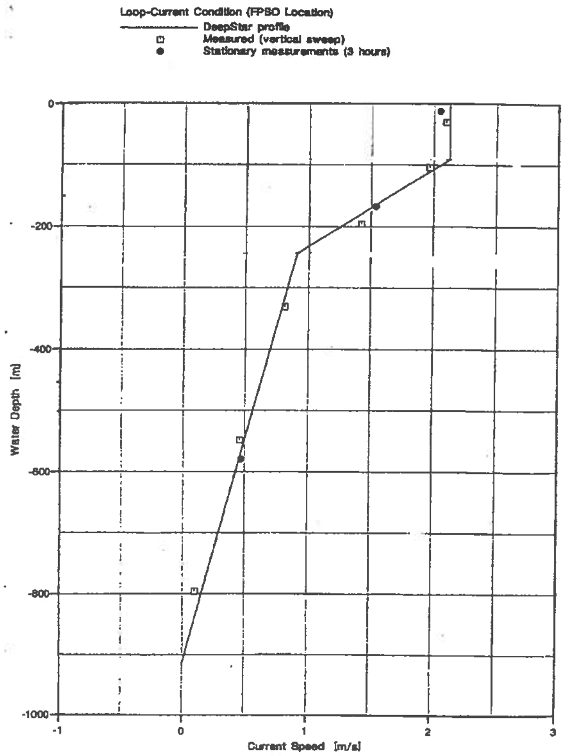


Figure 17: Specified and measured current profile-loop-current

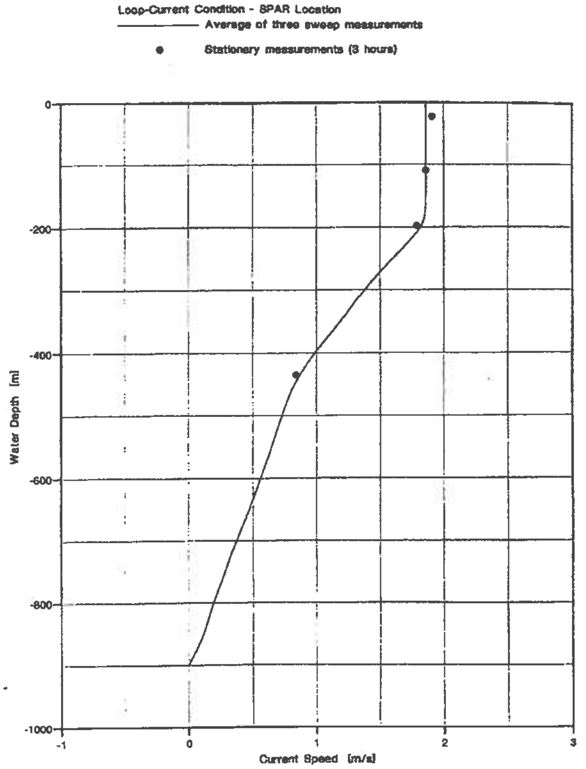


Figure 18: Adapted loop-current profile for Spar structure

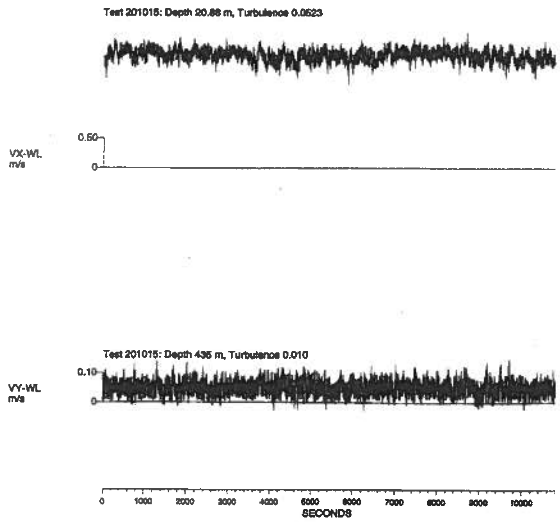


Figure 19: Current measurements for loop-current profile at depth of 20,88m full scale

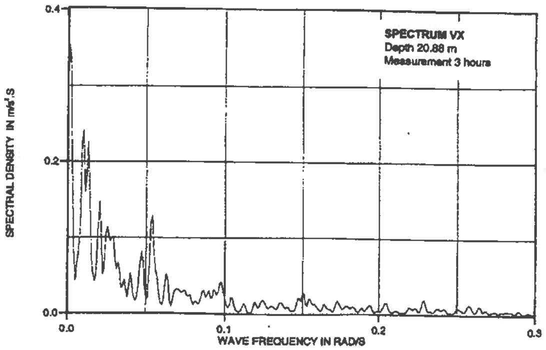


Figure 20: Turbulence spectrum of in-line current

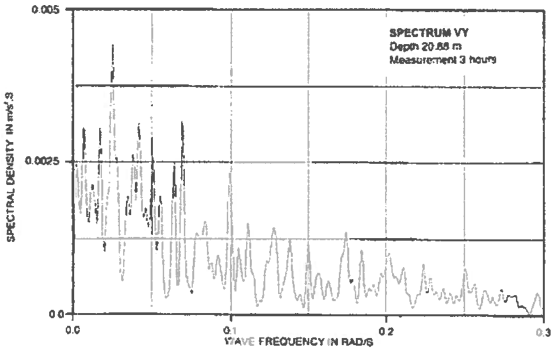


Figure 21: Turbulence spectrum of transverse current

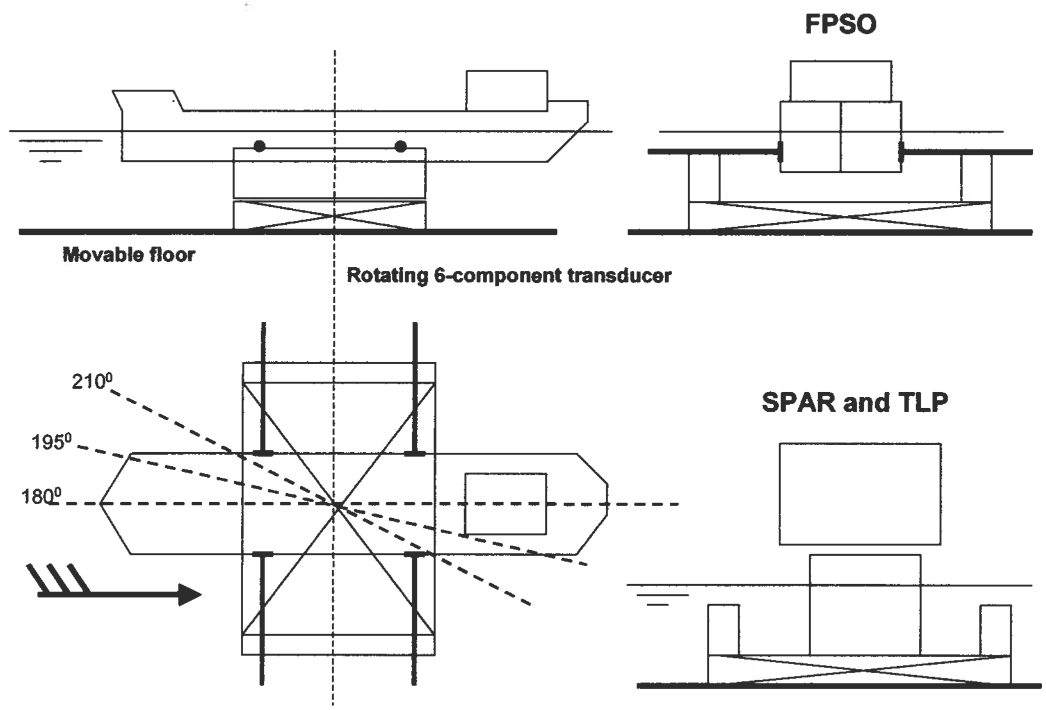


Figure 22: 6-compartment force balance transducer

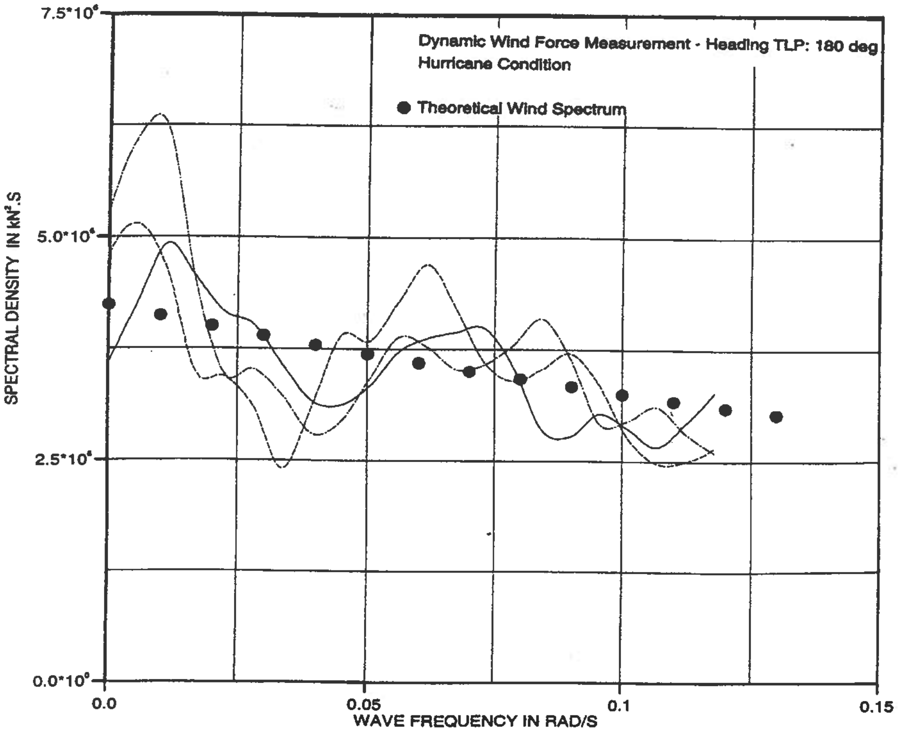


Figure 23: The theoretical and measured wind force spectra on the TLP (seed #1, seed #2, seed #3) under a wind direction of 180°-hurricane