47

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Behaviour of turret moored tankers in combined extreme metocean parameters

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Abstract

At present the mooring technology of turret moored tankers is challenged as exploration activities for oil and gas move into deep and ultra-deep water and more hostile environments. The more hostile environment concerns the Atlantic Frontiers and the typhoon prone areas. For the field development in these water depths and under these weather conditions, the availability of a cost effective mooring system can be a important factor in determining economic success. The approach for developing fields in the mentioned areas has typically relied upon the adaption of mooring technology developed for shallower water depth applications.

To improve the understanding of and the insight in the reliability and integrity in the application in the deep water mooring systems, numerical design tools can be used. As the numerical design tool a by model tests validated computer program based on the fully integrated dynamics of turret moored F(P)SO systems has been recently developed and applied to deep water. Further the computer program can be used to optimize the system and to enhance the safety of the design by applying numerous combinations of extreme weather conditions in order to discern the most severe weather condition.

In this paper the program has been described. The results of the validation with model tests on a tanker moored with a conventional mooring system in 350 m water depth are shown. The results of the computations agree well with the results of the model tests. Finally by means of computations with the tanker moored with a conventional system with and without spring buoys were investigated in 400 and 1200 m water depth applications. By varying extreme metocean parameters the understanding of and the insight in the reliability and integrity in the mooring system can be improved.

Introduction

The theoretical approach to mooring problems has been advanced considerably in the last decades. In 1971 theoretical knowledge of mooring systems did hardly exist. With the establishment of the 3-D diffraction theory in 1976, see Ref. 1, computations of the transfer functions of first order tanker motions with a high reliability could be carried out. Based on this program it became also possible to compute accurately the matrices of the quadratic transfer functions of the second order wave drift forces in 1980, see Ref. 2.

In order to compute the low frequency (l.f.) tanker motions in the horizontal plane, the speed dependent wave drift forces and the required quadratic transfer function of the wave drift damping were necessary. The computations with a tanker with forward speed in head waves were carried out with a reasonable degree of accuracy in 1988, see Ref. 3. Furthermore the procedure to determine experimentally the l.f. hydrodynamic viscous reaction forces and moment in the horizontal plane were also established in 1988, see Ref. 3. The CFD code to compute the quadratic transfer function of the wave drift forces with forward speed with current and waves coming from arbitrary direction were completed in 1996, see Ref. 4.

Besides the l.f. hydrodynamic viscous and wave drift damping forces as acting on the tanker hull also an important part of the system damping is introduced by the mooring line dynamics, see Ref. 5. With the development of the theoretical model for line dynamics in 1985, see Ref. 6, it was possible to show the importance of the low frequency damping induced by the line dynamics, see Ref. 7.

In order to compute the behaviour of F(P)SO systems all mentioned codes and tools were incorporated in a time domain computer program named Dynfloat. Pre-studies with the program in the development stage were reported in Ref. 8 and 9.

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Description of the Numerical Design Tool

The computer program Dynfloat determines the fully integrated dynamics of a tanker based floating (production) storage offloading system for deeper water. The program has been developed as a Joint Industry Program (JIP). The project was joined by seven companies in the field of the design, contracting, operation and building of FPSOs. The program computes in the time domain the dynamic forces of all mooring legs and couples these forces with the tanker. In this way the mooring line damping forces are implicit in the equations of motion. The computation procedure is given in the diagram of Figure 1.

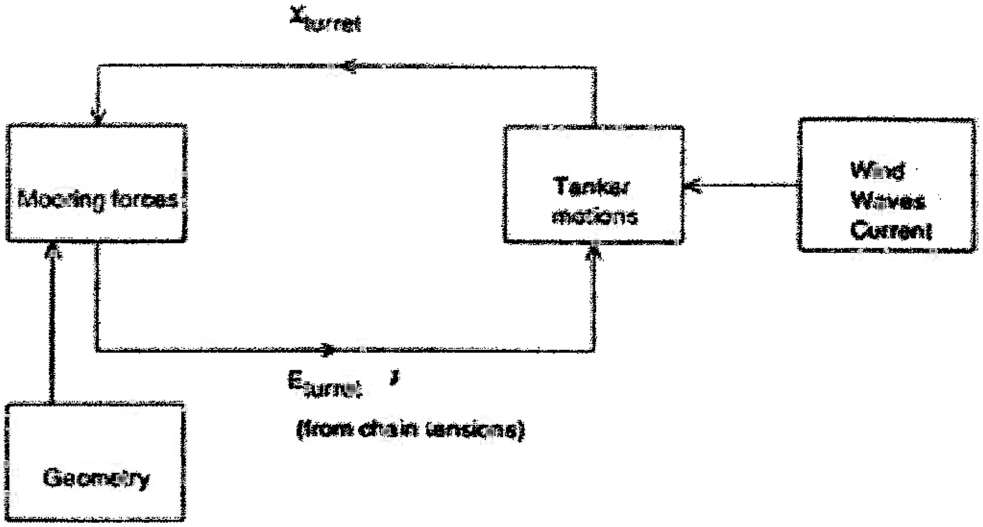

Figure 1 - Computational procedure

The results of the program are the time registrations and the statistical analysis of the mooring line forces, turret loading, possible riser forces and tanker motions.

In the following the description will be given of the mooring systems, the wave frequency motions and wave drift forces/moment and l.f. hydrodynamic viscous reaction forces and moment to be applied to the program.

Mooring. Figure 2 examples of deep water mooring systems are shown. The legs of the conventional mooring system may mainly consist of a combination of lengths of steel wires and chains (combi-lines). In order to prevent a high vertical pre-tension at the turret at deep water the mooring legs can be provided of spring buoys. An additional advantage is the creation of room for risers. Nowadays also mooring legs may consist of taut synthetic wires (buoyancy neutral) and may create the same advantages as mentioned for the spring buoy system.

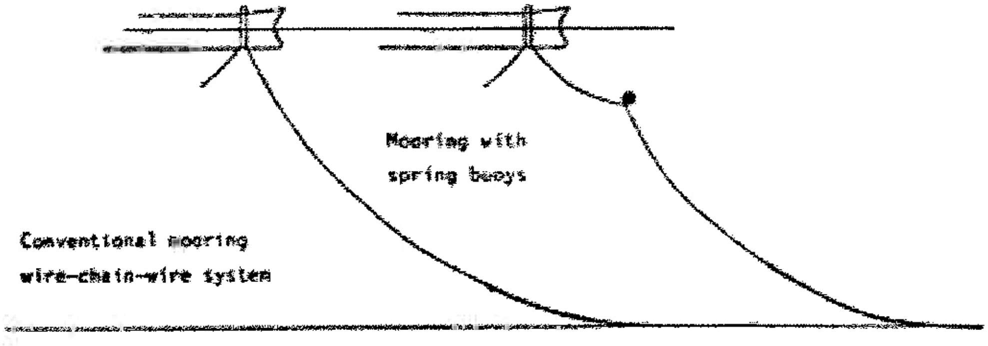

Figure 2 - Applied mooring systems in 400 m and 1200 m water depth

The legs (incl. possible clumps and spring buoys) can be composed using database options on the mooring line materials. The corresponding hydrodynamic reaction coefficients C_{IN}, C_{TT}, C_{DN} and C_{DT} have to be selected separately. Also friction coefficients between the legs and the seabed being C_{FN} and C_{FT}can be applied. Finally the mooring system is subjected to the different options for specifying the fairlead, anchors and seabed inclination.

By means of graphical checks the lay-out of the mooring arrangement (top view/side view) incl. turret mooring fairleads can be judged.

Wave frequency tanker motions and wave drift forces/moment. The transfer functions of the tanker motions, the quadratic transfer function of the wave drift damping and the matrices of the quadratic transfer functions of the wave drift forces are pre-calculated and stored in 60 files. Each file covers one specific tanker in a specific condition. The available wave directions are 180, 165, 150, 135, 120, 90, 60, 30, 15 and 0 degrees. The drafts of the tankers concern 100, 70 and 40% of the fully loaded draft. Further the data for the following ratio water depth/fully loaded draft are available: 20, 5, 3, 1.5, 1.2.

Four tanker forms are incorporated in the database. The tankers have the following characteristics: L/B = 5.00 and B/T = 2.91; L/B = 6.06 and B/T = 2.42; L/B = 6.55 and B/T = 2.77; L/B = 6.57 and 2.50.

If a particular tanker and condition is required the user can incorporate the data by means of an external file.

By means of the synthetic wave train as derived from the wave spectrum or a measured wave train read-in by an external file, the wave frequency motions and the wave drift forces/moment with or without current (including wave drift damping) are computed in the time-domain for all mentioned wave directions and stored for the actual simulations. During the simulation a linear interpolation as function of the tanker heading with regard to the wave direction will be carried out on these results.

Low frequency hydrodynamic viscous reaction forces and moment. The wave induced first order tanker motions, the wave drift forces and the wave drift damping forces can be computed by CFD codes. For the l.f. hydrodynamic viscous reaction forces and moment in surge, sway and yaw direction no CFD codes exist giving adequate results. The l.f. hydrodynamic viscous reaction forces and moment have to be determined experimentally. For tankers with different L/B, B/T ratio's, water depth to draft ratio's and loading conditions, the l.f. (non-linear) dynamic resistance force and moment coefficients have been determined by means of model tests. The coefficients were determined in both still water and current fields.

For the determination of the coefficients use is made of a l.f. large stroke oscillator. The oscillator is mounted to a carriage. By towing a current field is simulated. The tanker is connected to the oscillator by means of three force transducers. In this test set-up the tanker stays free to roll, pitch and heave. The oscillator can perform pre-adjusted l.f. amplitudes and periods in one of the three modes of motion or by combining the motions in two directions. By means of the measurements the (non-linear) dynamic l.f. hydrodynamic viscous reaction forces and moment coefficients can be deducted. The results are stored in data bases in a non-dimensional form. For a description of the test procedure and data analysis reference can be made to Ref. 3.

Combined Metocean Parameters

The F(P)SO system may be exposed to irregular waves, wind and current. The particulars of wave, wind and current can be chosen.

Waves. The irregular waves may consist of both wind waves and swell of arbitrary spectral form and direction.

Wind and current. For the wind a constant wind speed combined with a windspectrum may be applied. For the current the arbitrary vertical current profile, a time dependent current profile or a time trace concerning current speed and direction (manual read-in or by means of an external file) can be used.

For the computation of the wind and current loads use is made of the resistance coefficients as given by OCIMF, see Ref. 10 . The coefficients are incorporated in a data base. Other resistance coefficients incl. process equipment on deck can be manualy read-in.

Validation

In this paper an example of the results of the validation study is shown. The validation concerns a partly loaded 200 kDWT tanker moored by means of an internal turret system in 350 m water depth. The mooring system consists of ten radially spaced combi-lines. The system was exposed to a survival seastate in combination with collinearly directed current and wind.

For the computations use was made of pre-computed transfers functions of the wave frequency motions, the wave drift forces and the wave drift damping and read-in by an external file into the program. The transfer functions were applied to the wave train as adjusted in the basin. The wave train has a length of 3 hours full scale.

Wind was generated by means of a battery of wind fans. The adjusted wind force as applied during the model tests was used in the computation. For the total wind force the relative wind velocity concept was applied (to incorporate the wind damping).

For the tanker hull the low frequency hydrodynamic viscous reaction forces were applied as given in the database of the program (no additional surge damping was applied).

Due to the relative motions of the steel wires and chains in waves and current hydrodynamic reaction forces are introduced. For the hydrodynamic resistance coefficients of both the chain and steel wires the following values were used: C_{IN}=1.6, C_{IT} =1.2, C_{DN}=1.3 and C_{DT}=0.4.

The statistical results of the model tests and the computations are given in Table 1. From the results it can be concluded that a good agreement is achieved.

TABLE 1 - Measured and computed results of a tanker moored in 350 m water depth

Notation	unit	Mean		St.dev		Min		Max.
		Measured	Dynfloat	Measured	Dynfloat	Measured	Dynfloat	Measured
Surge	m	-47.75	-41.28	13.54	13.71	-94.49	-87.26	-10.81
Heave	m	-0.80	-0.01	5.07	5.05	-19.07	-19.11	16.53
Pitch	deg	0.24	0.00	1.91	1.89	-7.27	-6.85	6.29
Ten. L. 1	kN	3155.59	2587.43	1071.23	1094.57	680.84	20.15	9630.58
Ten. L. 2	kN	2517.23	2152.32	911.82	885.40	361.03	0.00	8256.25

Ten. L. 5	kN	584.77	632.73	193.26	291.74	170.02	0.00	1546.56
Ten. L. 6	kN	479.33	581.39	149.78	277.17	137.29	0.00	1332.94
Ten. L. 9	kN	1517.83	1355.05	554.54	517.42	265.96	0.00	5155.63
Ten. L. 10	kN	2589.68	2151.70	909.95	885.76	455.10	0.00	8513.59
Fx - T	kN	5158.13	4977.49	2336.09	2464.88	166.15	114.51	16602.45
Tz - T	kN	-10306.96	-9358.33	3486.64	3610.44	-31138.09	-34151.82	1501.03

Deep Water Mooring Systems

As an example computations were carried out for a F(P)SO to study the effects of both different weather parameters and water depths on the overall behaviour of the mooring systems. The systems were with and without spring bouys. The water depths chosen were 400 m and 1200 m. An 200 kDWT tanker was applied in both loaded and ballasted condition.

Extreme metocean parameters. To both water depths 5 survival weather conditions consisting of collinearly directed irregular waves, wind and current were applied. A review of the weather conditons are given in Table 2. In the survival seastates No. I, II and III all parameters were kept constant except for the peak period of the Jonswap spectra. For lower seastates IV and V all parameters of the weather conditons were changed.

TABLE 2 - Review combined metocean parameters applied to loaded and balasted tanker

Sea state No.	JONSWAP $\gamma = 3.3$		Current	Wind
	H_S (m)	T_P (s)	V_C(m/s)	V_W(m/s)
1	16	20.0	1.2	50
2	16	17.5	1.2	50
3	16	15.0	1.2	50
4	13	12.0	1.0	40
5	10	9.0	0.8	30

Tanker and mooring systems. The tanker concerns a loaded and ballasted 200 kDWT tanker. The particulars are given in Table 3. The mooring systems were connected to an internal turret systems. The particulars of the turret are given in Table 4. The mooring systems consist of conventional 10-leg configurations with and without spring buoys. For the mooring legs with spring buoys in each leg one spherical buoy was attached to the mooring leg. The global lay-out of the mooring system is presented in Figure 3. The particulars of the mooring legs and spring buoys are given in Table 4. The static load-displacement curve (pulled over line no. 6) of the four mooring systems are given in the Figures 4 and 5.

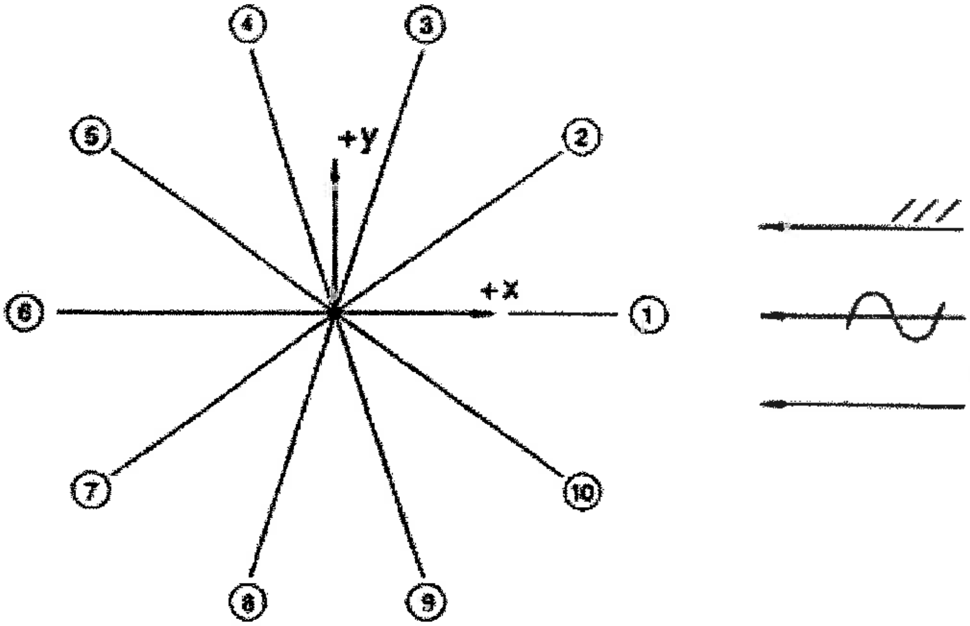

Figure 3 - Layout of mooring system in 400 and 1200 m water dedth

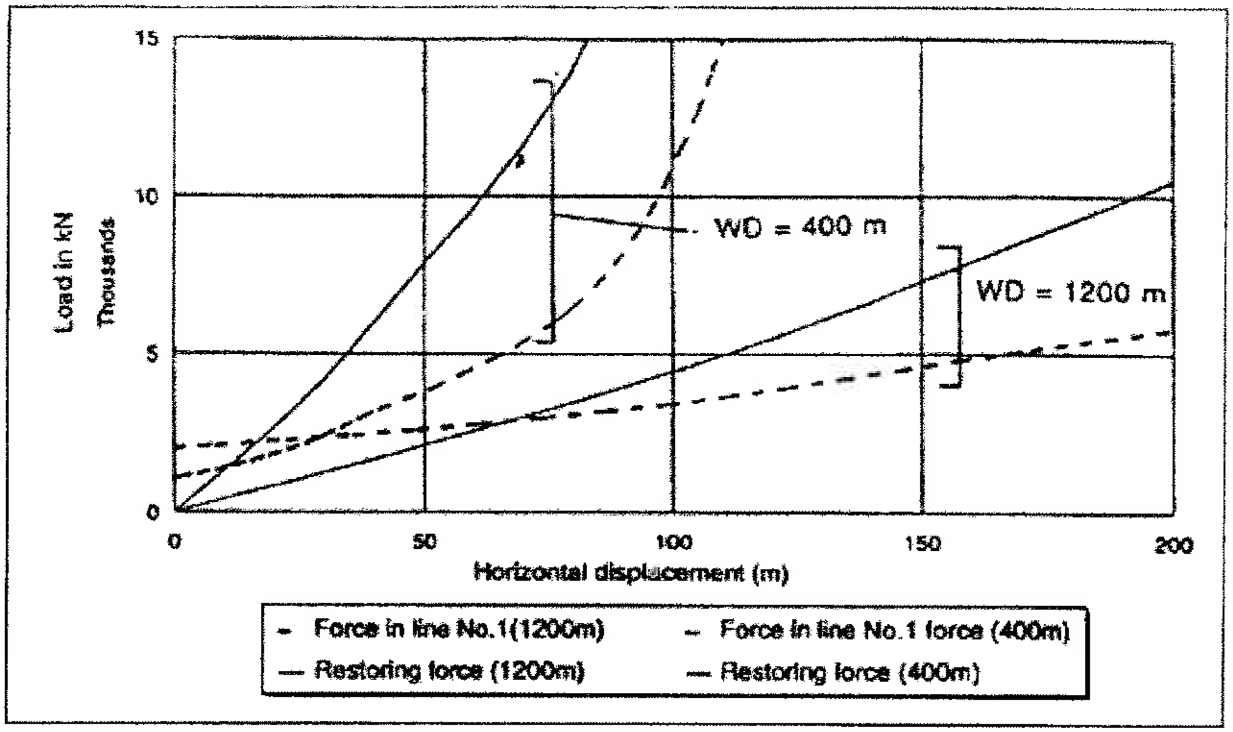

Figure 4 - Static load-displacement curves without spring buoys (200 kDWT tanker - 100% loaded)

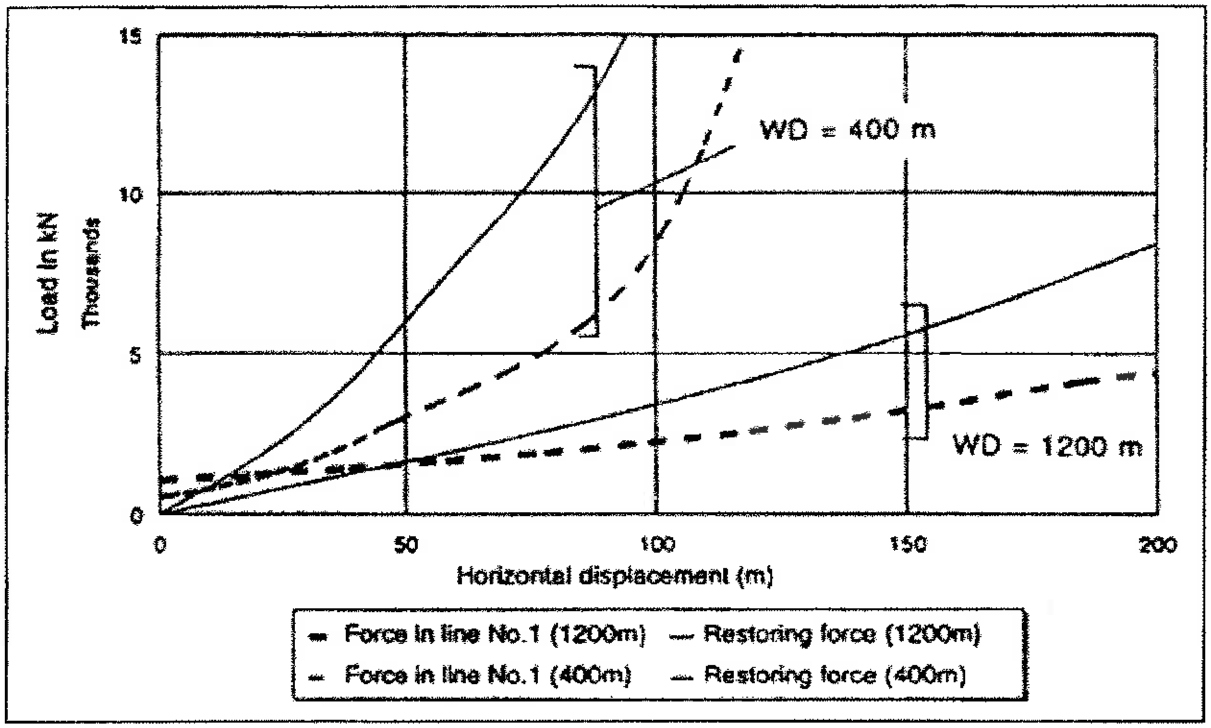

Figure 5 - Static load-displacement curves with spring buoys (200 kDWT tanker - 100% loaded)

TABLE 3 - Main particulars of 200 kDWT tanker

Designation	Symbol	Unit	Magnitude	
			Loaded	Ballasted
Length between perpendiculars	L_{PP}	m	310	310
Breadth	B	m	47.17	47.17
Depth	D	m	29.70	29.70
Draft	T	m	18.90	7.56
Displacement volume	V	m^3	234994	88956
Center of buoyancy forward section 10	X_B	m	6.60	10.46
Center of gravity above keel	Z_g	m	13.32	13.32
Longitudinal radius of gyration in air	K_{YY}	m	77.47	82.15
Transverse radius of gyration in air	K_{XX}	m	14.77	15.30

Vertical radius of gyration in air	K_{ZZ}	m	79.30	83.90
Wind area frontal	A_F	m^2	1362	1879
Wind area side	A_S	m^2	4270	7785

TABLE 4 - Particulars of mooring systems

Designation	**Unit**	**Water depth**			
		400 m	**1200 m**	**400 m**	**1200 m**
		no buoy	**no buoy**	**with buoy**	**with buoy**
Mooring system:					
Pre-tension angle	deg	45.3	59.8	36.2	48.0
Pre-tension	kN	1079	2060	530	1030
Chain table above sea bottom*	m	381.1	1181.1	381.1	1181.1
Length of mooring leg	m	2100	2800	2100	2800
Diameter turret	m	10	10	10	10
Center turret behind F_{PP}	m	38.75	38.75	38.75	38.75
Segment 1: steel wire					
Length from turret	m	200	300	200	300
Diameter	inch	5.5	5.5	5.5	5.5
Mass	kg/m	83	83	83	83
Stiffness (EA)	kN	1.15×10^6	1.15×10^6	1.15×10^6	1.15×10^6
Breaking strength	kN	15990	15990	15990	15990
Spherical buoy properties:					
Diameter	m	-	-	4.68	7.12
Total weight dry	kN	-	-	206	408
Net buoyancy	kN	-	-	334	804
Segment 2: steel wire					
Length	m	400	1100	400	1100
Diameter	inch	5.5	5.5	5.5	5.5
Segment 3: Chain					
Length	m	400	800	400	800
Diameter	inch	5	5	5	5
Mass	kg/m	353	353	353	353
Breaking strength RQ3	kN	11516	11516	11516	11516
Stiffness (EA)	kN	1.39×10^6	1.39×10^6	1.39×10^6	1.39×10^6
Segment 4: Steel wire					
Length to anchor	m	1100	600	1100	600

Diameter	inch	5.5	5.5	5.5	5.5
* loaded tanker					

For the hydrodynamic reaction coefficients of the steel wires and chains, the same coefficients were used as given in the validation study. For the resistance coefficients of the spherical buoy the following coefficients were used: $C_{IN} = 1.5$ and $C_D = 1.0$. In still water the position of the buoys with regard to the vertical turret-axis and the still water level for the loaded tanker: 400 m: z = 118 m; x = 178 m and 1200 m: z = 227 m and x = 221 m.

Simulations. Each simulations lasted for 3.5 hours incl. the start-up time of .5 hour. Only the last 3 hours were analysed. The results of the computations on the tanker surge, the forces in line no. 1 for the four mooring systems given the Figures 6 an 7. The associated longitudinal and vertical turret loadings are given in the Figure 8 and 9. The presented diagrams are based on the statistical output of the computations. For reference also lines are plotted corresponding to the mean plus 4 times the standard deviation.

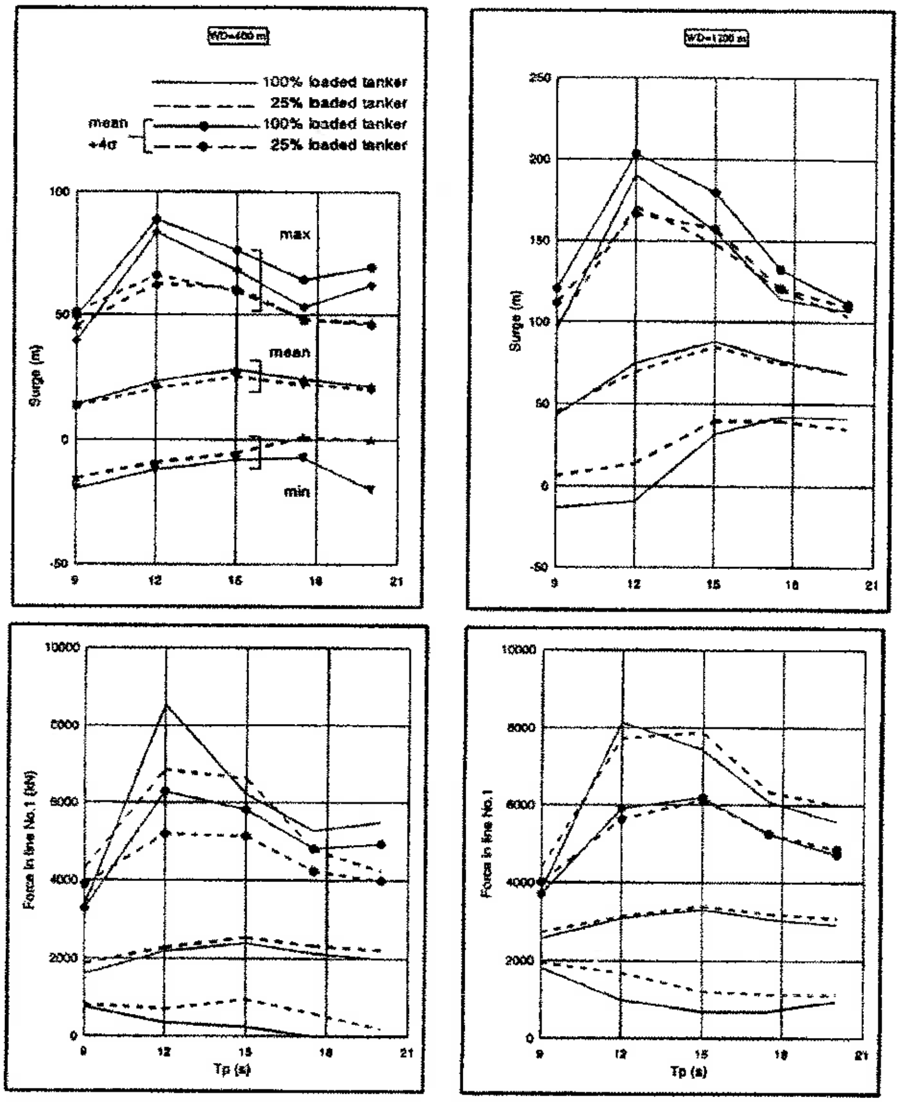

Figure 6 - Statistic results of surge motion and force in line No. 1 (without spring buoys)

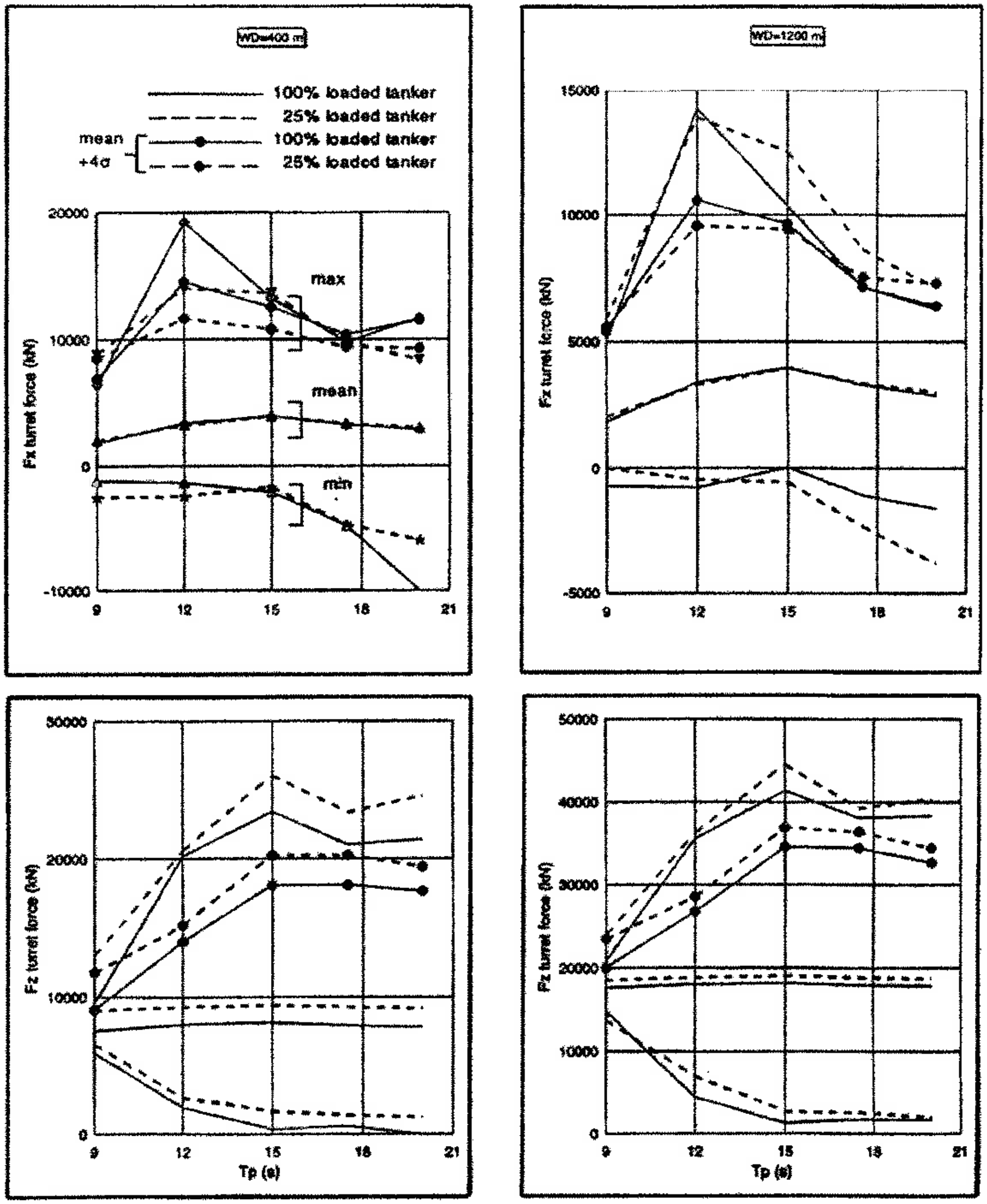

Figure 7 - Statistic results of turret loading (without spring buoys)

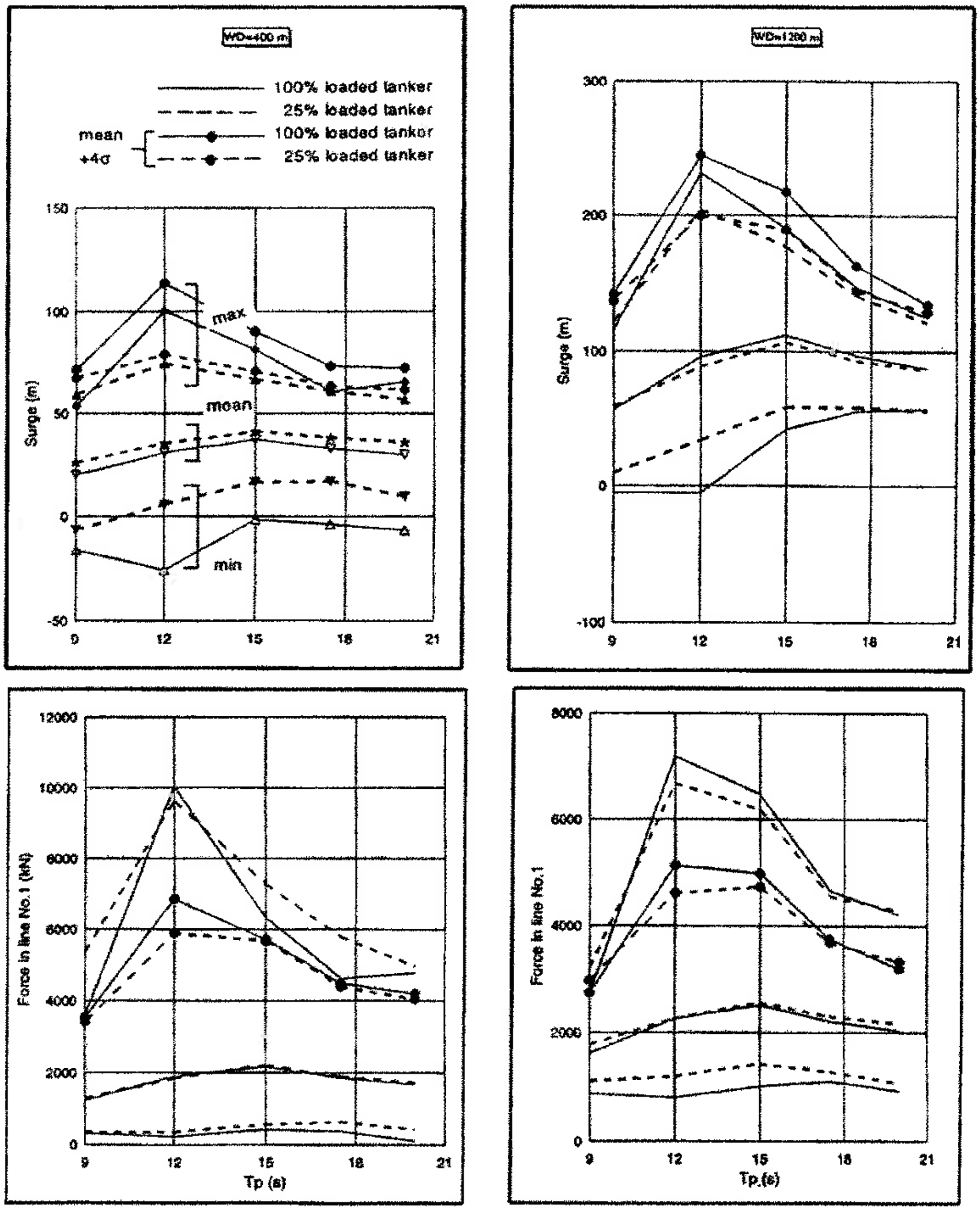

Figure 8 - Statistic results of surge motion and force in line No. 1 (with spring buoys)

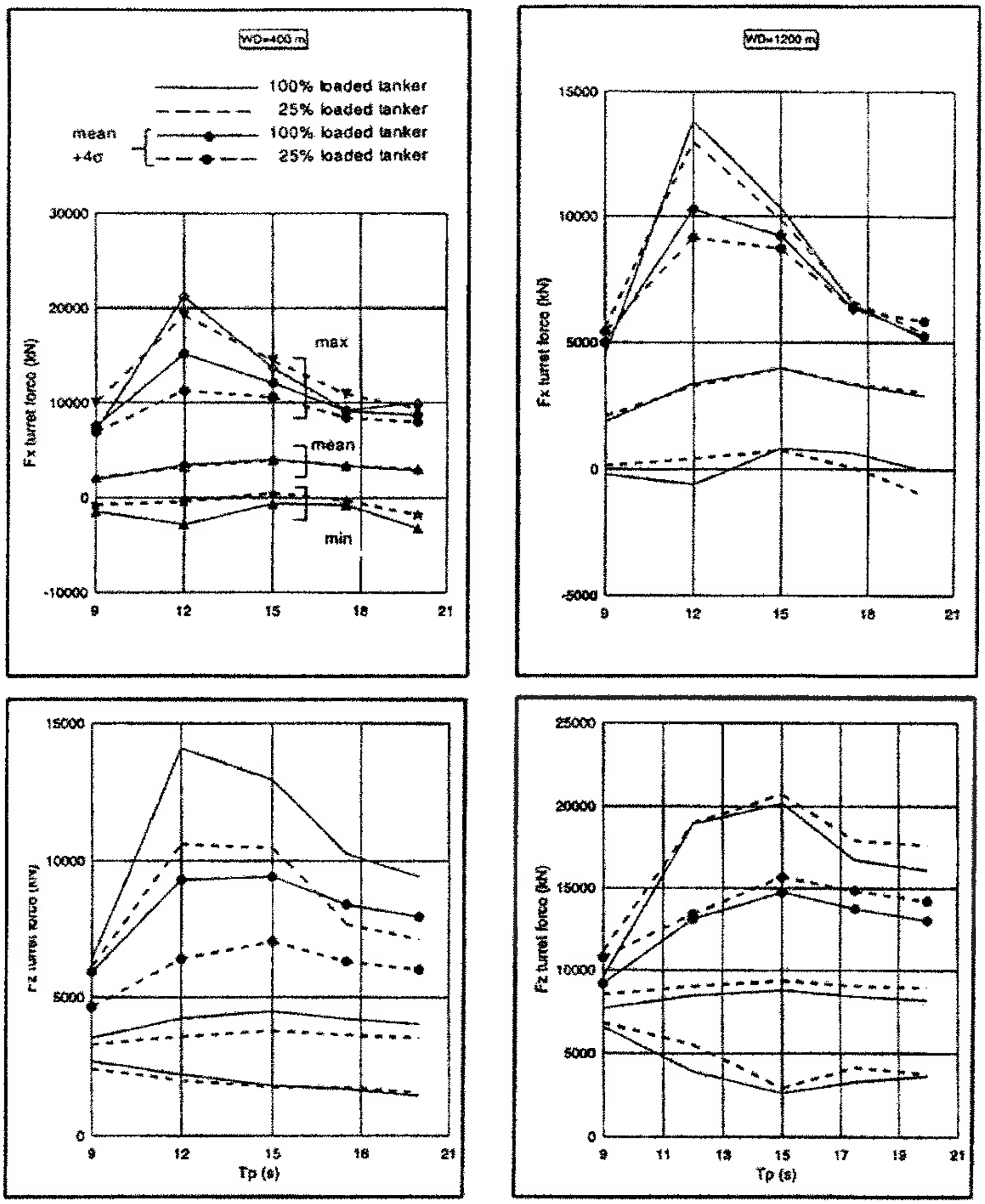

Figure 9 - Statistic results of turret loading (with spring buoys)

Discussion of Results

As shown in the Figure 4 and 5 the stiffness of the mooring systems decrease considerably with increasing water depth. Because of the decreased pre-tension (50%) at the turret in case of spring buoys the systems become even softer.

In terms of percentages of the water depth the computed maximum surge motions for the loaded tanker without and with buoy respectively and for the weather conditions I, II, II IV and V are given below

1200 m water depth: I: 9-10%, II: 9-12%, III: 13-16%, IV:16-19%, V: 8-10%

400 m water depth: I:15-16%, II: 14-15%, III: 16-21%, IV:20-25%, V: 10-14%.

From the results it can be concluded that for the 400 m water depth the riser displacement freedom will be more restricted than for deep water.

For the survival seastates I, II and III it can be concluded that for all cases the mooring loads and surge motions increase at decreasing wave periods. The reason for the increase is the shift of the wave spectra into the transfer function of the velocity dependent wave drift forces. In spite of the decreased significant wave height, current and wind speed in weather condition IV the highest values of the surge motions and mooring loads occur with respect to the survival seastes I, II and III. The reason is that with a peak period of the Jonswap spectrum of 12 seconds, the spectrum covers completely the maximum values of the transfer function of the wave drift force (Vc = 1.0 m/s) resulting in a high values of the wave drift force spectrum. The wave spectrum of weather condition IV must be considered as an extreme low peak period for such a storm wave spectrum (Hs = 13 m).

The ratio of the maximum dynamic force (computed) and the static maximum force (static load) in line No.1 at the same maximum surge motion is called the dynamic factor. All results are given incl. pre-tension. For the loaded tanker in the survival wave spectrum with the varied peak periods for both the 1200 and 400 m water depth respectively the dynamic factor has been determined and given below.

without buoys : Survival I:1.51-1.18, II:1.63-1.24, III: 1.57-1.34

with buoys : Survival I:1.47-1.21, II:1.44-1.19, III: 1.50-1.12

From the results it can be concluded that the dynamics in the mooring leg are considerably higher in the 1200 m than in the 400 m water depth.

By the application of spring buoys it can be concluded that the mooring line loads at the turret are considerably reduced. In the survivals I, II, III reduction in maximum line force for the loaded tanker with respect to the maximum line load without spring buoy amounts to 25, 26, 15 % respectively in 1200 m water depth. Comparing the dynamic factors in 1200 m water depth as given above it can be concluded that by applying the spring buoys even the dynamics are slightly reduced.

By application of spring buoys in 400 m water depth the reduction in the maximum line loads are smaller (10%, 11% and 2% respectively).

Due to the static weight and the higher inertia of the 10 lines without buoys in the 1200 m water depth the dynamic vertical forces acting on the turret are considerably higher than for the case in 400 m water depth. The application of spring buoys, however, reduces the vertical turret loads considerably.

In general it can be concluded that the tanker motions and the mooring loads are of the same order of magnitude in ballast and loaded condition. The deviations occur due to the increase of the wind loads and the different transfer functions associated with the loading condition.

Conclusion

1. To improve the understanding of and the insight in the reliability and integrity in the application in the deep water

mooring systems, numerical design tools can be used.

2. The numerical design can be used to optimize the system and to enhance the safety of the design by applying numerous combinations of extreme weather conditions in order to discern the most severe weather condition.
3. Computations are carried out with a conventional mooring system with and without spring buoys in 400 and 1200 m water depth. Some of the findings were:

   - at increasing water depth the stiffness of the mooring system may decrease considerably,
   - at increasing water depth the dynamic line factor may increase considerably,
   - application of spring buoys reduce the mooring loads considerably,
   - in survival condition the period sensitivity of the spectrum on the surge motions and mooring forces have to be analysed;

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