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A Wave Basin Model Test Study for a Jackup Moored on the Dock

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ABSTRACT

Offshore platforms under construction are normally moored on the dock during the outfitting stage. The safety of the platforms must be guaranteed during the whole stage of outfitting which may last for several months. This paper presents a wave basin model test study of a jackup moored on the dock in Shanghai Waigaoqiao shipyard in China. In the model test, the jackup and the sea states were scaled based on the Froude similarity law. The dynamic responses of the system, including the six degrees of freedom (6DOF) motions of the jackup and the barge, tensions on the mooring lines and the collision forces on the fenders, were measured in various sea states. Meanwhile, the current-and-wind-only sea states were simulated and the dynamic responses were measured for comparison with those in the wave conditions. The mooring line tensions were found to exceed the strength of the lines in offshore wind conditions. And this phenomenon may be attributed to the decrease of the jackup's yaw motion stiffness. In addition, several suggestions are proposed for optimizing the mooring system performance.

KEY WORDS: Jackup; dock mooring; model test; motion; tension; yaw motion stiffness.

INTRODUCTION

Jackup is one of the most popular drilling rig types used in shallow waters. A modern jackup is normally supported by three legs during operation. However, in the outfitting stage before delivery, it is moored on dock in shipyard. As the duration of the outfitting may last for several months, the jackup may be exposed to storms. The safety of the jackup must be guaranteed during the whole stage of outfitting.

To the best of our knowledge, studies on the jackup moored on dock have not been found in open literatures. However, similar studies regarding a ship or a semi-submersible moored on dock have been reported. Special attentions have been drawn on the motions of the ship/semi-submersible, the tensions in the mooring lines and the fender forces in-between the ship/submersible and the dock.

Oortmerssen (1976) simulated the behaviors of a moored ship in waves by introducing the impulse response function and Vantorre (1992) calculated the contact force on the fenders between the ship hull and constructions. Van der Molen and Wenneker (2008) developed a combination of a Boussinesq-type wave model with a time-domain panel model to determine the wave forces on the ship. And Mooring Equipment Guidelines (OCIMF, 1997) provided an overview of the requirements for safe mooring of ships along the dock. In addition, many software packages, such as MOORSIM (Oortmerssen et al., 1986), SHIPMOOR (Natarajan and Ganapathy, 1995) and OPTIMOOR (Flory et al., 1998), have been developed for analyzing the vessels, the fenders and the mooring lines. More recently, studies on dock mooring semi-submersible drilling platforms were also presented. Wang et al. (2010) examined the external loads of a semi-submersible through the numerical simulation and model test. Results of simulation and test were compared for validation. The authors said that it was essential to predict the motions of the semi-submersible and the tensions on the mooring lines by model tests.

It should be noted that there are some differences between jackups and other offshore structures. During outfitting stage, the jackup is moored with several mooring lines in the normal sea states and additional mooring lines will be used in case of the extreme sea states. A barge is placed between the jackup and the dock to avoid direct collisions between the jackup and the dock. Several fenders are used between the structures to resist the collisional loads. All the legs of the jackup are lifted to the topmost, which leads to a very high gravity center and a large projected area for wind load. Therefore, more attentions should be paid to the motions of the jackup and the tensions on the lines.

In this paper, we present an experimental study on the hydrodynamic performance of a jackup moored on the dock with 13 mooring lines. The results were discussed and analyzed in detail and some suggestions for optimizing the mooring system were proposed. The test results can be applied to other dock mooring jackup platforms.

MODEL TEST

A series of model tests were conducted at State Key Laboratory of Ocean Engineering (SKLOE), Shanghai Jiao Tong University in China.

All structures, including the jackup, the dock, the barge, the mooring lines and the fenders were all simulated in a scale ratio of 1:50. Four types of tests, including decay tests, white noise tests, current-and-wind-only tests and seakeeping tests, were carried out to get an in-depth understanding of the hydrodynamics of the dock mooring jackup. The waves, wind, current, the mooring line tensions, the forces on fenders and the six degrees of freedom motions of the jackup and the barge were measured and analyzed by an auto data acquisition and analysis system.

Test Facilities

The wave basin of SKLOE is 50m in length, 30m in width and 6.0m in depth, as shown in Fig 1.

This basin is equipped with a dual-flap type hydraulic wavemaker which can generate single-directional long-crested and short-crested waves with significant wave heights up to 0.5m in model scale. The high-pressure water-jet type current generating system can be used to generate uniform current up to a maximum velocity of 0.2m/s. Both steady wind and wind spectrum can be generated by the wind generating system with axial fans. The maximum wind speed can be reached up to 10 m/s. A large area adjustable artificial bottom with which the water depth can be adjusted from 0m to 5m.

Fig. 1 Wave basin of SKLOE

Various instruments were employed in the present model tests. A non-contact optical motion measuring system was fixed on the two sides of the basin to measure the motion responses of the jackup and the barge. The error of the system in the motion measurement is within 0.1mm. 17 tension transducers with the measurement range of 0~10kg (in model scale) were installed on the endpoints of the mooring lines to measure the tensions. 6 force transducers were placed in the fender models for measuring the collision loads. The wave elevations in the basin were recorded by 3 resistance-type wave probes with measuring error less than 1mm. Meanwhile, a micro acoustic Doppler velocimeter and a hot wire anemometer were used for measuring the current and wind speed respectively.

Similarity Laws

In the present test, the Froude Number and the Strouhal Number of the model and the prototype are kept the same, which means the similarities of the gravitational force and inertia force are satisfied, i.e.:

$$\frac{V_m}{\sqrt{gL_m}} = \frac{V_s}{\sqrt{gL_s}} \qquad \frac{V_m T_m}{L_m} = \frac{V_s T_s}{L_s}$$

where V, L and T represent the velocity, linear dimension and the motion period of the body, respectively. The subscripts m and s denote the variables for the model and prototype, respectively.

Based on the law of similarity, the relationships of physical variables between the prototype and model are listed in Table 1, where λ is the linear scale ratio and γ is the specific gravity of seawater (γ=1.025).

Table 1. Variables between the prototype and model

Item	Symbol	Scale Ratio
Linear dimension	L_s/L_m	λ
Linear velocity	V_s/V_m	$\lambda^{1/2}$
Angle	ϕ_s/ϕ_m	1
Period	T_s/T_m	$\lambda^{1/2}$
Area	A_s/A_m	λ^2
Volume	∇_s/∇_m	λ^3
Moment inertia	I_s/I_m	$\gamma\lambda^5$
Force	F_s/F_m	$\gamma\lambda^3$

Models Fabrications

Fig. 2 shows the model set-up for the whole system, including the jackup, barge, dock, mooring lines and fenders.

Fig. 2 Model set-up for the dock mooring jackup

The jackup model consisted of the wooden main body covered by glass reinforced plastics, three wooden legs and wooden topsides. The weight in air, center of gravity and radius of gyration were adjusted to the target by adding and shifting weight elements. It is worth noting that the topsides of the jackup were scaled directly to keep the equivalent area that exposed to the wind. Table 2 presents the detailed particulars of the jackup in both prototype and model scale.

Table 2. Particulars of the jackup

Particulars	Unit	Prototype	Model
Displacement	ton	17974.3	0.1403
Overall length	m	70.36	1.407
Overall width	m	76.00	1.520
Depth	m	9.45	0.189
Water depth	m	121.92	2.438
Draft	m	5.205	0.104
Leg length	m	166.98	3.340
COG (longitudinal)	m	30.354	0.607
COG (transverse)	m	0.006	0.000
COG (vertical)	m	27.895	0.558
Pitch gyradius (COG)	m	15.73	0.315
Roll gyradius (COG)	m	22.42	0.448
Yaw gyradius (COG)	m	12.139	0.243

The main body of the barge was made of wood and no topside was modeled since the barge was just utilized to avoid the collision between the jackup and the dock. Fig. 3(a) shows the overview of the barge, and the particulars of the barge are listed in Table 3.

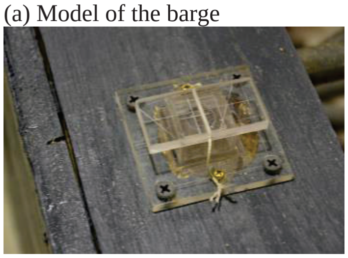
The dock was modeled by wood and steel girders in the basin to provide the accurate supports of the fenders and the mooring dolphins, as shown in Fig. 3 (b)

Table 3. Particulars of the barge

particulars	Unit	Prototype	Model
Barge length	m	60.0	1.200
Barge width	m	15.0	0.300
Barge depth	m	2.3	0.046
Draft	m	1.2	0.024
Displacement	ton	1013.4	0.0079


(a) Model of the barge


(b) Model of the dock


(c) Model of the fender

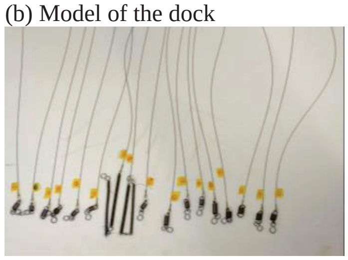

(d) Model of the mooring lines

Fig. 3 Model of the structures

In order to simulate the mechanical properties of the fenders, nonlinear spring sections were placed inside small plastics boxes, which were inserted into the barge and the dock, as shown in Fig. 3(c).

The mooring models were composed of spring sections and wires, with the length and stiffness equivalent to the scaled full-length mooring system, as shown in Fig. 3(d). Two different sets of mooring systems are selected for normal sea states and extreme sea states, respectively. The details of the mooring systems will be introduced later.

Environment Modeling

The water depth along the dock in Waigaoqiao shipyard is 10m. In the model tests, the water depth was adjusted to 0.2m in model scale by moving the artificial bottom.

A white noise wave spectrum with the significant wave height of 2.5m and peak periods ranging from 5s to 20s in prototype was selected for the RAO tests.

Two ITTC wave spectrums were utilized for modeling the irregular waves. The detailed parameters of the ITTC spectra are listed in Table 4. The wave spectra were calibrated carefully with the current existing, and one example of the calibrated power spectrum density function compared with the target values is given in Fig. 4.

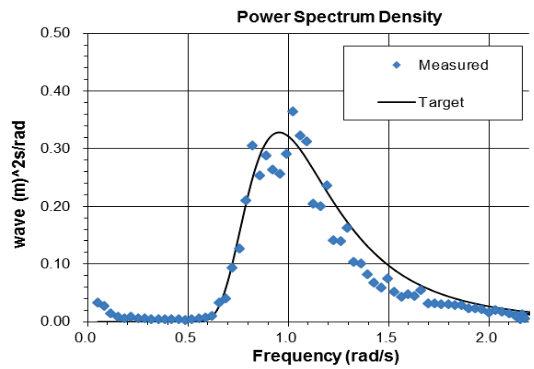


Fig. 4 Power spectrum density function of the ITTC spectrum

The wind was generated by means of the computer-controlled wind fans which could change its directions in the wave basin. As shown in Table 5, Force 9 wind, Force 10 wind and Typhoon were simulated respectively.

The specified current speed near water surface was 1.54m/s in prototype and 0.22m/s in model scale, calibrated by adjusting the current generating system and measured by a micro acoustic Doppler velocimeter.

Table 4. Parameters of the ITTC spectra

No.	Hs(m)		Tp (s)	
	Prototype	Model	Prototype	Model
2	1.55	0.031	5.00	0.707
3	1.87	0.037	5.09	0.720

Table 5. Parameters of the wind

No.	Prototype (m/s)	Model (m/s)	Comment
1	22.6	3.20	Force 9 wind
2	28.4	4.02	Force 10 wind
3	30.87	4.37	Typhoon

Model set-ups

Two coordinate systems were selected in the present model tests: the earth-fixed system O-XYZ and the rotated earth-fixed system o-xyz.

Fig. 5 shows the detail of the coordinate systems and the directions.

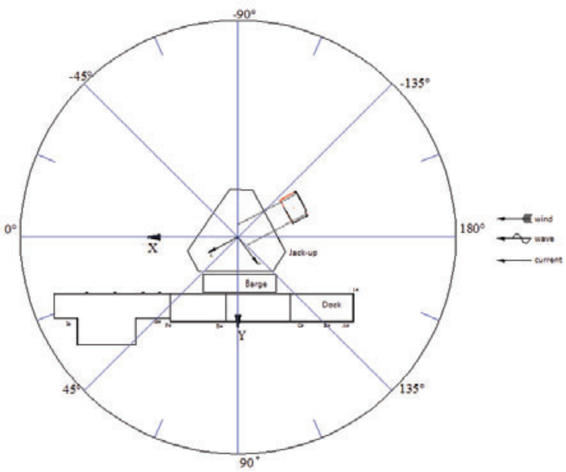


Fig. 5 The coordinate systems

The model of the jackup was excited by an initial heel angle in calm water during the decay tests, and neither the mooring system nor the other models were included. The white noise tests were conducted for the jackup with a 3 soft line horizontal mooring system, as shown in Fig. 6. The jackup was allowed to move freely in roll and pitch around its COG (center of gravity) in white noise tests.

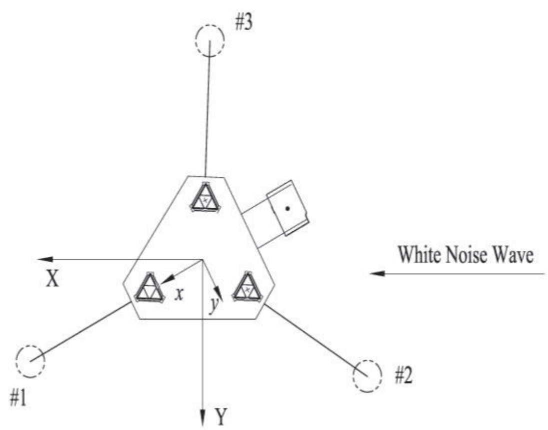
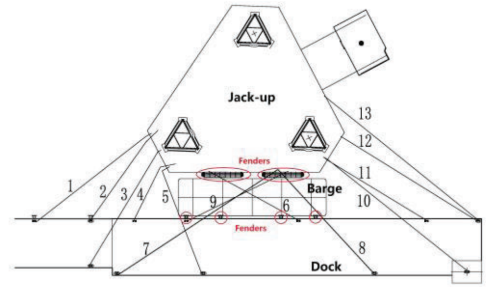
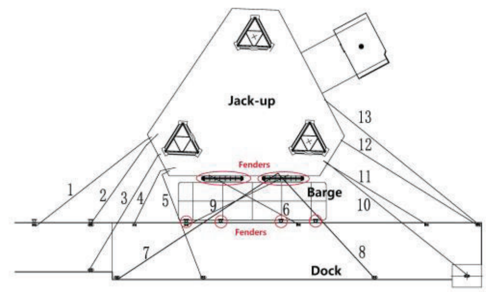


Fig. 6 Jackup with a 3 soft line horizontal mooring system

During the current-and-wind-only tests and the seakeeping tests, the jackup, the dock and the barge were all included, and the jackup located at the center of the basin. There are 4 typical fenders (No.1~4) between the dock and the barge and 2 fenders (No.5~6) between the jackup and the barge. In normal sea states, 13 mooring lines are used in total. However, in the extreme sea states, 4 additional mooring lines are used. And the pretensions on the mooring lines are all 10 tons in prototype. Fig. 7 presents the general configuration of the mooring systems and the fenders.



(a) Mooring system in normal sea states



(b) Mooring system in extreme sea states

Fig. 7 Two sets of mooring systems

Test Matrix

Four types of model tests were carried out, including decay tests, white noise tests, seakeeping tests and current-and-wind-only tests, as shown in Table 6.

Roll and pitch decay tests for determination of natural periods and damping coefficients of the jackup in calm water were conducted at first. The white noise tests were carried out in head sea (0° direction) to derive the motion RAO results in the six degrees of freedom. The barge and the dock were not included in the above tests.

Then the dynamic responses of the system, including the 6DOF motions of the jackup and the barge, the tensions on the mooring lines, and the collision forces on the fenders, were measured directly in the seakeeping tests. A set of combinations of the waves, the wind and the current, as listed in Table 6(c), were designed to simulate the various sea states in prototype. All the signals measured in the seakeeping tests were analyzed in both the time domain and the frequency domain.

Current-and-wind-only tests were conducted to obtain dynamic responses in the current-and-wind-only sea states. The tensions on the mooring lines were compared with those in the seakeeping tests to assess the influence of the current and the wind.

Table 6. Test matrix for the jackup

(a) Decay tests

Case	content
1~2	Roll & pitch decay tests

(b) White noise tests

Case	Mooring System	Hs	Tp	Wave Dir.	comment
		(m)	(s)	(deg)	
3	Horizontal Mooring	2.5	5~20	0	White noise test

(c) Seakeeping tests

Case	Hs	Tp	Wave Dir.	Current Dir.	Wind Speed	Wind Dir.	Comment
	(m)	(s)	(deg)	(deg)	(m/s)	(deg)	
4A	1.55	5	135	180	22.6	-90	Force 9 (Offshore)
5A	1.55	5	135	180	28.4	-90	Force 10 (Offshore)
6A	1.87	5.09	45	0	22.6	-90	Force 9 (Offshore)
7A	1.87	5.09	45	0	28.4	-90	Force 10 (Offshore)
8A	1.87	5.09	45	0	22.6	0	Force 9
9A	1.87	5.09	45	0	28.4	0	Force 10
10A	1.87	5.09	45	0	22.6	45	Force 9
11A	1.87	5.09	45	0	28.4	45	Force 10
12A	1.87	5.09	45	0	30.87	0	Force 12 (Inshore)
13A	1.87	5.09	45	0	30.87	45	Force 12 (Inshore)
14A	1.87	5.09	45	180	30.87	90	Force 12 (Inshore)

(d) Current-and-wind-only tests

Case	Wind Speed	Wind Dir.	Current Dir.	Comment
	(m/s)	(deg)	(deg)	
4B	22.6	-90	180	Force 9 (Offshore)
5B	28.4	-90	180	Force 10 (Offshore)
6B	22.6	-90	0	Force 9 (Offshore)
7B	28.4	-90	0	Force 10 (Offshore)
8B	22.6	0	0	Force 9
9B	28.4	0	0	Force 10
10B	22.6	45	0	Force 9
11B	22.6	45	0	Force 10
12B	30.87	0	0	Force 12 (Inshore)
13B	30.87	45	0	Force 12 (Inshore)
14B	30.87	90	180	Force 12 (Inshore)

Data Acquisition and Analysis

All measurements were recorded on the computer with a sampling rate of 40Hz and a physical filtering frequency of 40Hz. The analog-to-digital signal conversion was processed by an A/D converter. The measuring duration was 13 minutes model scale corresponding to 1.5 hour prototype time for each seakeeping tests. In the current-and-wind-only tests, the measuring duration is 5 minutes in model scale.
The channels acquired in the seakeeping tests and current-and-wind-only tests are listed in Table 7.

Table 7. Channel description for seakeeping tests

No.	Channel	Unit	Comment
1	WaveCal	m	Calibrated wave at Jackup center
2	SurgeJackup	m	Jackup: surge motion of at COG
3	SwayJackup	m	Jackup: sway motion of at COG
4	HeaveJackup	m	Jackup: heave motion of at COG
5	RollJackup	deg	Jackup: roll motion
6	PitchJackup	deg	Jackup: pitch motion
7	YawJackup	deg	Jackup: yaw motion
8	SurgeBarge	m	Barge: surge motion of at COG
9	SwayBarge	m	Barge: sway motion of at COG
10	HeaveBarge	m	Barge: heave motion of at COG
11	RollBarge	deg	Barge: roll motion
12	PitchBarge	deg	Barge: pitch motion
13	YawBarge	deg	Barge: yaw motion
14~26	F.line1~13	ton	Tensions on Line 1~13
27~30	F.moor1~4	ton	Tensions on Mooring 1~4
31~34	FDockFender1~4	ton	Forces on Fender 1~4(on dock)
35~36	FBargeFender5~6	ton	Forces on Fender 5~6(on barge)

All the results of seakeeping tests and current-and-wind-only tests were presented in statistic tables, including mean values, maximum and minimum values, standard deviation, positive significant values, negative significant values and double significant values.

RESULTS AND DISCUSSION

Decay Tests

The natural period and non-dimensional damping coefficient of each degree of freedom motion have been derived from each measured decay test curve. Figs. 8-9 show the roll and pitch decay test results respectively.

The natural period of the roll motion is 12.374s while that of the pitch motion is 12.346s. And the damping coefficients of the roll motion and the pitch motion are 0.1132 and 0.0981 respectively.

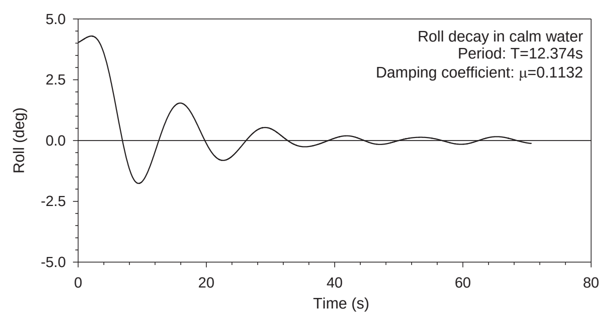


Fig. 8 Result of roll decay test in still water

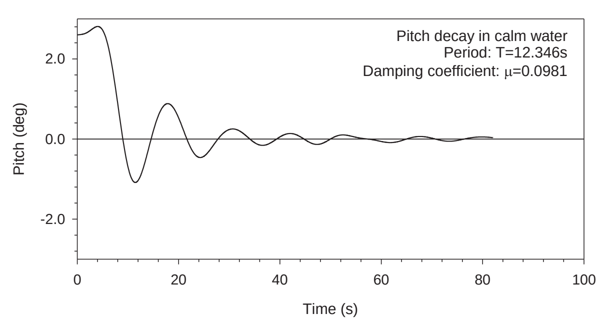


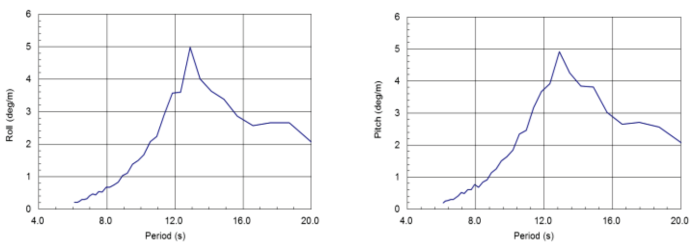
Fig. 9 Result of pitch decay test in still water

White Noise Tests

By using a white noise wave, the hydrodynamic performance of the jackup has been examined. The corresponding response amplitude operators (RAOs) have been calculated from the response spectrum divided by the white noise wave spectrum.

Fig. 10(a) and Fig. 10(b) show the RAOs of the roll motion and the pitch motion of the jackup, respectively. Both the roll RAO and the pitch RAO reach the maximum at the period of 12.9s, which is in good agreement with the results calculated from decay tests.

From the results of the decay tests and the white noise tests, measures should be taken to prevent resonance when the period of the wave is close to 12.9s.



(a) RAO result of roll motion (b) RAO result of pitch motion
Fig. 10 Results of white noise tests

Responses in Seakeeping Tests

In seakeeping tests, the maximum tension of each mooring line was recorded. Table 8 presents the first three maximum values among the mooring lines' maximum tensions and the corresponding line numbers in each case. The mean values of the top three maximum tensions are calculated. Meanwhile, the standard deviations of jackup's yaw motions along with the descriptions of the wind direction and the wind force scale are also listed in the table for detail analysis.

We take Case 4A as an example. The mooring lines with the first three maximum tensions are No.9, No.5 and No.4, the largest tensions on which are 424.9t, 308.3t and 297.0t, respectively; the mean value of these three tensions are 343.4t; the standard deviation of yaw motion is 0.3 degree; and force 9 offshore wind is simulated.

It can be seen from Table 8 that some of the mooring tensions are more than 400t in the first four cases, and the largest one is even 554.8t. These tensions have already exceed the strength of the mooring lines. Actually, it is also difficult to have 400Te SWL land anchors and much more difficult to have 425Te SWL quayside mooting bits. So measures should be taken to prevent the accidents from happening.

It is worth noting that the mooring lines which sustain most of the external loads change with the wind direction. The main load-carrying mooring lines are No.4, No.5, No.6 and No.9 in the offshore wind conditions, while they become No.6, No.11 and No.12 in 0 and 45 degree wind conditions and No.1, No.4 and No.9 in 135 and 180 degree wind conditions.

It is observed that the mean values of the maximum tensions in offshore wind conditions are much larger than those in other conditions. It is worth noting that the large tensions in the first four cases (Cases 4A~7A) always occur with the large standard deviations of the jackup's yaw motions which indicate the large yaw motions in these cases.

To provide a more clear description of the relevance between the yaw motion and the line tension, variations of the standard deviations of yaw motions versus the mean values of top 3 maximum tensions are plotted in Fig. 11. In general, the larger yaw motions correspond to larger tensions. A possible explanation for the large mooring line tensions may be related to the deduction of the yaw motion stiffness, which has a decreased restriction of the jackup's yaw motion, leading to an increase of the tensions.

Although the wind in the last case is the strongest one, the mooring line tensions are much smaller than those in other cases. This may be relevant to the direction of the wind. The jackup is possibly pushed to the fenders tightly by the inshore wind. Therefore the mooring lines become loose.

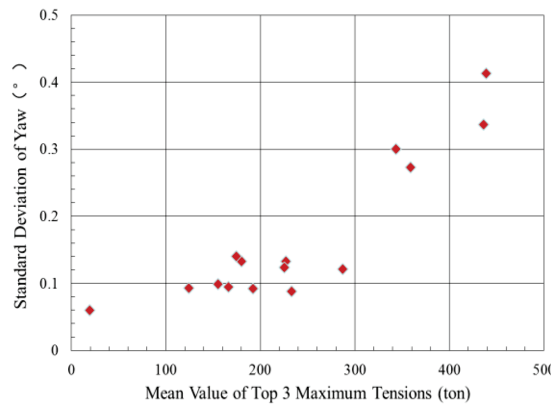


Fig. 11 Variations of the standard deviation of yaw motion versus the mean value of top 3 maximum tensions

Responses in Current-and-wind-only Tests

To further understand the influence of the current and the wind, the current-and-wind-only tests have been examined. The details of the statistics have been listed in Table 9.

As shown in Table 9, the main load-carrying mooring lines are No.3, No. 4, No.9, No.12, No.13 in offshore wind conditions, and they shift to No.6, No.11 and No.12 in 0 and 45 degree wind conditions and No.1, No.3 and No.9 in 135 and 180 degree wind conditions.

Comparing the results from the seakeeping tests and the current-and-wind-only tests, it can be found that the tensions on the mooring lines caused by the wind and the current are no more than one third of the total loads. This indicates that the current and wind loads are not the main causes of the large tensions. On the other hand, the great tensions mainly come from the wave loads. This conclusion can also be demonstrated from the comparison of the results listed in Table 9. It can be seen in Table 9 that the mean values of the top three maximum tensions in offshore wind conditions are not the largest among those of all conditions. One can take Case 6B and Case 10B as examples. The mean value of the top three maximum tensions in Case 6B is smaller than that in Case 10B. But when the same waves are added, taking Case 6A and Case 10A (listed in Table 8) as examples, the results in Case 6A are much larger than those in Case 10A. As described in the above section, this is due to the smaller yaw motion stiffness, or the decrease of the restriction of the yaw motion in Case 6A. It results in the larger yaw motion in the same wave condition, and larger mooring line tensions are caused finally.

Times Series of the Yaw Motion and the Tension

To get a further understanding of the relation between the jackup's yaw motion and the mooring line tensions, times series of the two quantities in seakeeping tests are compared in Figs.12~15. For the sake of clear description, only time series in offshore wind conditions are plotted and all the values are in prototype. The No.9 line is selected as an example due to its large tensions in all the offshore wind conditions.

Through the Figs.12~15, it is found that the phase difference between the yaw motion and the tension is neglectable. To quantify the correlation of the yaw motions and the tensions, variations of the tensions versus the yaw motions are plotted in Fig. 16, taking Case 4A as an example. As is shown in Fig. 16, almost all the points in the diagram are distributed in a banded linear area marked with two lines. This interesting finding demonstrates a high correlation between the yaw motion and the tension of the line. In general, conclusion can be drawn that the tension has a close relation with the yaw motion of the jackup. The decreased restriction of the jackup's yaw motion leads to the increase of the mooring line tensions, which may easily exceed the strength of the lines.

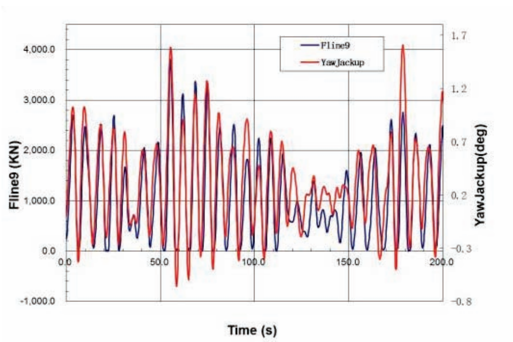


Fig. 12 Time series in Case 4A

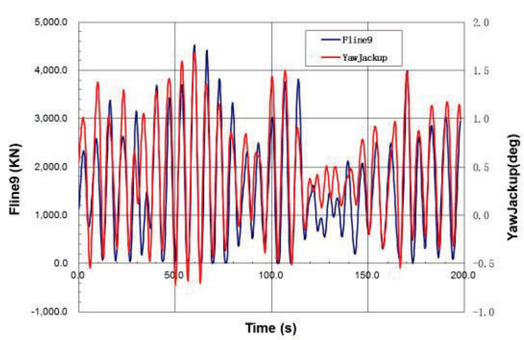


Fig. 13 Time series in Case 5A

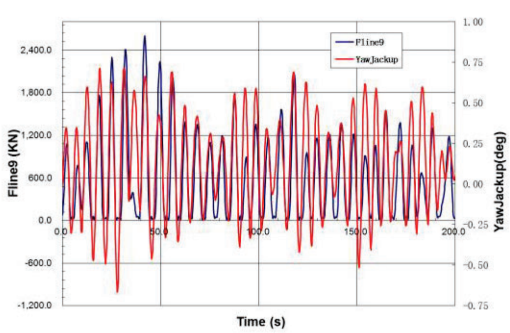


Fig. 14 Time series in Case 6A

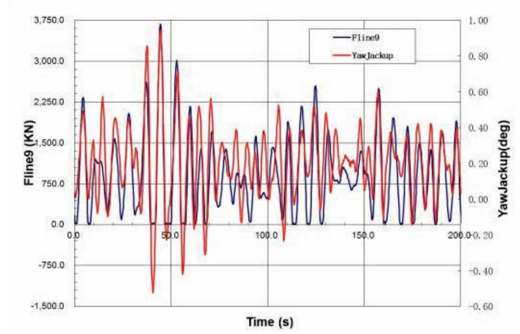


Fig. 15 Time series in Case 7A

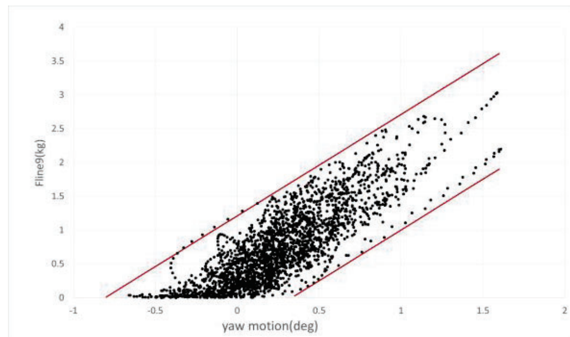


Fig. 16 Variations of the tension versus the yaw motion in Case 4A

CONCLUSIONS

This paper presents the methodology and results of a wave basin model test for a jackup moored on the dock in Shanghai Waigaoqiao shipyard in China. The natural period and damping coefficient have been derived in decay tests and the white noise tests. The motions of the jackup, the tensions on the mooring lines and the relations between these two quantities have been experimentally investigated in the seakeeping tests and the current-and-wind-only tests. The cause of the large mooring line tensions are discussed in detail and the new findings can be applied to engineering practice.

It is noted that the offshore wind blows the jackup away from the dock, which may cause the deduction of the jackup's yaw motion stiffness and increase the jackup's yaw motion in waves. As a result, the mooring lines are pulled violently, leading to the large tensions.

Finally, suggestions for optimizing the mooring system performance are drawn as follows:

- An increase of the pretensions of the mooring lines can restrict the yaw motion of the jackup;
- The distribution area of the fenders can be enlarged to enhance the yaw motion stiffness;
- To avoid line broken accidents, a larger mooring line strength is required. In addition, the quayside mooring bits and land anchors with larger holding capacities are needed.

REFERENCES

Flory, JF, Banfield, SP, Ractliffe, A (1998). "Computer mooring load analysis to improve port operations and safety," *Ports '98 Proceedings*, 840-849.

Natarajan, R, Ganapathy, C (1995). "Analysis of moorings of a berthed ship," *Marine structures*, 8(5), 481-499.
OCIMF (1997). *Mooring Equipment Guidelines*, OCIMF.
Oortmerssen, GV (1976). "The motions of a moored ship in waves," Netherlands Ship Model Basin.
Oortmerssen, GV, Pinkster, JA, van den Boom, H (1986). "Computer Simulation of Moored Ship Behavior," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 112(2), 296-308.
Van der Molen, W, Wenneker, I (2008). "Time-domain calculation of moored ship motions in nonlinear waves," *Coastal Engineering*, 55(5), 409-422.
Vantorre, M (1992). "Mathematical modeling of fender forces and memory effects for simulation of ship manoevres in confined waters," *10th International Harbour Congress*, Antwerpen, 15-19.
Wang, Q, Wu, XP, Lu, HN, Chen, G, Wu, XY (2010). "Numerical Calculation and Model Test Study on a Quay Mooring Semi-Submersible Drilling Platform," *29th International Conference on Ocean, Offshore and Arctic Engineering*, Shanghai, 421-431.

Table 8. Analysis of the maximum tensions of the mooring lines in seakeeping tests

Case No.	Top 3 maximum tensions(ton)			Mean Value of top 3 tensions (ton)	Standard deviation of yaw	Wind Direction	Comment
	Maximum	Second Maximum	Third Maximum				
4A	#9(424.9)	#5(308.3)	#4(297.0)	343.4	0.300	-90	Force 9 wind (offshore)
5A	#9(554.8)	#4(395.7)	#5(357.3)	435.9	0.337	-90	Force 10 wind (offshore)
6A	#9(414.0)	#6(373.7)	#5(288.5)	358.7	0.273	-90	Force 9 wind (offshore)
7A	#6(470.5)	#9(460.7)	#4(385.5)	438.9	0.413	-90	Force 10 wind (offshore)
8A	#12(197.6)	#6(186.9)	#11(155.4)	180.0	0.133	0	Force 9 wind
9A	#12(247.5)	#6(236.2)	#11(197.9)	227.2	0.133	0	Force 10 wind
10A	#12(167.5)	#6(160.9)	#11(137.5)	155.3	0.099	45	Force 9 wind
11A	#6(220.8)	#12(189.7)	#11(165.7)	192.1	0.092	45	Force 10 wind
12A	#6(198.3)	#12(174.2)	#11(151.2)	174.6	0.140	0	Force 12 wind
13A	#6(159.9)	#12(112.6)	#11(100.5)	124.3	0.093	45	Force 12 wind
14A	#9(34.7)	#7(12.4)	#1(10.5)	19.2	0.060	90	Force 12 wind (inshore)

Table 9. Analysis of the maximum tensions of the mooring lines in current-and-wind-only tests

Case No.	Top 3 maximum tensions(ton)			Mean Value of top 3 tensions (ton)	Wind Direction	Comment
	Maximum	Second Maximum	Third Maximum			
4B	#4(90.3)	#3(85.5)	#9(80.6)	85.5	-90	Force 9 wind (offshore)
5B	#4(170.4)	#9(145)	#3(118.1)	144.5	-90	Force 10 wind (offshore)
6B	#9(62)	#13(60.6)	#12(58.4)	60.3	-90	Force 9 wind (offshore)
7B	#4(114.1)	#12(105)	#13(94.1)	104.4	-90	Force 10 wind (offshore)
8B	#12(73.5)	#6(63)	#11(61.4)	66.0	0	Force 9 wind
9B	#12(131)	#6(105.8)	#11(105.4)	114.1	0	Force 10 wind
10B	#12(84.6)	#6(82.7)	#11(73.3)	80.2	45	Force 9 wind
11B	#12(130.1)	#6(109.6)	#11(104.4)	114.7	45	Force 10 wind
12B	#6(81.3)	#11(55.8)	#12(49.8)	62.3	0	Force 12 wind
13B	#6(90.6)	#11(41)	#12(33.2)	54.9	45	Force 12 wind
14B	#7(6.1)	#8(5.8)	#1(4.2)	5.4	90	Force 12 wind (inshore)