



## MECHANISM AND MODEL TESTING OF PIPELAY VESSEL ROLL AFFECTED BY LARGE PERIOD SWELLS

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# MECHANISM AND MODEL TESTING OF PIPELAY VESSEL ROLL AFFECTED BY LARGE PERIOD SWELLS

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Key words: swell, pipelay vessel, roll, model test, motion feature.

## ABSTRACT

Pipelay vessels, such as the Hai Yang Shi You 201, have been seriously affected by large period swells in the East China Sea, where the roll amplitude is extremely large for normal pipe lay. Two conditions that can generate dramatic rolls, namely, parametric and synchronous rolling, were analyzed theoretically in this study. Model tests were also performed on the pipelay vessel Hai Yang Shi You 201 with course angles of 0°, 30°, 60°, and 90° in swells of varying periods and wave heights to examine the aforementioned effect. The test data proved that drastic roll is not caused by parametric rolling, when the pipelay vessel is hit by a swell whose period is equal to approximately half of the natural rolling period. Results showed that drastic roll is instead caused by synchronous rolling, which occurs when a vessel is hit by a swell whose period is close to the natural rolling period. Combined with meteorological data, the results can serve as basis for the selection of a construction climate window.

## I. INTRODUCTION

Pipelay vessels are important construction equipment in seabed pipe installation, and segmented oil and gas pipelines should be welded on vessels in most laying methods such as the widely used S-lay and J-lay (Heerema, 2005; Leffler et al., 2011). Thus, the stability of pipelay vessels entails difficult requirements. Extremely large movement amplitudes of the pipelay vessel during construction affect the quality of the pipe-laying construction and can even endanger ships and cause harm to the safety of equipment installed on the board of the vessel. In view of the large-scale development in the East

China Sea in the near future, pipelay vessels in this area, such as the Hai Yang Shi You 201, can be seriously affected by large period swells under conditions of slow wind speed and short wave height. Construction requirements should be met according to weather forecasts and actual weather conditions, but the roll motion of pipelay vessels is actually drastic and the roll amplitude is too large for normal pipelay. Thus, the sea standby time and construction cost of equipment increase greatly.

This study investigates the motion feature of pipelay vessels in a swell environment and particularly analyzes why the roll amplitude of such vessels is too large to adopt corresponding counter measures for the reduction of roll amplitude and to decrease both sea standby time and construction cost. Measuring points are set up in the Huangyan areas to monitor the characteristics of the region, and existing meteorological data are analyzed to obtain the periodic characteristics of the area. Two conditions that may cause dramatic roll-parametric and synchronous rolling-are analyzed theoretically. A scale model of the Hai Yang Shi You 201 is created, and the motion feature of the scale model is tested with heading angles of 0°, 30°, 60°, and 90° in swells with varying periods and wave heights. Some useful conclusions are obtained from these analyses.

Huge investments have been spent on pipelay vessels and equipment. For example, in the case of the Hai Yang Shi You 201, research and design took seven years, manufacturing to delivery took 43.5 months, investment reached about RMB 3 billion, and usage cost was also expensive. Thus, large roll amplitudes that can cause standby at sea and even damage equipment can also generate enormous economic losses. The research achievements of this study, combined with monitoring data of swells, can serve as reference for the selection of a construction climate window. The reasonable selection of sea conditions when a pipelay vessel is moved out to the sea can improve movement performance and enhance operation efficiency, thereby reducing standby loss at sea.

## II. CHARACTERISTICS OF SWELLS IN THE EAST CHINA SEA

Ocean waves are the most important factors that cause the swaying movements of vessels, and waves usually occur in a mixture of wind waves and swells. Wind waves, which are

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Fig. 1. Location of the measuring points in the East China Sea.

generated by winds and always influenced by wind actions, have a small period and a pointed crest. Swells are likely to be caused by other wind wave propagations, including the stopping, weakening, or changing of direction of winds. Wind waves with longer wavelengths can be transmitted from the origin and increasingly become symmetrical swells as their amplitude decreases. Swells are characterized by large periods, smooth wave surface, small amplitude, and minimal energy loss during transmission. As well with a wavelength of hundreds of meters is even difficult to perceive. As early as 1947, swells with periods of 15-24 s were discovered in Pendeen, England (Munk et al., 1963), and swells with periods of 20-25 s with a maximum significant wave height between 4 and 5 m were recorded in 1988 (Gjevik et al., 1988). When the roll motion of the pipelay vessel Hai Yang Shi You 201 is very drastic and the roll amplitude is large, the wind speed is reduced, and wind waves become insignificant in the area. However, the wave monitor results show that low-frequency swells occur in the sea area, indicating that the roll motion is probably caused by swells.

The location of the East China Sea is shown in Fig. 1. The East China Sea, which opens into the Pacific to the east, has broad waters, and its swells likely spread from the northwestern Pacific and are possibly transformed from wind waves resulting from sudden changes in the local wind speed and direction. Another reason is the wind waves that are generated by the action of cold air in the swell-generating area of the northwestern Pacific (i.e., including the Yellow Sea, Sea of Japan, the ocean to the south of Japan, Taiwan Strait, the ocean to the east of Taiwan Strait and Bashi Channel (Luzon Strait), and the ocean to the east of the Philippines), as well as the cyclone weather system that separates the generating area from the spreading area in the East China Sea. In addition to these reasons, a sudden change in wind and wind direction in the East China Sea during cyclone weather processes may also transform local wind waves into swells.

Measuring points are set up in the Huangyan area to monitor the characteristics of swells in this region for 12 months, as shown in Fig. 1. The monitoring data are statistically analyzed, and the results show that the periods of waves with significant wave heights are mainly spread over 3-5 s and that the probability is about 90%. The probability of swells with a period of

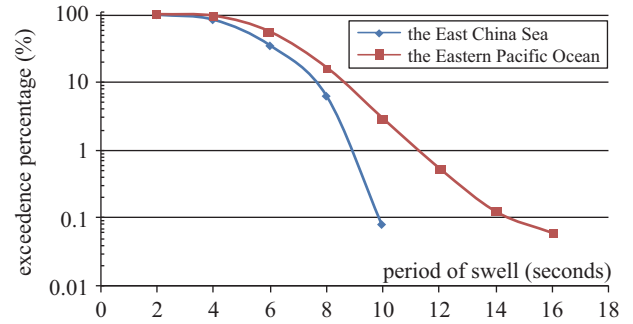


Fig. 2. Period distribution of swells in the East China Sea and in the Eastern Pacific Ocean.

more than 8 s is under 10%, while that of swells with a period of more than 10 s is less than 0.01%. The results of the analysis are compared with those of the Pacific Ocean, as shown in Fig. 2. The results show that the proportion of waves with large periods in the East China Sea is less than that in the Pacific Ocean.

The meteorological data in this sea area from 1983 to 2013, for a total of 30 years was collected and analyzed, the results show that the periods of swells are mainly distributed within 14 s, and the possibility of swells occurring with a period of more than 10 s is still large. Hence, the present study mainly focuses on the influence of swells with a period of less than 14 s on pipelay vessels.

### III. MECHANISM OF PARAMETRIC EXCITATION ROLL

Synchronous rolling occurs when the natural rolling period of a vessel is approximately equal to the period of a wave in beam seas, which is a dangerous situation for a vessel at sea. The roll amplitude may reach a large value based on linear theory (Krylov A. N., 1898; Bishop and Price, 1979), and can be expressed as

$$\varphi_{\alpha} = \frac{\alpha_0 X_{\varphi}}{\sqrt{(1 - \Lambda^2)^2 + 4\mu_{\varphi\varphi}^2 \Lambda^2}} \quad (1)$$

where  $\Lambda$  is the ratio of the natural rolling period of a vessel to the period of a wave,  $\alpha_0 X_{\varphi}$  is related to wave height and wavelength, and  $\mu_{\varphi\varphi}$  is the dimensionless attenuation coefficient.

A change in the course angle can alter the encountering frequency; thus, the roll motion can be dampened by altering the course angle. However, the roll of a vessel with small damping in a longitudinal wave may also enlarge when a special encountering frequency is met; this is called parametric rolling. Considering nonlinear damping and nonlinear restoring moments, roll motion can be mathematically modeled as

$$I'\ddot{\phi} + D(\dot{\phi}, \phi) + R(\phi, t) = 0 \quad (2)$$

where  $I'$  is the virtual moment of inertia,  $D$  is the damping, and  $R$  is the restoring. All terms are time dependent, but explicit time dependence is usually retained only in  $R$  because the other factors are minor entities. Both  $D$  and  $R$  are nonlinear and display this feature, especially in the case of large motion amplitudes.

The problem can be simplified by linearizing Eq. (2), which restricts the moment to analyze the stability of solution  $\phi(t) \equiv 0$ ; Eq. (2) then becomes

$$I'\ddot{\phi} + M\dot{\phi} + \overline{\Delta GM}(t) = 0 \quad (3)$$

Considering a sinusoidal time variation of the transversal metacentric height with amplitude  $\delta GM$  around the average value  $\overline{GM}$  and with each side of the equation divided by  $I'$ , a Mathieu-type equation is obtained as follows (Abramowitz and Stegun, 1964; Spyrou and Thompson, 2000; Younesian et al., 2005; Jordan and Smith, 2007):

$$\ddot{\phi} + 2\mu\dot{\phi} + \omega_0^2 \left( 1 + \frac{\delta GM}{\overline{GM}} \cos(\omega_e t + \varepsilon) \right) \phi = 0 \quad (4)$$

Phase  $\varepsilon$  can be disregarded without affecting the subsequent analysis, and Eq. (4) can then be changed into the following more familiar form:

$$\ddot{\phi} + 2\mu^* \dot{\phi} + 4 \frac{\omega_0^2}{\omega_e^2} \left( 1 + \frac{\delta GM}{\overline{GM}} \cos(\omega_e t) \right) \phi = 0 \quad (5)$$

This Mathieu equation is characterized by the roll amplitude solution, which is infinitely great when the encountering frequency is at a certain value and when damping is disregarded. Given the occurrence of damping, the roll amplitude with special encountering periods is actually reduced to a large value; these special encountering periods are

$$T = T_\phi \left( \frac{n}{2} \right) (n = 1, 2, \dots) \quad (6)$$

This conclusion is valid in discussing dynamic vessel stability and accounts for large roll amplitudes during these special encountering periods. Eq. (3) should in fact be substituted with a more complicated nonlinear equation, especially in the case of large roll angles. The theory of nonlinear Mathieu equation is not well developed for complexity (Silva et al., 2010); thus, mechanism analysis is usually qualitative and refers to experimental results.

In 1998, a post-Panamax, C11-class containership encountered extreme weather and sustained extensive loss and damage in deck-stowed containers; many studies investigated

the motions of the vessel during this storm event through a series of model tests and numerical analyses (France et al., 2003). The possibility of parametric rolling is summarized to relate to the simultaneous verification of the following conditions (Sanchez and Nayfeh, 1990; Francescutto, 2001; Munif et al., 2006):

- (a) The ratio of the encounter wave period  $T$  to the natural roll period  $T_\phi$  is close to the following condition:

$$\frac{T}{T_\phi} \approx \frac{n}{2} \quad (7)$$

where  $n$  is the integer.

- (b) The periodic variation in the metacentric height caused by the combined effect of vessel motions and waves is sufficiently large.  
(c) Roll damping is sufficiently small.

In theory, parametric excitation roll includes situations in which the ratio of the encounter wave period to the natural roll period are 1/2, 1, or 3/2, but this phenomenon is at present observed only when the ratio of the encounter wave period to the natural roll period is 1/2 and 1. The situation in which the ratio of the encounter wave period to the natural roll period is 1/2 is usually called parametric rolling, whereas the situation in which the encounter wave period is equal to the natural roll period is called synchronous rolling.

Certain differences can be found between pipelay vessels and other merchant ships. For example, merchant ships are affected more by parametric rolling under the following sea conditions: low relative speed and low roll damping. However, for a pipelay vessel during construction, the speed is too slow that this factor can be disregarded, the direction of the vessel is restricted by the designed pipeline, the relative velocity is high, and the roll damping increases when the vessel is under head conditions.

Given the widespread periods of the swells in this sea area, the testing range for the wave period completely includes the situation in which the ratio of the encounter wave period to the natural roll period is 1/2 and 1 to determine the reason behind the occurrence.

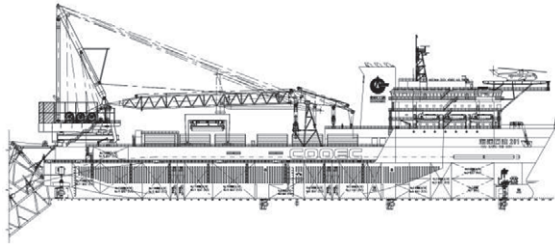
#### IV. DESIGN OF THE MODEL TEST OF THE MOVEMENT CHARACTERISTICS OF THE PIPELAY VESSEL

##### 1. Design of the Model Test

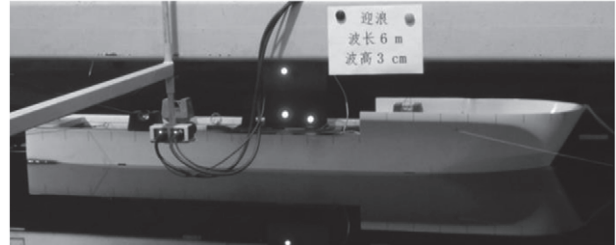
The Hai Yang Shi You 201, China's first deepwater pipelay vessel with an operating water depth that reaches up to 3,000 m, was used as the target vessel in this study. This vessel was equipped with a lifting capacity of 3,500 tons of heavy rotary crane. Whether the pipelay vessel was on standby or in operating condition, the navigational speed was small or even zero; thus, speed was disregarded in the model test.

**Table 1. Main data of the scale model of the pipelay vessel.**

	Hai Yang Shi You 201	Scale model (1/80)
Overall length	204.65 m	2,558 mm
Length between perpendiculars	185.00 m	2,313 mm
Molded breadth	39.20 m	490 mm
Molded depth	14.00 m	175 mm
(Molded) designed draft	8.5 m	106 mm
Displacement	52,104,900 kg	99.29 kg (scale model 35 kg)
Center of gravity		
Longitudinal center of gravity	88.57 m	1107 mm
Transverse center of gravity	-0.11 m	-1 mm
Vertical center of gravity	13.51 m	169 mm
Natural rolling period $T_\phi$	12.5 s	1.40 s



(a) Lateral view of the vessel



(b) Scale model of the subject vessel

**Fig. 3. Lateral view and scale model of the pipelay vessel.**

A 1/80 scale model made of fiber-reinforced plastic was created for the experiments, and a 10% pipelay departure condition was considered. Table 1 shows the main dimensions and mechanical data, in which the density ratio of seawater and freshwater in the pool is considered. Lateral views of the vessel and the scale model adjusted in place are shown in Fig. 3.

In Fig. 3, the characteristics of the Hai Yang Shi You 201 are shown. The vessel has a much longer parallel mid-body; the profile of the mid-body is vertical; the outline at the stern is also vertical; the bow is less pointed; and the outward bow is much smaller than that of container vessels, destroyers, and fishing boats.

## 2. Testing Procedure

The model ship of the experimental towing tank was located in Tianjin University, China. The model was 137 m long, 7 m wide, and 3 m deep, and a wave-absorbing beach and a flap-type wave generator were installed on two ends of the pool. A wave height recorder and the scale model were installed about 30 and 35 m away from the wave generator located in the mid-width direction. The generated regular waves with different periods and heights can simulate swells in an actual sea environment.

According to the period characteristic of the swells in the East China Sea, a swell that can generate synchronous and parametric rolling occurred in this area; thus, experiments were conducted on regular waves with period spreads from  $0.5T_\phi$  to  $1.7T_\phi$  and different wave heights. The relationship between the period and wavelength can be expressed in the

following dispersion equation:

$$T = \sqrt{\frac{2\pi}{g} L \coth\left(2\pi \frac{D}{L}\right)} \quad (8)$$

The movement of the scale model was measured using an untouched six-degrees-of-freedom (DOFs) measurement system, which located and measured the target by focusing light based on the visible light measurement principle. Given that sensors, such as gyroscopes and displacement meters, were not required in the experiment, the measurement did not experience interference, was highly accurate, and convenient to operate.

Ships can produce sway motions in six DOFs, in which heave, roll, and pitch are periodic motions that center on the equilibrium position induced by a restoring force or moment. When a pipelay vessel operates at sea, certain criteria should be met (Bai and Bai, 2005). The motion criterion of Hai Yang Shi You 201 was a roll angle of less than  $2.5^\circ$  and a pitch angle of less than  $2^\circ$  (Xu, 2014).

## V. TEST DETAIL AND RESULTS

### 1. Testing the Scale Model in the Longitudinal Wave

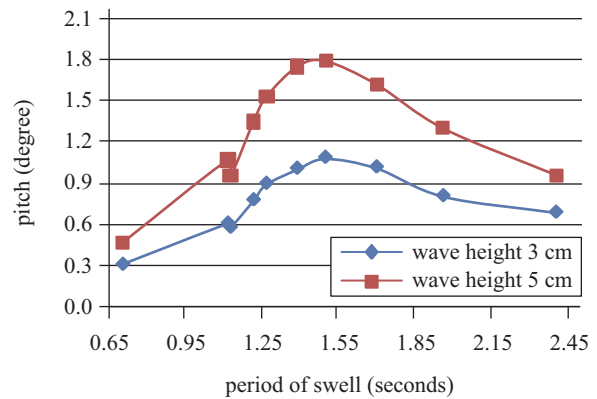
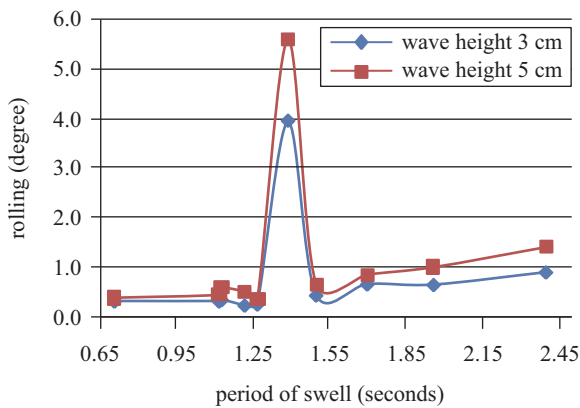
First, experiments were conducted on the scale model in longitudinal waves, as shown by the experiment details in Table 2.

**Table 2. Test details of the model in longitudinal waves.**

No.	Wave length of swell		Wave height of swell		Period of swell		$T/T_\phi$
	Actual state/m	Scale model/m	Actual state/m	Scale model/cm	Actual state/s	Scale model/s	
1	64	0.8	2.4, 4.0	3, 5	6.4	0.71	0.51
2	100	1.25	2.4, 4.0	3, 5	10.0	1.12	0.80
3	160	2	2.4, 4.0	3, 5	10.1	1.13	0.81
4	185	2.313	2.4, 4.0	3, 5	10.9	1.22	0.87
5	200	2.5	2.4, 4.0	3, 5	11.4	1.27	0.91
6	240	3	2.4, 4.0	3, 5	12.4	1.39	0.99
7	280	3.5	2.4, 4.0	3, 5	13.4	1.50	1.07
8	360	4.5	2.4, 4.0	3, 5	15.2	1.70	1.21
9	480	6	2.4, 4.0	3, 5	17.5	1.96	1.40
10	720	9	2.4, 4.0	3, 5	21.5	2.40	1.71

**Table 3. Experimental motion results of the model in longitudinal waves.**

swell	Period 0.71 s ( $T = 0.5T_\phi$ )		Period 1.39 s ( $T = T_\phi$ )		Period 1.96 s ( $T = 1.4T_\phi$ )	
	Wave height 3 cm	Wave height 5 cm	Wave height 3 cm	Wave height 5 cm	Wave height 3 cm	Wave height 5 cm
Heave (mm)	2.23	3.23	4.71	8.19	8.76	15
Pitch (°)	0.31	0.47	1.01	1.75	0.81	1.30
Roll (°)	0.34	0.42	3.94	5.57	0.67	1.03



**Fig. 4. Motion rule of the scale model in longitudinal waves.**

The natural rolling period of the scale model was 1.40 s, and theoretical analysis showed that parametric rolling might occur when the scale model was hit by a regular wave with a wavelength of 0.8 m and period of 0.71 s, whereas synchronous rolling might occur when the scale model was hit by a regular wave with a wavelength of 3 m and period of 1.39 s. The period range in the test was expanded to  $1.4T_\phi$  at the maximum, and this range was found to provide an excellent spread when the reason behind drastic roll was investigated.

In the above experiments, the motions of the six DOFs were measured and recorded, the maximum yaw angle was about  $2.5^\circ$ , the maximum sway was about 1 mm, the maximum surge was about 9 mm, and the motions in these three DOFs were not obvious. Heave, pitch, and roll were periodic motions, where

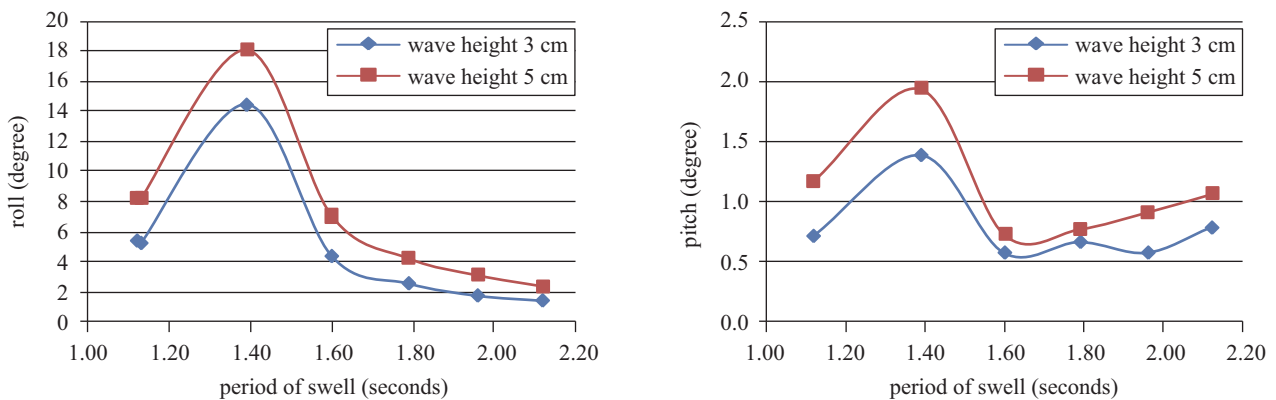
the amplitude of the heave was about 13 and 20 mm in 3 and 5 cm-high waves, respectively. The amplitude of the roll and pitch, which are the motion criteria, as shown in Fig. 4, and the amplitude of the three-periodic motion under conditions of  $T = 0.5T_\phi$ ,  $T = 1.0T_\phi$ , and  $T = 1.4T_\phi$  are summarized in Table 3.

In Table 3, the heave of the scale model evidently increased depending on the rise in the test wavelength, and the pitch of the scale model was maximized when the model was hit by a wave with a wavelength that was close to the length between perpendiculars. These results were in accordance with the general rule and with the motion criterion.

Fig. 4 shows that parametric rolling does not occur when the model is hit by a swell with periods that are close to half of the natural rolling period  $T = 0.5T_\phi$ . The roll of the model is not

**Table 4. Test details of the scale model in beam seas.**

No.	Wave length of swell		Wave height of swell			Period of swell		$T/T_\phi$
	Actual state/m	Scale model/m	Actual state/m	Actual state/m	Scale model/m	Actual state/m		
1	100	1.25	2.4, 4.0	3, 5	10.0	1.12	0.80	
2	160	2	2.4, 4.0	3, 5	10.1	1.13	0.81	
3	240	3	2.4, 4.0	3, 5	12.4	1.39	0.99	
4	320	4	2.4, 4.0	3, 5	14.3	1.60	1.14	
5	400	5	2.4, 4.0	3, 5	16.0	1.79	1.28	
6	480	6	2.4, 4.0	3, 5	17.5	1.96	1.40	
7	600	7.5	2.4, 4.0	3, 5	19.0	2.12	1.51	

**Fig. 5. Motion rule of the scale model in beam sea.**

obvious under this condition, possibly because of the special type of pipelay vessel. Fig. 2 evidently shows that the pipelay vessel has a much longer parallel mid-body, and a smaller-outward bow and outward stern than container vessels, destroyers, and fishing boats. Thus, the periodic change in the water plane coefficient and transversal metacentric height is smaller when the vessel is hit by waves. Moreover, the occurrence of parametric rolling was experimented on a destroyer and was thought requiring the vessel to have a certain speed (Franciscutto, 2001).

Synchronous rolling occurred when the model was hit by a swell with periods close to the natural rolling period  $T = T_\phi$ . The roll of the model was obvious and was much larger than that at  $T = 0.5T_\phi$  under this condition, and the roll amplitudes under the two conditions with different wave heights both exceeded the motion criterion.

These results that considered the drastic roll of the pipelay vessel in the East China Sea were not parametric rolling but synchronous rolling, which resulted from waves with periods close to the natural rolling period of the vessel.

## 2. Testing the Scale Model in Beam-Sea Conditions

Experiments were also conducted on the scale model in beam-sea conditions to verify the aforementioned conclusion. The experiment details are shown in Table 4, and the roll and pitch amplitudes, which are the motion criteria, are shown in Fig. 5.

The results also show that synchronous rolling occurred when the model was hit by a swell with periods close to the natural rolling period  $T = T_\phi$ . The roll of the model was obvious and was much larger under this condition than that in longitudinal waves, and the roll amplitudes under the two conditions of 3 and 5 cm wave heights reached about  $14^\circ$  and  $18^\circ$ , respectively, which certainly both exceeded the motion criterion. When the model was hit by a swell with periods close to half of the natural rolling period  $T = 0.5T_\phi$ , the roll of the model was not obvious; the results were similar to those in longitudinal waves.

These results reconfirmed that the drastic roll of the pipelay vessel in the East China Sea is not parametric rolling but synchronous rolling, which results from waves with periods close to the natural rolling period of the vessel.

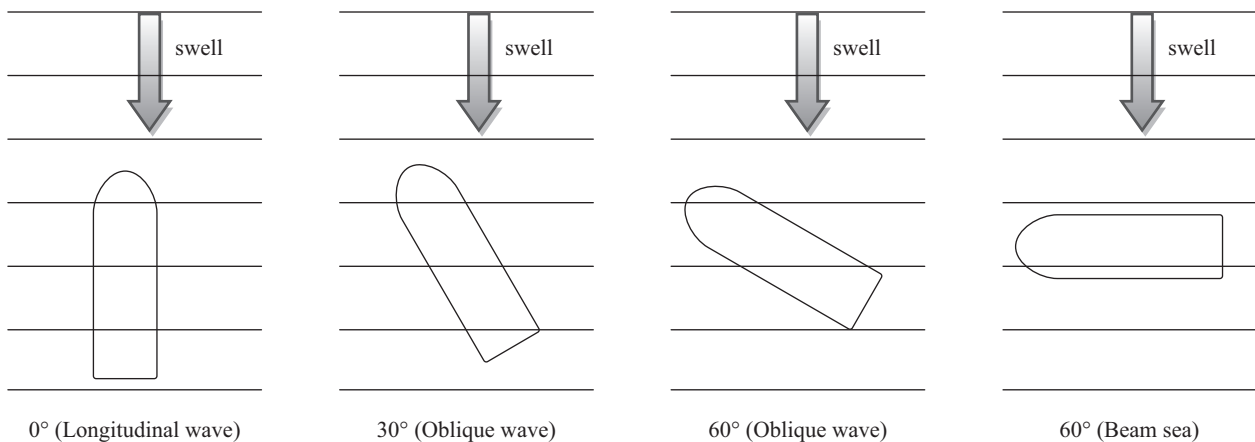
## 3. Testing the Scale Model in Oblique Wave

According to navigation experience, changing the course angle can reduce the roll because the encounter wave period is also altered, and this phenomenon can be explained theoretically. To further research the motion rule in waves with periods close to the natural rolling period ( $T = T_\phi$ ), the scale model was subjected to experiments in oblique waves, particularly with the course angles of  $30^\circ$  and  $60^\circ$ . Experiments on the model hit by waves with a period of 1.96 s ( $T = 1.4T_\phi$ ) were also conducted for comparison. This period was far from the natural rolling period of the model, which exceeded the



**Table 5. Test details of the scale model in oblique wave.**

No.	Course angle/°	Wave length of swell		Wave height of swell		Wave period of swell	
		Actual state/m	Scale model/m	Actual state/m	Scale model/cm	Actual state/s	Scale model/s
1	30	240	3	2.4	3	12.4	1.39
2	30	240	3	4.0	5	12.4	1.39
3	30	480	6	2.4	3	17.5	1.96
4	60	240	3	2.4	3	12.4	1.39
5	60	240	3	4.0	5	12.4	1.39
6	60	480	6	2.4	3	17.5	1.96



**Fig. 6. Course angles of the scale model.**

harmonic wave area, and synchronous rolling was believed to have not occurred.

The experiment details are summarized in Table 5. The course angle of the model is shown in Fig. 6, together with the experiments in longitudinal wave and beam sea, to easily understand the layout of the model. The motion rule of the six DOFs with different course angles is summarized in Fig. 7.

Roll is the most important factor that affects pipelay vessel operation. Fig. 4 shows that the roll amplitude is small when the swell period is not in a harmonic wave area. Drastic roll occurs when the model is hit by waves with periods close to the natural rolling period. The roll amplitude decreases as the course angle decreases. The roll motion is at its faintest when the model is in the longitudinal wave. The roll amplitudes are 3.9° and 5.5° when the model is hit by 3 and 5 cm-high waves, respectively. The roll motion is at its most intense when the model is in beam sea, and the roll amplitudes are 14° and 18° when the model is hit by 3 and 5 cm-high waves, respectively. The drastic roll motion is shown in Fig. 8.

In addition, the pitch amplitude exhibits no obvious change with a change in the course angle and within the scope of the operation criterion. The sway motion is much larger when the model is in beam sea than when it is in longitudinal wave, whereas the surge motion is much larger when the model is in longitudinal wave than when it is in beam sea; these contrasting occurrences corresponded to ordinary rules.

In conclusion, the operation and safety of the pipelay vessel

is susceptible to periods of swells. Once a pipelay vessel is hit by waves with periods close to the natural rolling period, synchronous rolling occurs and the roll amplitude exceeds the criterion in any course angle.

## VI. CONCLUSION

The period characteristic of waves in the East China Sea was analyzed in this study according to the distribution range of wave periods. Parametric and synchronous rolling, which are caused by waves with periods of  $T = 0.5T_\phi$  and  $T = T_\phi$ , respectively, and which in turn potentially cause drastic roll, were analyzed theoretically.

A 1/80 scale model of the Hai Yang Shi You 201 was created, and the motion feature of the scale model was tested in longitudinal wave and in beam sea with different periods and wave heights. The conclusion is that the drastic roll of the pipelay vessel in the East China Sea is not parametric rolling but synchronous rolling, which results from waves with periods that are close to the natural rolling period of the vessel.

Experiments were conducted on the scale model in oblique waves with course angles of 30° and 60°, and the motion rule of the scale model in synchronous rolling wave with different course angles was summarized. The roll amplitude decreased as the course angle was reduced, but the roll amplitude exceeded the criterion in any course angle.

The period is not considered in the current wave classifi

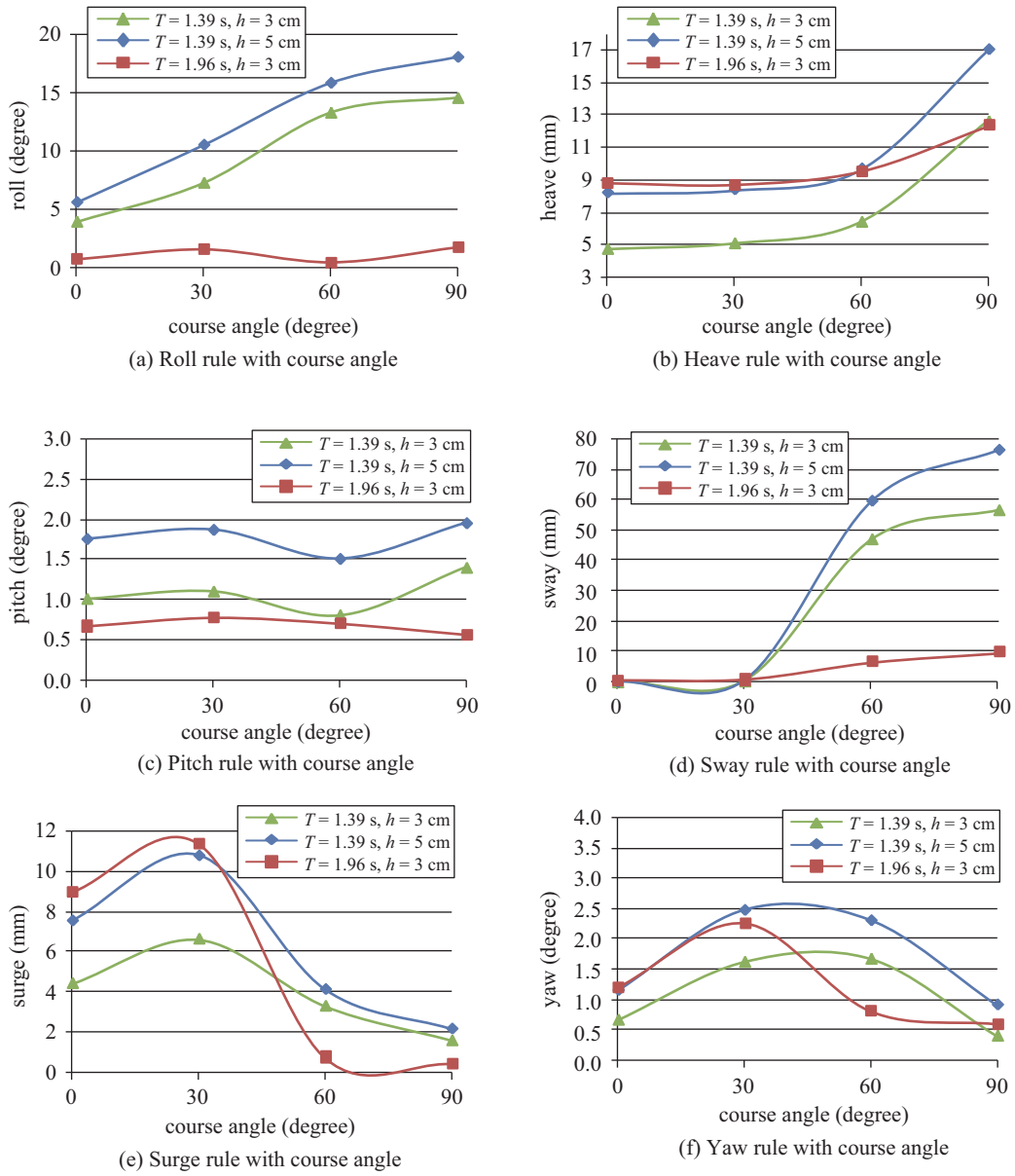


Fig. 7. Motion rule of the scale model in synchronous rolling wave with different course angles.

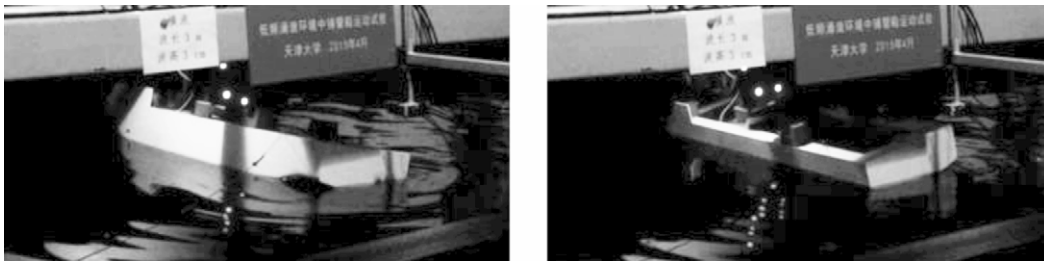


Fig. 8. Drastic roll motion of the scale model in synchronous rolling.

cation method in China, the amplitude of swells is usually small, and swells with large periods have longer wavelengths and are difficult to perceive at sea. Hence, monitoring the

period when operating at sea is recommended, and the monitoring period data can serve as basis for selecting a construction climate window. When swells with periods that are close

to the natural rolling period are discovered, the offshore operation of a pipelay vessel should be delayed to reduce losses caused by standby time. Moreover, the pipelay vessel design should consider wave periods during operation at sea, and the natural rolling period of the vessel should be isolated from the period scope of the operation at sea.

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