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A Preliminary Analysis on the Statistics of about One-Year Air Gap Measurement for a Semi-submersible in South China Sea

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ABSTRACT

Air gap performance has been a key issue in the design of semi-submersible platform. In this paper, a comprehensive study on air-gap is carried out based on the field measurement data of a semi-submersible in South China Sea using statistical analysis. The analysis shows that the energy extremes of air gap mainly appear in the wave frequency range. By fitting the probability density and cumulative probability distribution curve, the air gap extreme can be predicted. And the air gap performance of the platform is relatively stable in different months because the curves in different months appear very close. Moreover, the correlation between air gap and vertical motion of the platform is analyzed, which indicates that parts of the low-frequency data are unreliable, and a method to evaluate the reliability of the field measurements is proposed.

KEY WORDS: air gap; long-term measurement; frequency; statistics; correlation.

INTRODUCTION

Semi-submersible offshore drilling platform has drawn a wide range of attention in the offshore community because of its large deck area, large displacement, strong wind resistance and excellent motion performance. One of the key issues regarding the performance of the semi-submersible platform is the air gap which is defined as the vertical distance between the lower deck of platform and the wave surface. Sufficient air gap should be ensured to reduce the possibility of the damage from the wave impact on the lower deck. On the other hand, a larger air gap would result in a great change in draft and gravity center of the platform, which may directly affect the overall design and cost of the platform. Thus, the air gap is often determined based on the compromise among those concerns.

Air gap is closely related to two aspects, the wave elevation at the specific position of the platform and the vertical motion response of the platform.

Currently most requirement and restrictions of the air gap are on the minimum value during the service life. In fact, its characteristics and probability distribution are also important in addition to extreme values. Simply elevating deck of the platform to reduce the wave impacts on the deck is neither a good idea nor economical. Sweetman (2004) proposed a method to reduce the cost. The principle of the method is to reinforce the structures which are more likely to be impacted by the waves.

Present air gap design methodologies for floating structures rely mostly on empirical knowledge and model tests. A number of studies have been reported, focusing on the flow mechanisms and related variables such as the ship vertical motions, freeboard, wave parameters, and forward speed. Kazemi and Incecik(2006) conducted physical model tests on a semi-submersible in regular waves in the wave tank of Newcastle University, and evaluated the air gap responses at different locations of its deck and measured the impact forces. It was proved that the maximum wave enhancement and consequently the minimum air gap occurred in an area where the wave run-up occurs. Kriebel and Wallendorf (2001) carried out a model test on a single module of the Mobile Offshore Base in irregular head seas for two sea states. And the results of wave spectra, RAO's, and probability distributions were reported to show significant non-linear effects at full scale in severe sea conditions.

Although the air gap in irregular waves can be accurately measured in a model test, obtaining reliable estimates for the extreme response is still challenging. Naess (2009) attempted to assess the extreme response by utilizing the level of upcrossing rate function combined with an optimization procedure that allows prediction at extreme response levels. The variation in predictions and the uncertainty bounds on the estimates between the Weibull Method and the Naess-Gaidai Method were compared. The later method was better in irregular waves.

In this paper, a set of the field measurement data of a semi-submersible in South China Sea is analyzed. The data includes air gap and three-dimensional acceleration of the semi-submersible platform. A comprehensive study on air-gap using statistical analysis based on the data sample is conducted, deriving the severity of air gap and the probability distribution of the air-gap values at one location on the deck. The correlation between the vertical motion and air gap was also analyzed, and a method to evaluate the reliability of the field measurements was proposed. An effective method for analyzing the long-term wave measurement data which avoids the error of scale effect in model test is proposed. Moreover, the empirical laws for the significant wave height in South China Sea is also summarized.

METHODOLOGY

This section provides the basic theory used in this study, including the probability density and cumulative distribution equation to calculate the statistical characteristics; the conversion relationship among the air gap, wave elevation and motion of the platform; and the correlation formulas.

Probability distribution of air-gap

Gaussian distribution is a common continuous distribution which plays an important role in mathematical statistics. Theory suggests that if a stochastic process is formed by the combined effects of a large number of independent random variables, while each individual variable only has a small role in the overall impact, the stochastic process often satisfies Gaussian distribution approximately. Wind generated waves basically satisfy these assumptions, so the instantaneous values of wave run-up satisfy the probability density expression of Gaussian distribution.

A stochastic process which is linearly transformed from a Gaussian process also satisfies the Gaussian distribution. This is one of the main features of the Gaussian process. Therefore, if the waves are considered as a Gaussian distribution, then the instantaneous values of ship motion and hull stress, which are caused by waves, also satisfy the Gaussian distribution. Therefore, the air gap, which can be obtained by a linear operation between the absolute value of the wave and ship motion, satisfies Gaussian distribution as well. It can be written as:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma_x}}\exp\left[-\frac{(x-\mu_x)^2}{2{\sigma_x}^2}\right] \quad (1)$$

where x is a stochastic process, μ_x is the mean value of x and ${\sigma_x}^2$ is the variance of x.

In ocean engineering, it is assumed that air gap follows Gaussian distribution, then the amplitude x follows the two-parameter Weibull distribution. The expression is:

$$f(x) = \frac{\delta}{\kappa}\left(\frac{x}{\kappa}\right)^{\delta-1} exp\left[-\left(\frac{x}{\kappa}\right)^{\delta}\right]$$

(2)

$$F(x) = 1 - exp\left[-\left(\frac{x}{\kappa}\right)^{\delta}\right]$$

(3)

where δ is the shape parameter and κ the scale parameter.

It could also be written as:

$$F(x) = 1 - exp\left[-A\left(\frac{x}{x_0}\right)^{B}\right]$$

(4)

where x_0 is the maximum amplitude of the entire air gap calendar curve, A, B are formal parameters, respectively, and they are written as

$$A = Blnx_0$$
$$B = \delta$$

(5)

If we can get A and B from data fitting, then we could get the corresponding value of δ and κ, as well as the final cumulative probability distribution. B = 2, the above formula is the Rayleigh distribution.

Vertical motions effect on air gap

In general, the air gap is a combination of the incident waves, the diffracted waves and the vertical motion of the platform. The total wave can be explained by the incident and diffracted waves. The data measured by the wave probes are the relative wave elevations. The following equation shows the relationship:

$$r(t) = a(t) - \delta(t)$$

(6)

$$\delta(t) = \eta_3(t) + y\cdot\sin(\eta_4(t)) - x\cdot\sin(\eta_5(t))$$

(7)

where $r(t)$ is the time history of the relative wave elevation; $a(t)$ is the time history of the total wave elevation; $\delta(t)$ is the time history of the vertical motion; $\eta_3(t)$, $\eta_4(t)$ and $\eta_5(t)$ are measured heave, roll and pitch motions, respectively. (x, y) describes the location of the wave probe.

Correlation and significance tests

The variables in this study like the air gap and the vertical motion are linearly related and they satisfy Gaussian distribution. Pearson correlation coefficient is used as a quantitative indicator to describe the degree of linear correlation. It can be calculated according to the following equation:

$$p = \frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}}$$

(8)

$$\bar{X} = \sum_{i=1}^{n} X_i/n \quad , \quad \bar{Y} = \sum_{i=1}^{n} Y_i/n$$

(9)

where p is in the range of [-1,1]. The higher absolute value of p means the higher degree of linear correlation between two variables. p=0 indicates that there is no linear correlation between the two variables. The positive and negative sign of p indicates a positive and negative correlation, respectively.

Significance tests are required to avoid correlation analysis errors caused by sampling error. The statistical test for Pearson correlation coefficient is to calculate t statistic:

$$t = \frac{r}{\sqrt{\frac{1-r^2}{n-2}}}$$

(10)

Where r is the correlation coefficient. Statistics t satisfy t distribution with degrees of freedom (n-2). The corresponding critical value (or p value) in t distribution table can be found according to the given significance level and degrees of freedom. If $|t| > t_{\frac{\alpha}{2}}$ (or $p < \alpha$), r is statistically significant, and vice versa.

DATA ACQUISITION

The data used in this study is collected with a wave probe and an acceleration sensor installed on a semi-submersible platform in the South China Sea.

The wave probe measuring the air gap was mounted at the center of the port side under the deck of the platform. The sampling frequency is 5Hz, generating a data file every 15 minutes. The available air gap data is from November 30, 2014 to September 15, 2015. Most of the data is authentic except a small part missing.

The three-dimensional accelerometer is used for measuring the accelerations of the platform. Since the air gap refers to a relative distance from the bottom of the lower deck to the water surface, the coordinate system used in this paper is the platform-fixed coordinate system. Therefore, the heave motion of the platform has been considered. The acceleration in z direction can reflect the heave motion of the platform.

DATA ANALYSIS AND DISCUSSION

This section describes the processing and analysis based on the measured data, which is of great significance for air gap prediction. Firstly, time domain analysis can show the trend and the overall statistical properties of the air gap. The power spectral density of air gap can be obtained from the time series data, and it can reflect the energy distribution of the air gap in different frequency range. The extreme value of air gap can be predicted through statistical analysis of the probability distribution. In addition, a method to evaluate the reliability of the measured data is proposed based on the correlation analysis.

Time-series analysis

The mean and minimum values in each three-hour is calculated, see Figs. 1 and 2. As shown in Fig. 1, there are two periods of time (in the beginning and medium of the data record, respectively) during which the platform may be in transit condition and the air gap value is much larger than the other data in operating draft. In this study, only the data in operating draft is used for the following analysis. Therefore, the extracted data are in the range of from February 1st to March 31st, and from May 15th to September 15th, and exactly last six months. The overall mean of the air gap is 19.87m and the minimum is 15.74m.

Fig.3 shows the maximum, minimum and mean value of air gap in different months. It can be concluded that the mean values of each month are very close and the extreme values of both maximum and minimum are obtained in August, when the storms appear frequently in South China Sea.

Power spectral density analysis

Power spectral density indicates the energy distribution of the air gap at different frequencies. It is found that the energy reaches a peak in the vicinity of 0Hz, which is due to the drift phenomenon. So the filtering operation is necessary. The most common wave period is in the range of 5s-10s, with a corresponding frequency range of 0.1Hz-0.2Hz. Comparing with the experiment results (Liang et al., 2010), the peak should not appear in the frequency lower than 0.02Hz. Therefore, a high pass operation is employed using the filtering frequency 0.02Hz.

The frequency range is very large and at least two peaks appear in the power spectral density because of the complex sea conditions. Therefore, the data is analyzed both for high and low frequency and the results are shown in Fig. 4.

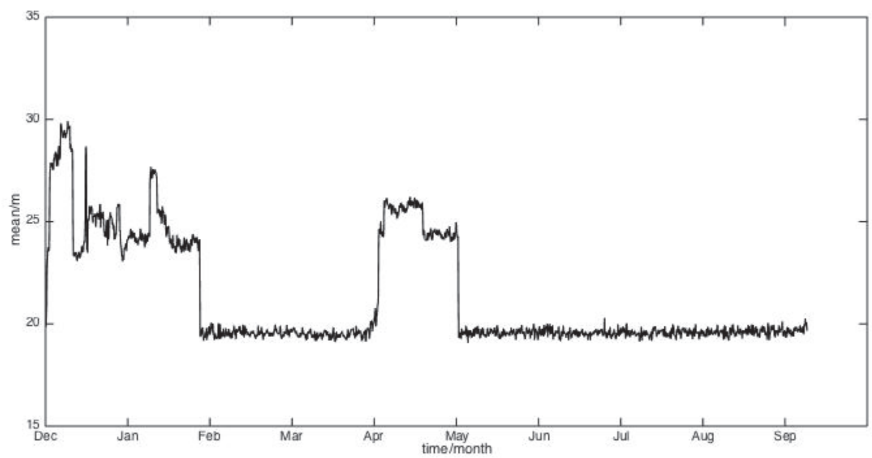


Fig. 1. The mean of every three-hour data

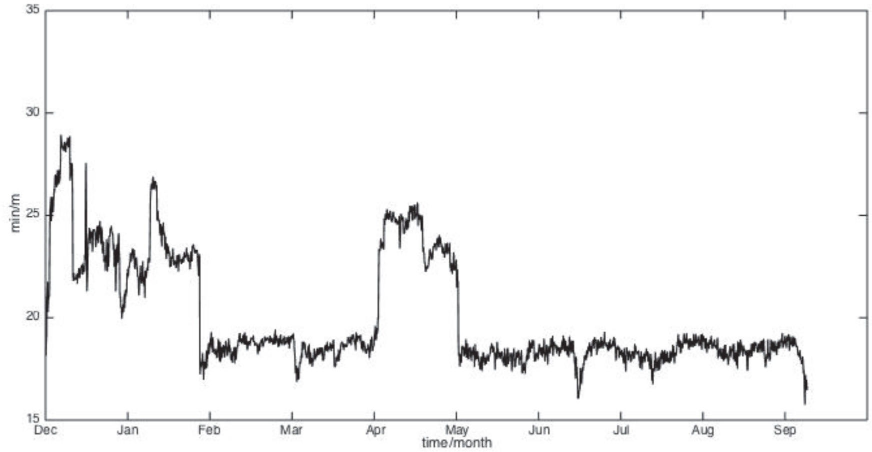


Fig. 2. The minimum of every three-hour data

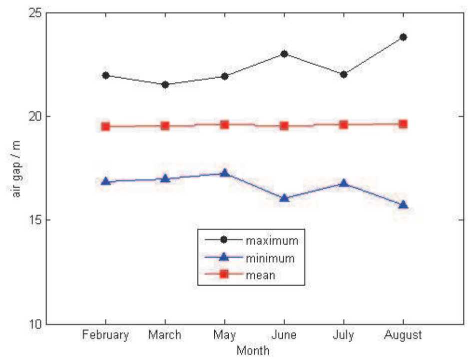
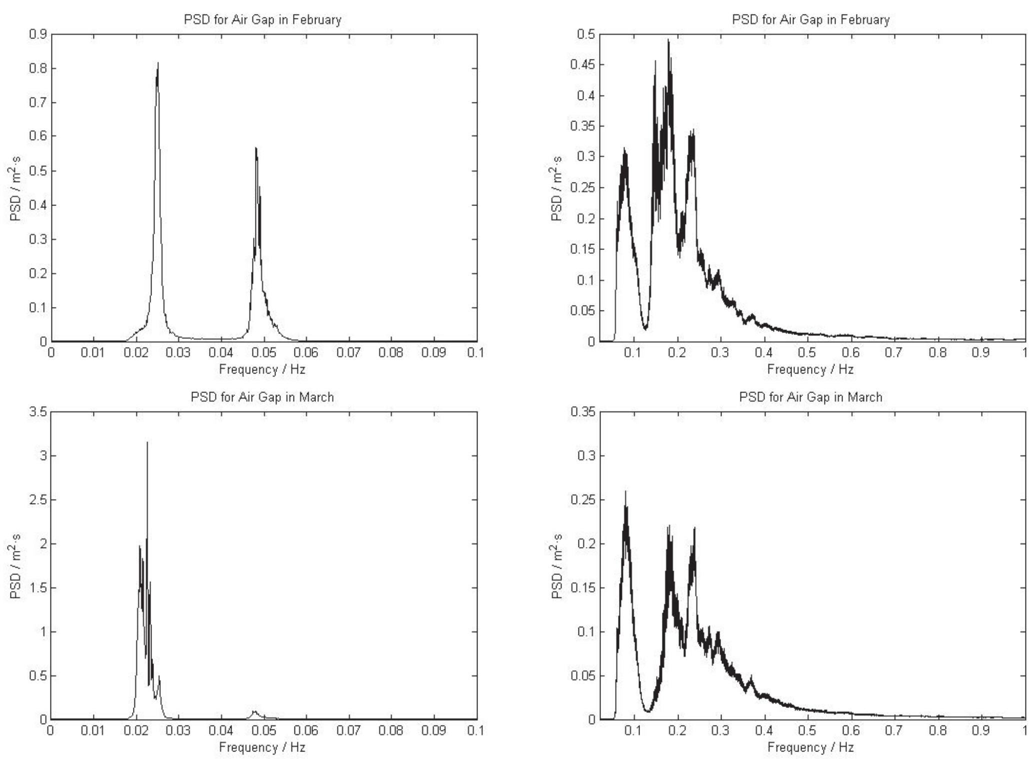


Fig.3. The maximum, minimum and mean value of air gap in different months



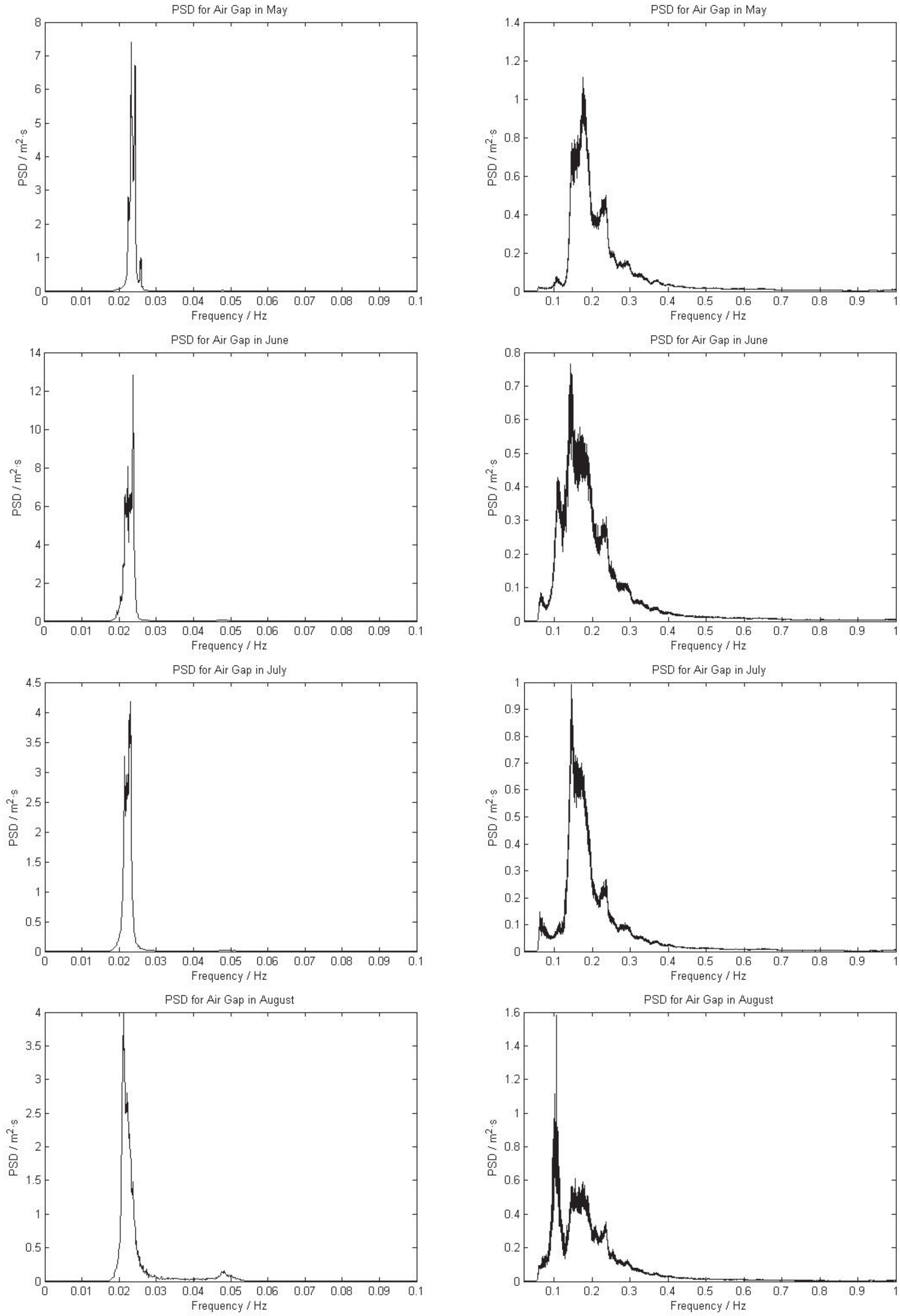


Fig.4. Power spectral density of every one-month air gap: low frequency (left) and high frequency (right).

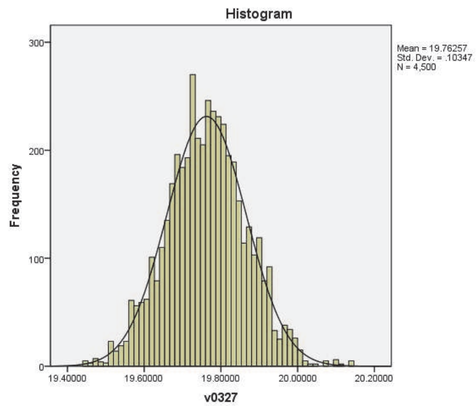
As shown in Fig. 4, the monthly power spectrum density distribution has several distinct peaks. For the low-frequency part there is only one peak which is between 0.02-0.03Hz in most months and the spectrum is very narrow. And this frequency range is close to the roll and pitch natural period. However, there is also a peak at about 0.05Hz in February, which may be related to the heave natural period. As for the high-frequency part, there is a peak near 0.2Hz in every monthly power spectrum density distribution, and 0.2Hz is close to the wave frequency. It can be seen that not only the incident wave, but also the response of platform motion can influence the energy distribution of air gap.

Probability distribution of air gap

Special attentions are usually paid to the minimum of the air gap. The statistical properties of the air gap can be predicted accurately based on the accurate estimation of the probability density function. Since sea conditions are not recorded in this field measurement, a comprehensive statistical analysis of the long-term data is of significance in air gap forecast.

It is generally considered that the instantaneous value of the air gap follows a Gaussian distribution. The hypothesis should be proved as following:

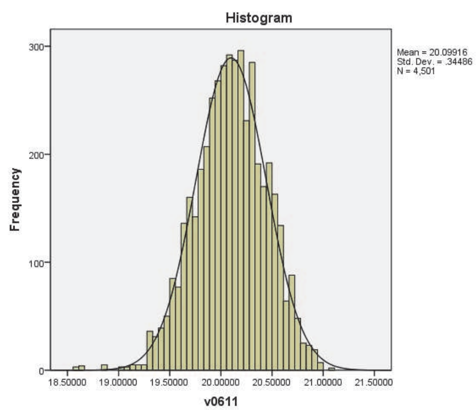
Fig. 5 shows the results of the Gaussian distribution verification by K-S tests based on the randomly selected 15-minute air gap time series. The original assumption that the data follow the normal distribution is valid because the significance is greater than 0.05. It should be noted that a small part of the data does not follow the normal distribution after tests though it is satisfied from the point of P-P plot and the probability density histograms. This is because some errors exist when the sample is of large amount (Fleishman, 1978). Fig.6 and Fig.7 show that the monthly air gap data follow the Gaussian distribution, too.



Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of v0327 is normal with mean 19.76 and standard deviation 0.10.	One-Sample Kolmogorov-Smirnov Test	.174	Retain the null hypothesis.

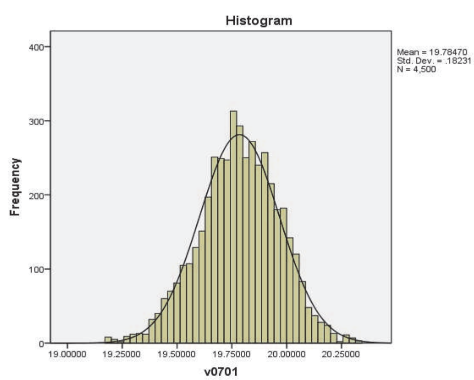
Asymptotic significances are displayed. The significance level is .05.



Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of v0611 is normal with mean 20.10 and standard deviation 0.34.	One-Sample Kolmogorov-Smirnov Test	.144	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.



Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of v0701 is normal with mean 19.78 and standard deviation 0.18.	One-Sample Kolmogorov-Smirnov Test	.062	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Fig.5. Frequency distribution histogram and hypothesis test summary of the 15-minute data

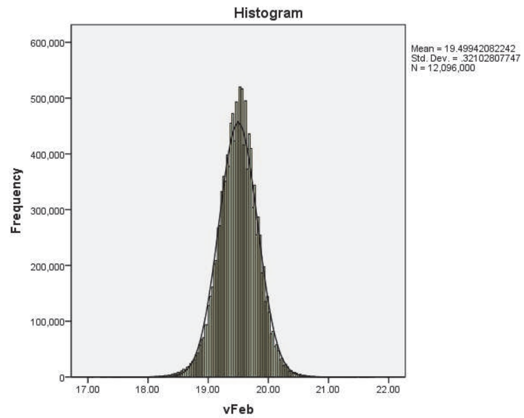


Fig.6. the frequency histogram of February

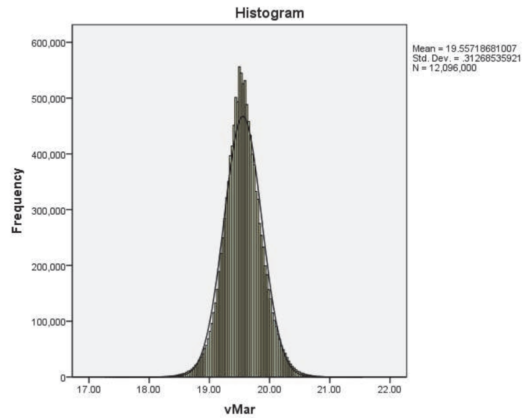


Fig.7. the frequency histogram of March

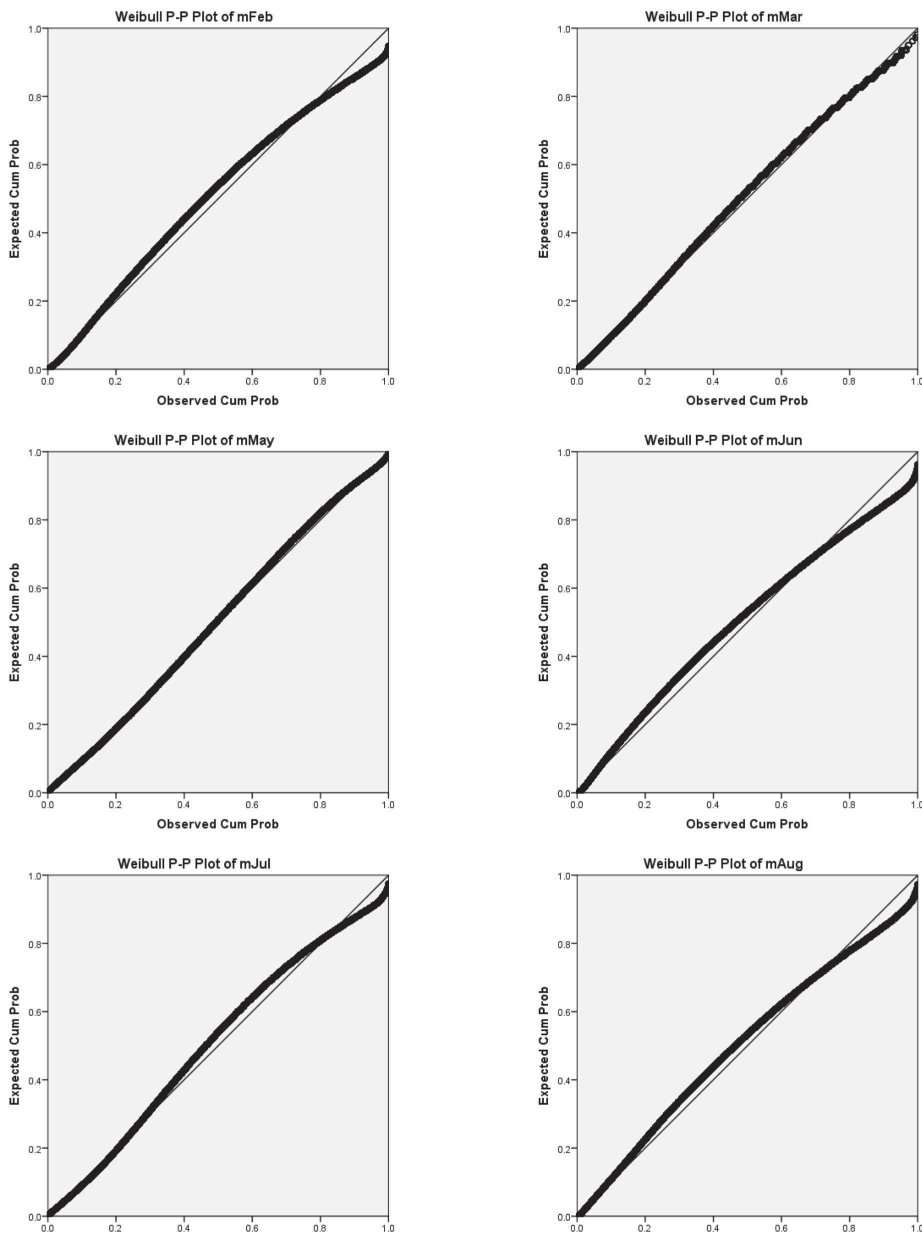
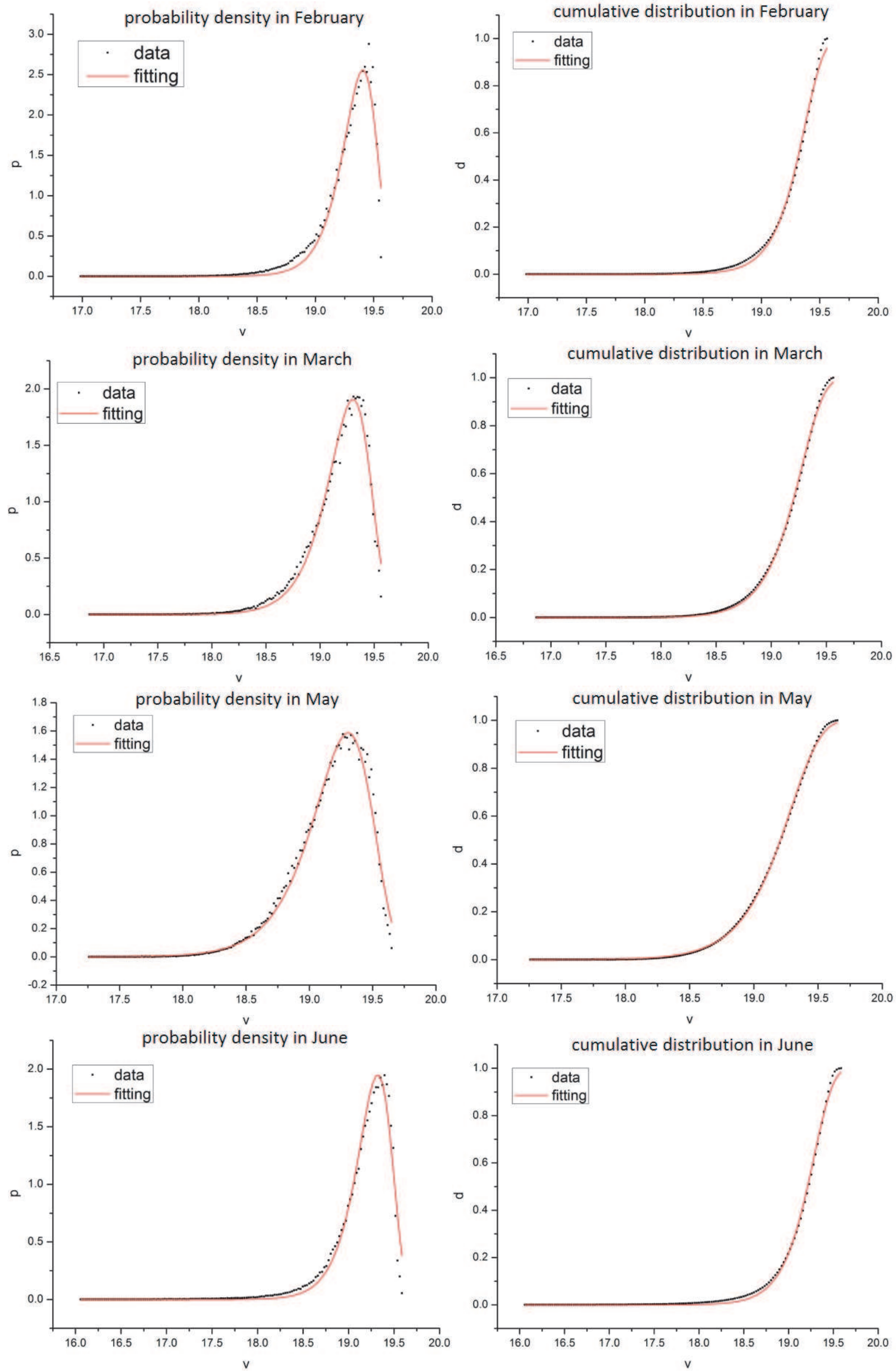


Fig.8. P-P plot test of Weibull distribution of one-month data



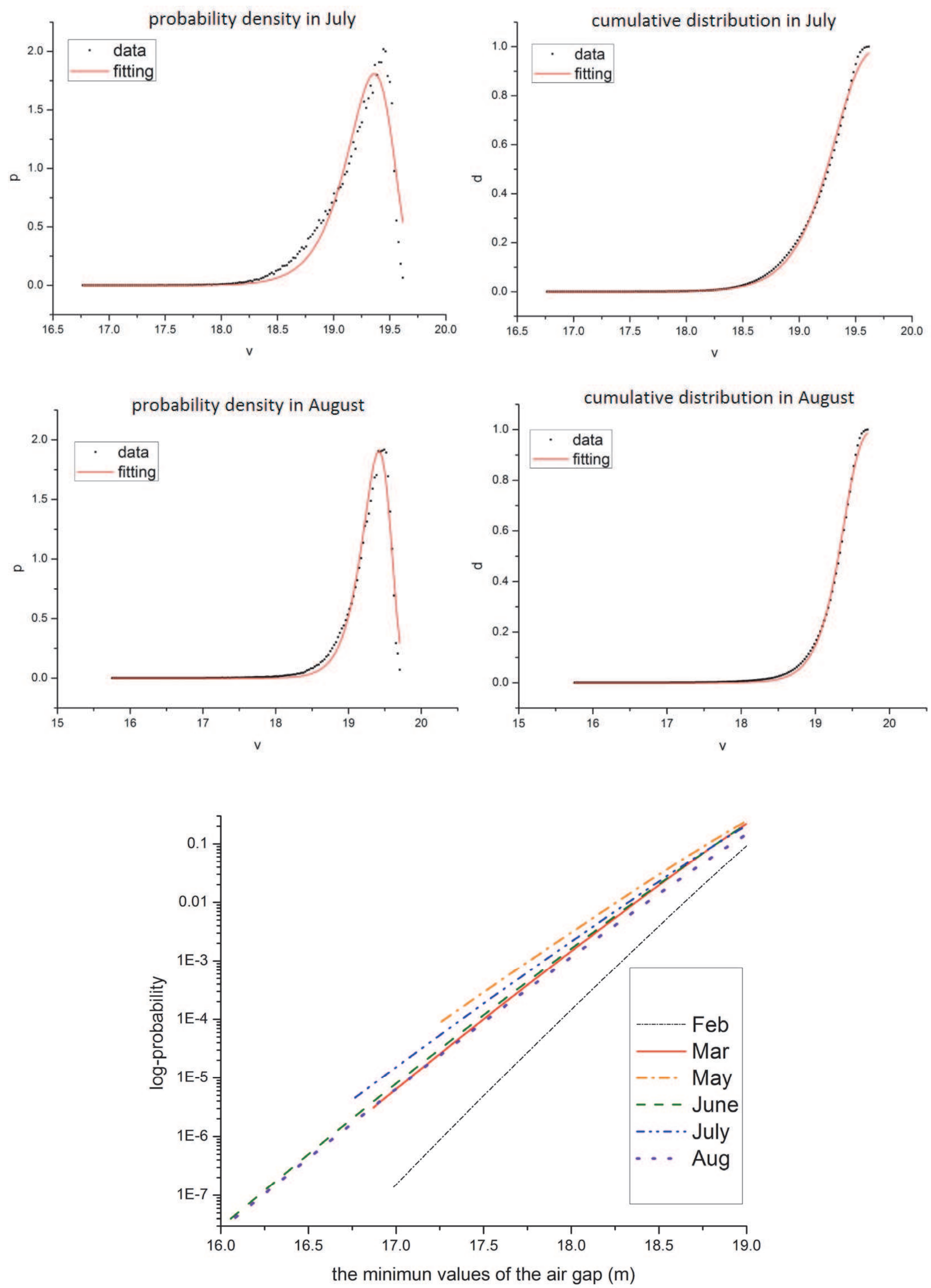


Fig.9. The fitting probability density and cumulative distribution curves

Table1 the fitting parameters of the function

month	Probability distribution		cumulative distribution	
	δ	κ	δ	κ
Feb	134.99964	19.40847	120.11194	19.37332
Mar	100.23086	19.30682	94.98219	19.28036
May	83.32436	19.30927	83.54911	19.29119
Jun	102.53645	19.32367	92.90381	19.28944
Jul	95.31907	19.36532	86.56266	19.32528
Aug	100.86524	19.42158	90.8977	19.38929

Fig. 8 shows the results of the Weibull distribution verification by P-P plot tests based on the minimum values of every one-month air gap time series. The minimum values of air gap follow the Weibull distribution as equation (2).The parameter of the probability density function and cumulative distribution function can be fitted and the results are shown in Table 1.

The scale parameter κ is almost constant. The shape parameter δ varies within certain range because the data is not normalized. The probability of an extreme value range can be estimated approximately by the fitted probability density function and cumulative distribution function.

It can be concluded by comparing the curves in different months that the extreme values with the largest probability are very close, which shows the stability of the air gap. But the exceedance probabilities are different because of the different conditions. Continual storm will increase the probability of the smaller extreme. As shown in Fig.9, the probabilities of the smaller value (smaller than 19m) in July and May are slightly higher than that in other months. The data used in these curves is from 15th May to 15th June and 15th July to 15th August, which are also part of the months when typhoon appears most often. Statistics show that typhoon appears three times in a row in the South China Sea from late July to early August in 2015, each lasting 3-4 days, and that must be the reason for the small extreme value. The smaller 30% of the overall air gap is important. The probability that the air gap is less than 18.5m is about 0.0039 by estimates.

Correlation analysis

A number of studies on the air gap have been reported using both wave basin experiments and various numerical simulations, focusing on the flow mechanisms and the various related factors such as the ship vertical motions, freeboard, wave parameters, and forward speed. Xiao et al. (2015) showed that the motion of the platform has an important impact on the air gap, especially the vertical motion. Since the air gap is a linear combination of the wave value and the vertical motion, there must be a very close correlation relationship between the air gap and the vertical motion.

In the model tests, the data could be measured with high reliability. On one hand, the possible influences in the model test could be carefully recognized, on the other hand, the sea conditions are clearly defined and simulated. However, in the actual field measurement, it is difficult to judge whether the measured data is reliable or not because of the complexity of the sea conditions and the long duration of measurement.

Now we assume that the air gap and the vertical motion has a close relationship, the correlation between them are analyzed. The vertical motion of the platform can be obtained by integrating the vertical acceleration of the platform.

The heave natural period of the platform is about 20s according to the estimation, which can also be found in the PSD. Select three 15-minute data, filter the acceleration in *z* direction by different frequencies and integrate twice to obtain the vertical motion. Analyze the correlation between the motion and air gap and the following results are found:

the correlation is negative if the acceleration data are not filtered; more and more significant correlation with the filter frequency increasing in a certain range. A temporary conclusion is that some of the low-frequency data may be unreliable.

Based on the characteristics of the sensor, we can find that there is a fixed offset value with some inclination of sensor. And part of the low-frequency data can be discarded. It proves the above conclusion. Measured data can be tested through this method and part of the invalid data can be rejected.

CONCLUSION

Based on the filed measurement data for a semi-submersible platform in South China Sea, a set of nearly one-year air gap and acceleration data is obtained. In this study, we analyzed the data in both time and frequency domain. The main conclusions are drawn as follows.

The power spectral density is used to explain the frequency distribution of the air gap. Due to the significant drift motion of the platform, it is necessary to filter the measured air gap data using the appropriate frequency. Further, the processing method of the measured data is very different from the experimental data, approximations and assumptions on some details may lead to much difference in results. It is important to select the appropriate method of calculating the PSD.

Gaussian distribution and Weibull distribution can effectively describe the distribution of the air gap and its extreme values. The distribution function is consistent with the measured data, and the empirical Weibull distribution model is an effective tool for extreme estimating. The air gap of the platform remained stable overall during the year, with some minor extreme in individual months due to bad sea conditions.

The filed measurement data seem more superior than the experimental data as they are more “real”. However, due to the complicated offshore environments and the existence of many unknown factors, the reliability of the measured data is questionable. A method to distinguish data reliability using correlation analysis is proposed in this paper. The results are in line with the characteristics of the data herein.

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