A MASTER'S THESIS

# The Prediction of Irregular Waves on Northeastern Jeju Island using the Wave and Wind Data

JEJU NATIONAL UNIVERSITY
GRADUATE SCHOOL

Major of Wind Power Ocean and Civil Engineering Faculty of Wind Energy Engineering

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# The Prediction of Irregular Waves on Northeastern Jeju Island using the Wave and Wind Data

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**A thesis submitted in partial fulfillment of the requirement for the degree of Master of Engineering**

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## Summary

In order to analyze wind wave in the field of frequency domain and assess application of a JONSWAP spectrum in IEC 61400-3 for wind offshore structures, wave and wind data was observed along the northeastern shore of Jeju island from Sep. 5, 2012 to Oct. 5, 2012 and Jan. 11, 2013 to Feb. 11, 2013. The JONSWAP spectrum is one of the models of wave spectrum that shows corresponding energy density of wave for each frequency. The JONSWAP spectrum needs some parameters such as $\gamma$value, peak frequency, peak period, significant wave height. Generally, $\gamma$ value is used 3.3 or 1. However, many scientist suggested $\gamma$ value depends on characteristic of area because of a large error. In this study, Available $\gamma$ in study area are suggested using the observed wave data. In order to suggest calculating $\gamma$ value for study area, the observed wave data was analysed using Fourier transform

As a result, the highest frequency is below 1m in the case of significant wave height and during the first observation, the mean of height was predicted at 0.523m and during the scend observation, it was 0.423m. Furthermore, in peak frequency, the highest frequency was 0.12Hz～0.15Hz(period is nearly 6.67s～8.33s), the results of $\gamma$ from using significant wave height and peak frequency is 2.72 And the significant wave height calculated by straight linear regression equation was $1.635H_s$.

The predicted irregular waves along the northeastern shore of Jeju island using 1st regression model, SMB method, and JONSWAP spectrum wave model, and the observed wave data are compared the predicted significant wave height using SMB method, that is often used to study of offshore structure design with significant wave height using 1st regression function. In this study, each calculated significant wave heights is applied to JONSWAP spectrum and compare spectral moments of order 0 values because the spectral moment of order 0 the coefficient of determination by

two kinds of transformed functionsvalues is the gross area of JONSWAP spectrum and importance parameter for calculation significant wave height.

As a result, Each coefficient of determination by two kinds of transformed functions as shown 0.58 to 0.61, the. This means that the SMB method was able to get better results than the regression function. However, in the case of RMSE (Root Mean Square Error), regression function has a lower value than SMB method (RMSE values are 0.45 and 28.47). By transformed functions, spectral moments of order 0 are 0.0473 and 0.4194, respectively and by observed significant wave height, spectral moments of order 0 are 0.0502 and 1.0054. According to the comparison of result of these values, results of the regression function are more accurate than SMB method. Finally, The significant wave height by the regression function model is transformed using the observed wind data from Jan. 11, 2013 to Feb. 11, 2013. The result of the comparison between calculated significant wave height and observed significant wave height is that the regression function shows more accurate than SMB method.

# CHAPTER 1
# INTRODUCTION

## 1.1 Objectives

In modern times, interest for renewable energy resources such as solar, wind and tidal is amplified as the solution for energy shortage problems. One of renewable energy resources, wind energy has freely available abundant resources, and is freer from constraint of space such as onshore and offshore than other renewable energies. Also, wind power is rising to important technology in the country industrial structure, because it is able to secure the electronic energy in price fluctuation (Kim, H.M, 2011). However, onshore wind energy farm has problems such as securing sites, noise, and electromagnetic waves. In order to solve problems, offshore wind energy farm is developed. Offshore wind energy farm has less limits such as sites, size than onshore wind farm, and generates more electronic energies on account of abundant wind resource. Therefore, the many researches on offshore wind energy have been carried out. For instance, Gaudiosi(1999) presented the research of offshore wind energy prospects about the European counties. In Japan, study on the predominance of offshore wind turbine was carried out by Iguchi et al.(2000), and study on the development of medium and large scale wind turbine in coastal zone was carried out by Nagai et al.(2008)(Go, M.J, 2014).

In case of the domestic wind power, accrue installation capacity reach about 356.8MW, owing to the promoting government development difference system and region supply business. And the accrue installation capacity is growing. Also, Korea has a plan large scale offshore wind farm in southwest seashore (Ministry of Knowledge Economy et al., 2010)

The offshore wind turbines are able to be classified with two types according to substructure form that is fixed and float type as shown in Fig. 1.

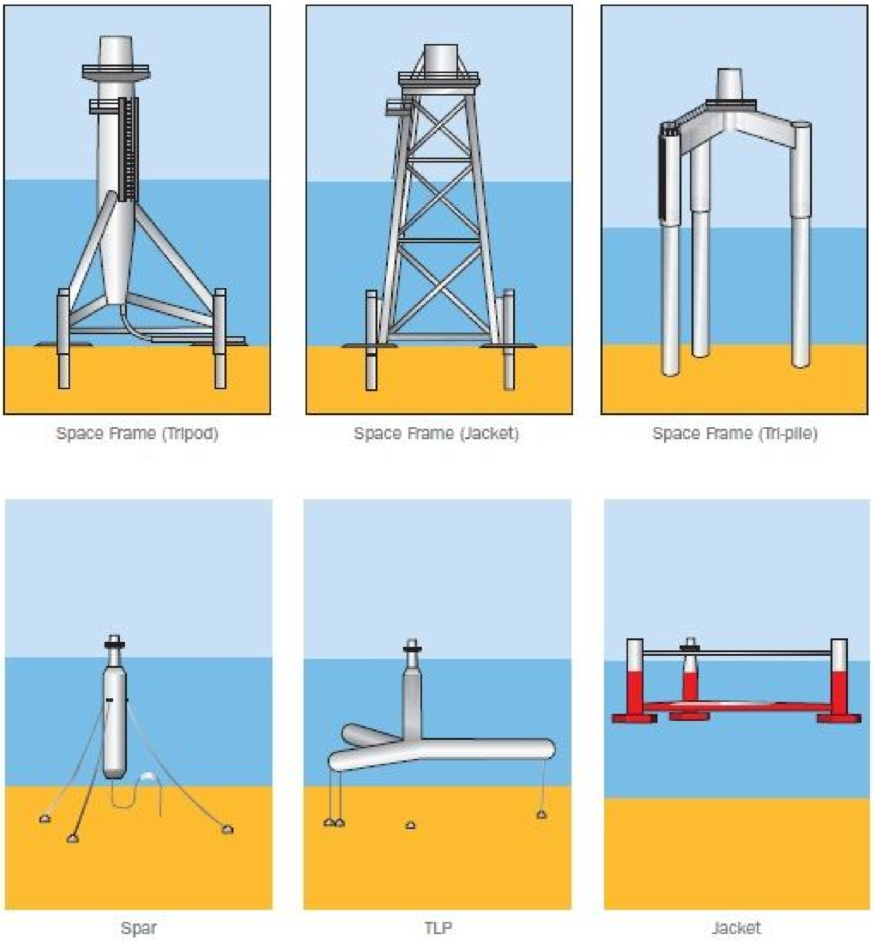


Fig. 1. The kind of offshore wind turbines substructure(Renewable Green Energy Power, 2014).

- **Space frame structures.**

Space Frame Structures come in three variations. First, the tripod, which is a standard three legged structure that have a central steel shaft that is attached to the turbine tower. Similar to the monopiles, each leg is inserted into the sea bed, but together they form a much stronger structure suitable for waters 65 – 165 feet (20 –

50 meters) deep. Second the jackets, have a similar concept to the tripod but they differ in the fact that they consist of a larger plan area through the majority of the structure, allowing the steel shaft to be positioned away from the centre of the axis. This design results in considerable savings of materials. Similar to the tripod, each leg is inserted into the sea bed using piles. Thirdly, the Tri-piles, consist of three foundation legs (piles), which are connected at the turbine tower with a transition piece located above the water level.

- **Floating structures.**

Floating structures have great flexibility in the production and are easier to install. However, they pose a major challenge that have to do with the stability of the wind turbine(Renewable Green Energy Power et al., 2014).

### 1.2 Purpose of study

When a turbine is onshore, this is easy because the foundation is a concrete slab that is heavy enough to create sufficient moment and holding force to withstand the movements and bending moments of the wind acting on the turbines. When a turbine is offshore, the outcome is the same, but there are four additional factors to consider when designing the foundation (Thomsen et al., 2012):

Water depth
Wave load
Ground conditions
Turbine-induced frequencies

For that, It is necessary to observe wave in the coast to construct wind energy farm. Current observation technique furnishes the accurate data. However, in the case of time and space, it has considerable limits. For instance, observation equipments are often lost, and missing data is frequently occurred by strong wind such as typhoon. It is necessary to study on alternative of wave observation to compensate the defect. Fig. 2 is the flow chart of this study. First of all, in order to analyze wave in the field of frequency domain and assess application of proposed JONSWAP spectrum in IEC 61400-3, wave and wind data was observed along the northeastern shore of Jeju island from Sep. 5, 2012 to Oct. 5, 2012 and Jan. 11, 2013 to Feb. 11, 2013. The JONSWAP spectrum is one of the models of wave spectrum. that shows corresponding energy density of wave for each frequency. The JONSWAP spectrum needed some parameters, there are $\gamma$value, peak frequency, peak period, significant wave height. Generally, $\gamma$ value is used 1 or 3.3. However, many scientist suggested $\gamma$ value depends on characteristic of area because of a large error. In Korea, Suh, K,D (2010) suggested $\gamma$ value to 2.14, it is difficult to apply to shallow-sea such as northeastern shore of Jeju island or the study area, because this value is calculated by observed data in deep-sea. In this study, Available $\gamma$ in study area are suggested using the observed wave data. In order to suggest calculating $\gamma$ value for study area, the observed wave data was analysed using Fourier transform.

Secondly, The predicted irregular waves along the northeastern shore of Jeju island using 1st regression model, SMB method, and JONSWAP spectrum wave model and compared the predicted significant wave height using SMB method, that is often used to study of offshore structure design such as Nakamura et al., (2002), Kim et al., (2013), with significant wave height using 1st regression function. In this, each calculated significant wave heights is applied to JONSWAP spectrum and compare spectral moments of order 0 values because the spectral moment of order 0 values is the gross area of JONSWAP spectrum and importance parameter for calculation significant wave height.

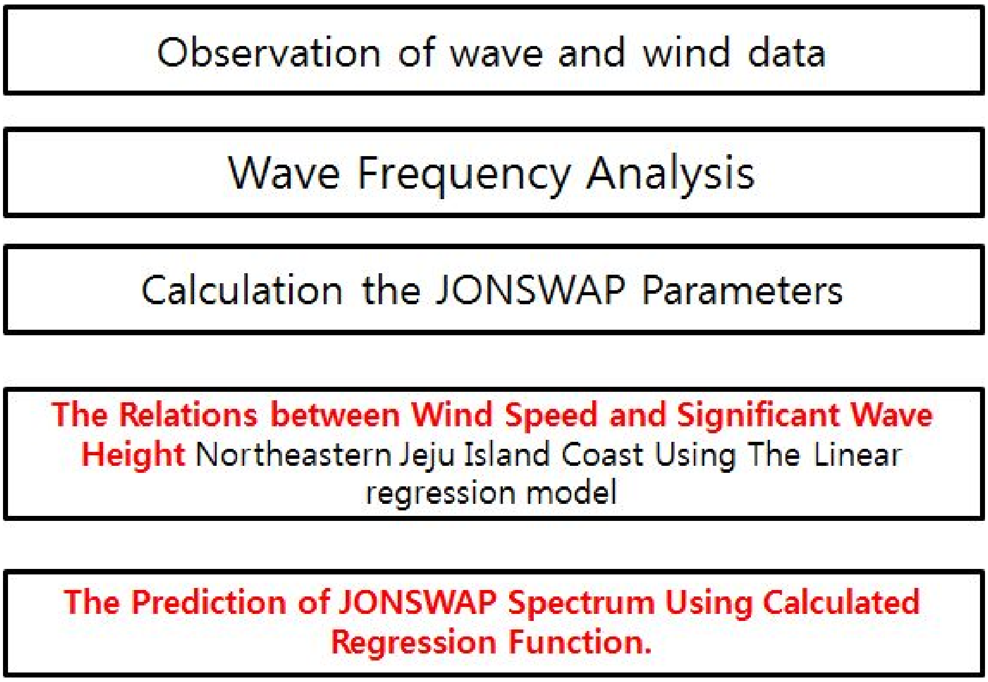


Fig. 2. the flow chart of this study.

# CHAPTER 2

# Basic Equation

## 2.1 The fourier transform

Any continuous, periodic function can be represented as a linear combination of sines and cosines. A sine is a function is a function of the form: $Asin(2\pi\omega t+\Phi)$, where A is the amplitude, $\omega$ si the frequency measured in cycles (or periods) per second, and $\Phi$ is the phase, which is used for getting values other than 0 at $t=0$. A cosine function has exactly the same components as the sine function, and can be ciewed as a shifted sine (or more accurately a sine with phase $\pi/2$).

Thus, given a function $f(t)$, we can usually rewrite it (or at least approximate it), for some $n$ as:

$$f(t)=\sum_{k=1}^{n}\left(A_k\cos(1\pi\omega_k t)+B_k\sin(2\pi\omega_k t)\right) \qquad (1)$$

Both sines and cosines are combined, rather than only sines, to allow the expression of functions for which $f(0)\neq 0$, in a way that is ismpler than adding the phase to the sine in order to make it into a cosine.

As an example of a linear combination of sinusoids consider the function:

$$f_1(t)=0.5\sin\pi t+2\sin 4\pi t+4\cos 2\pi t \qquad (2)$$

Its three sinusoidal components and the function $f_1$ itself are depicted in Fig. 3, as a, b, c and d respectively. The function $f_1(t)$ consists of sines and cosines of 3 frequencies.

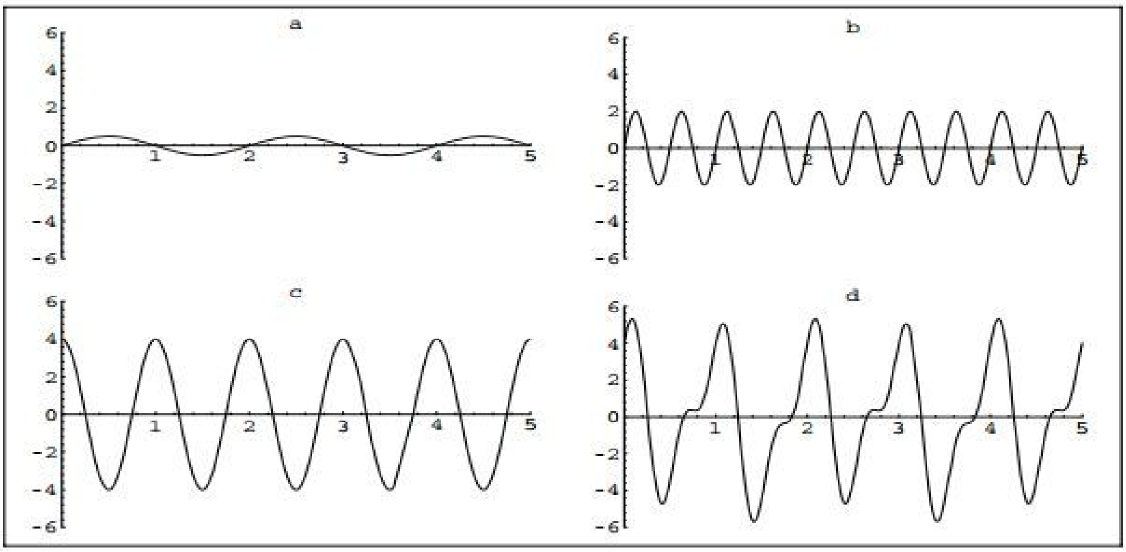


Fig. 3. A plot of $f_1(t)$, $(d)$, and its components (a, b, c), for t=0.5.

Thus, the frequency analysis of $f_1(t)$, can be summarized in a table such as Table 1, which provides for each frequency of $f_1$ the amplitude of the sine wave and of the cosine wave with this frequency.

Table 1. Frequency contents of the function $f_1(t)$.

| k | Frequency $(\omega_k)$ | Cosine amplitude $(A_k)$ | Sine amplitude $(B_k)$ |
|---|---|---|---|
| 1 | 1/2 | 0 | 1/2 |
| 2 | 2 | 0 | 2 |
| 3 | 1 | 4 | 0 |

The representation of a periodic function (or of a function that is defined only on a finite interval) as the linear combination of sines and cosines, is known as the Fourier series expansion of the function. The fourier transform is a tool for obtaining such frequency and amplitude information for sequences and functions, which are not necessarily periodic. (Note that sequences are just a special case of functions.)

### 2.2 The frequency analysis of waves

Waves in nature rarely appear to look exactly the same from wave to wave, nor do they always propagate in the same direction. If a device to measure the water surface elevation, as a function of time was placed on a platform in the middle of the ocean, it might obtain a record such as that shown in Fig. 4. This sea can be seen to be a superposition of a large number of sinusoids going in different directions. It is this superposition of sinusoids that permits the use of Fourier analysis and spectral techniques to be used in describing the sea. Unfortunately, there is a great amount of be used in randomness in the sea, and statistical techniques need to be brought to bear. Fortunately, very large waves or, alternatively, waves in shallow water appear to be more regular than smaller waves or those in deeper water, and not so random. Therefore in these cases, each wave is more readily described by one sinusoid, which repeats itself periodically(R. G. Dean and R. A. Dalrymple, 2000).

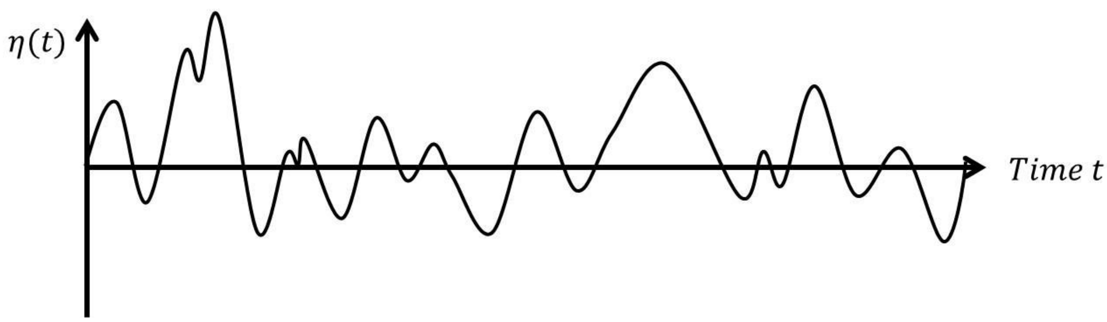


Fig. 4. Example of a possible recorded wave form(R. G. Dean and R. A. Dalrymple, 2000).

In this study, in order to calculate PSD(Power Spectrum Density) of waves.

$$F(f) = \int_{-\infty}^{\infty} |G(f)|^2 df \qquad (3)$$

where F(f) is the PSD, G(f) is the FT(Fourier Transform). PSD is calculated using this function from hourly time domain data and spectrum moment order 0 and significant wave height as follow:

$$m_n = \int_{0}^{\infty} f^n F(f) df \qquad (4)$$

$$H_s \cong 4\sqrt{m_0} \qquad (5)$$

There were a lot more function of wave characteristics as follow Table 2.

In case of maximum wave height, as shown Table 1., (1.6~2.0)Hs has used many researches. Theoretically, wave number is used to choose values among 1.6 to 2.0. However, this study calculated the rate of significant wave height and maximum wave height by observed wave data in study area using 1stregression model, and maximum wave height was calculated by zero-upcross method as follow.

$$Y = aX \qquad (6)$$

Table 2. Formula of Characteristic of Ocean wave in Frequency Domain(J. Twidell and G. Gaudiosi (2009).

| Analysis of wave characteristic. | |
|---|---|
| Description | Relation |
| Spectral moment | $m_n = \int_0^{\infty} f^n \times s(f)df$ |
| Variance or mean square | $\sigma^2 = m_0 \quad (m^2)$ |
| Standard deviation or Root-Mean-Square(RMS) | $\sigma = \sqrt{m_0} \quad (m)$ |
| Significant wave height | $H_s \simeq 4\sigma \quad (m)$ |
| Visual Estimate of the wave height | $H_v \simeq H_s \quad (m)$ |
| Mean zero crossing period | $T_z = \sqrt{\frac{m_0}{m_2}} \quad (\text{sec})$ |
| Mean period of the spectrum | $T_m = \sqrt{\frac{m_0}{m_2}} \quad (\sqrt{\text{sec}})$ |
| Mean crest period | $T_c = \sqrt{\frac{m_2}{m_4}} \quad (\text{sec})$ |
| Estimate of the most probable maximum wave height in a sea state for 1000 waves | $H_{\max} = (1.6 \sim 2.0)H_s$ |

$$a = \frac{\sum_{i=1}^{N}(X_i Y_i)}{\sum_{i=1}^{N}(X_i^2)} \tag{7}$$

where Y is maximum wave height, X is significant wave height.
Lastly, peak frequency and peak period are calculated using function as follow

$$f_p = f|_{F(f)=\max} \tag{8}$$

$$T_p = 1/f_p \tag{9}$$

**2.3 The JONSWAP spectrum**

The JONSWAP spectrum is formulated as a modification of the PM spectrum for a developing sea state in a fetch limited situation. The spectrum was derived to account for a higher peak and a narrower spectrum in a storm situation for the same total energy as compared with the PM spectrum. The JONSWAP spectrum is therefore often used for extreme event analysis(IEC 61400-3 et al., 2009).

Two modification factors are introduced, a peak enhancement factor, , and a normalizing factor, . The first factor increases the peak and narrows the spectrum, the second reduces the spectral density to ensure that both spectral forms have the same Hs (energy). The formulation has been chosen so that = 1 recovers the PM spectrum.

The spectral density of the surface elevation is given by

$$S_{JS}(f) = C(\Upsilon) S_{PM}(f) \Upsilon^{\alpha} \tag{10}$$

where

$\Upsilon$ is the peak-shape parameter,

$C(\Upsilon)$ is the normalising factor $= \dfrac{\int_0^{\infty} S_{PM}(f)\,df}{\int_0^{\infty} S_{PM}(f)\Upsilon^{\alpha}\,df}$

Fig. 5 shows a comparison between the JONSWAP spectrum and the PM spectrum for a a typical North Sea storm sea state (Hs = 14.4m, Tp = 15.4s and =3.3)(IEC 61400-3 et al., 2009).

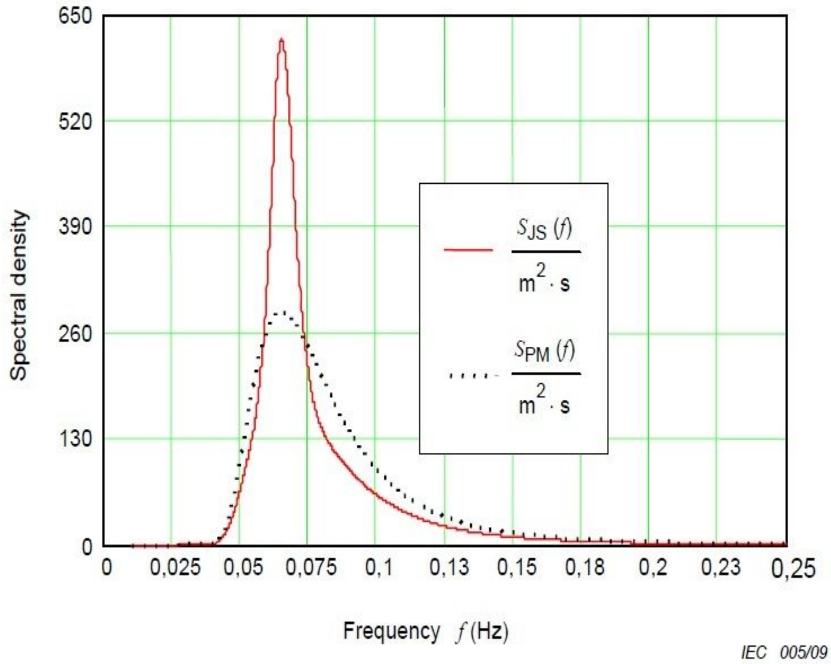


Fig. 5. JONSWAP and PM spectrums for typical North Sea storm sea state(IEC-61400-3, 2009).

In lieu of more detailed information, the following values may be used:

$$\alpha \cong \frac{0.0624}{0.230 + 0.0336\gamma - 0.185(1.9+\gamma)^{-1}} \qquad (11)$$

$$\beta = \exp\left(-0.5\left(\frac{\frac{f}{f_p} - 1}{\sigma}\right)^2\right)$$

$$\sigma = \begin{cases} 0.07 & \text{for } f \leq f_p \\ 0.09 & \text{for } f > f_p \end{cases}$$

Using the above values the JONSWAP spectrum is frequently written:

$$F(f)_{JONSWAP} = \alpha H_s^2 T_p \left(\frac{f}{f_p}\right)^{-5} \exp\left\{-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right\}(1 - 0.287\ln\gamma)\gamma^\beta \qquad (12)$$

### 2.4 The 1st regression analysis

In statistics, regression analysis is the statistical process for estimation the relationships among variables. It includes many techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. More specifically, regression analysis helps one understand how the typical value of the dependent variable (or 'Criterion Variable') changes when any one of the independent variables is varied, while the other independent variables are held fixed. Most commonly, regression analysis predicts the conditional expectation of the dependent variable given the independent variables – that is, the average value of the dependent variable when the independent variables are fixed. Less commonly, the focus is on a quantile, or other location parameter of the conditional distribution of the dependent variable given the independent variables. In all cases, the estimation target is a function of the independent variables called the regression function. In regression analysis, it is also of interest to characterize the variation of the dependent variable around the regression function which can be described by a probability distribution. Regression analysis is widely used for prediction and forecasting, where its use has substantial overlap with the field of machine learning. Regression analysis is also used to understand which among the independent variables are related to the dependent variable, and to explore the forms of these relationships. In restricted circumstances, regression analysis can be used to infer causal relationships between the independent and dependent variables. However this can lead to illusions or false relationships, so caution is advisable(Armstrong, J. Scorr, 2012) for example, correlation does not imply causation.

Many techniques for carrying out regression analysis have been developed. Familiar methods such as linear regression and ordinary least squares regression are parametric, in that the regression function is defined in terms of a finite number of unknown parameters that are predicted from the data. Nonparametric regression refers to techniques that allow the regression function to lie in a specified set of functions, which may be infinite-dimensional.

The performance of regression analysis methods in practice depends on the form of the data generating process, and how it relates to the regression approach being used. Since the true form of the data-generating process is generally not known, regression analysis often depends to some extent on making assumptions about this process. These assumptions are sometimes testable if a sufficient quantity of data is available. Regression models for prediction are often useful even when the assumptions are moderately violated, although they may not perform optimally. However, in many applications, especially with small effects or questions of causality based on observational data, regression methods can give misleading results.(David A. Freedman, 2005),(R.Dennis Cook, 1982)

In statistics, simple linear regression is the least squares estimator of a linear regression model with a single explanatory variable. In other words, simple linear regression fits a straight line through the set of n points in such a way that makes the sum of squared residuals of the model (that is, vertical distances between the points of the data set and the fitted line) as small as possible.
The adjective simple refers to the fact that this regression is one of the simplest in statistics. The slope of the fitted line is equal to the correlation between y and x corrected by the ratio of standard deviations of these variables. The intercept of the fitted line is such that it passes through the center of mass (x, y) of the data points. Other regression methods besides the simple ordinary least squares (OLS) also exist (see linear regression model). In particular, when one wants to do regression by eye, people usually tend to draw a slightly steeper line, closer to the one produced by the total least squares method. This occurs because it is more natural for one's mind to consider the orthogonal distances from the observations to the regression line, rather than the vertical ones as OLS method does.

Suppose there are n data points $\{Y_i, X_i\}$, where = 1, 2, ⋯, $n$. The goal is to find the equation of the straight line as follow:

$$Y = aX + b \tag{13}$$

which would provide a "best" fit for the data points. Here the "best" will be understood as in the least-squares approach: such a line that minimizes the sum of squared residuals of the linear regression model. In other words, numbers b(the y-intercept) and a(the slope) solve the following minimization problem:

$$\sum_{i=1}^{n} \epsilon_i^2 = \sum_{i=1}^{n} (Y_i - aX_i - b)^2 \tag{14}$$

$$a = \frac{\sum_{i=1}^{n} (X_i - \overline{X})(Y_i - \overline{Y})}{\sum_{i=1}^{n} (X_i - \overline{X})^2} = \frac{\sum_{i=1}^{n} X_i Y_i - \frac{1}{n} \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{\sum_{i=1}^{n} (X_i^2) - \frac{1}{n} \left( \sum_{i=1}^{n} X_i \right)^2} = \frac{Cov[X, Y]}{var[X]} = r_{XY} \frac{S_Y}{S_X}$$

$$b = \overline{Y} - a\overline{X}$$

where $r_{XY}$ is the sample correlation coefficient between $X$ and $Y$, $S_X$ is the standard deviation of $X$, and $S_Y$ is correspondingly the standard deviation of $Y$. A horizontal bar over a quantity indicates the sample-average of that quantity.

# CHAPTER 3

# Study area and observation data

## 3.1 Study area

Wave data in this study is observed along the northeastern shore of Jeju island as shown Fig. 6. The coordinates of study area and water depth are longitude 126°47’23.6”, latitude 33°34’21.1”, and 18m, respectively. This area is about 1.3km from shoreline as the crow flies. Two offshore wind turbines of Doosan Heavy Ind. & Constr. and STX are operated in a nearby study area, currently. The observation had progressed during Sep. 5, 2012 to Oct. 5, 2012 and Jan. 11, 2013 to Feb. 11, 2013. In the same time, wind speed was observed by MAT-mast observation tower at 31m, 38m, 48m, 58m and 70m, and 10m, 30m, 50m and 58m in Handong-ri. Handong-ri located at six kilometers from study area. Table 3 shows information about used pressure type wave recorder, and wave data is observed at interval of about 2Hz (0.5s). Fig. 7 shows information of MAT-mast, and wind data is observed at interval of about 10 minutes. In this regard 10 minutes mean average of value of observed wind data during 10 minutes.


Fig. 6. Observation area off the coastline of Jeju island.

Table 3. Wave gauge information.

| Depth | | Tide and Wave | |
|---|---|---|---|
| Range | 10/20/50/100/200/500/740m (dBar) | Tide averaging | 1 sec to 8 hours |
| Accuracy | ±0.05% full scale | Wave (burst) | 512,1024,2048,4096 sample |
| Resolution | <0.001% full scale | Burst rate | 1,2, or 4Hz |

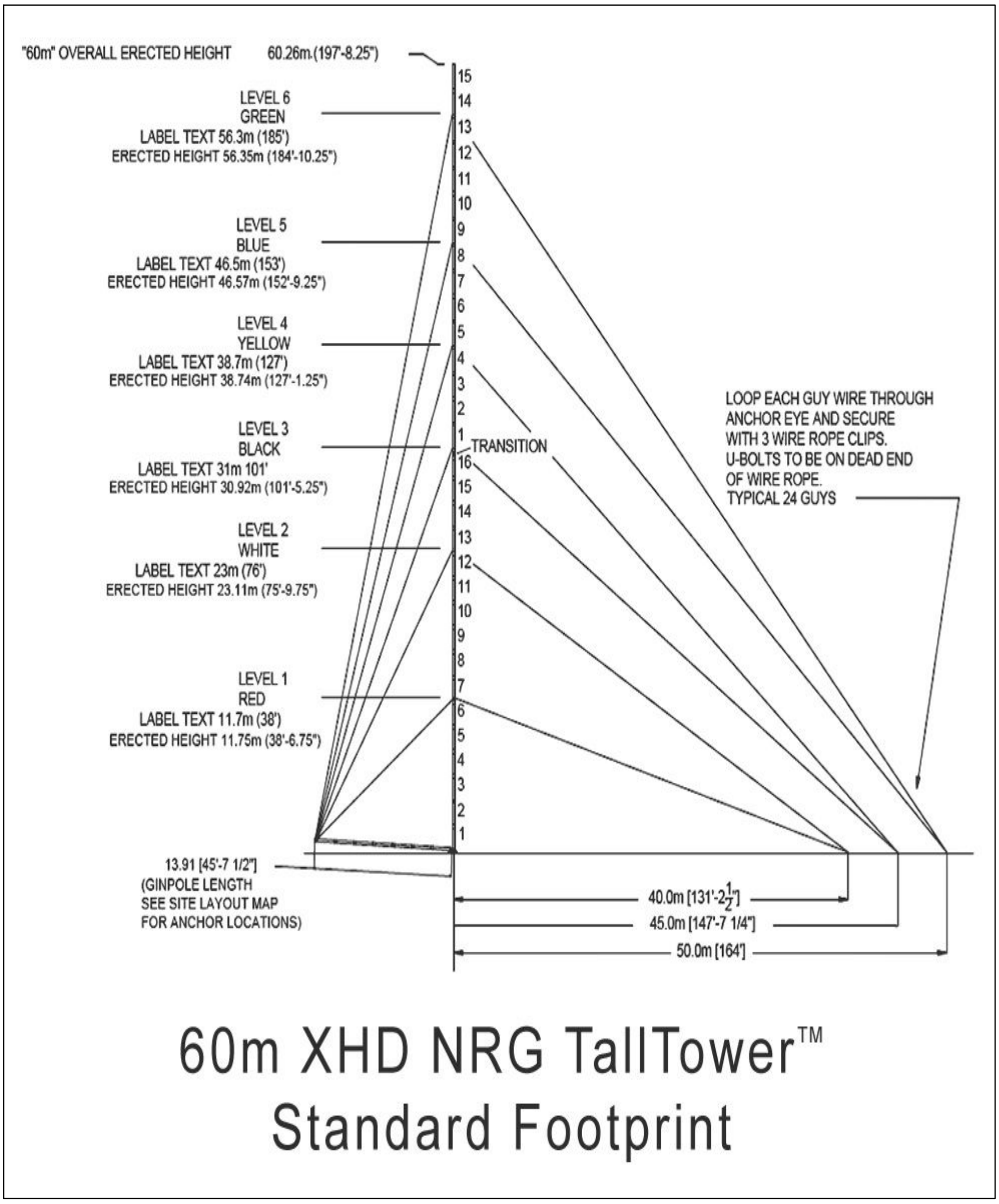


Fig. 7. Met-mast for wind data figure(Windpower, 2014).

### 3.2 Wave data

1st observation wave data is shown as Fig. 1, in the case of 1st observation, as shown in Fig. 8. Wave height observed relatively high, There are effected by typhoon from 15th of September to 17th of September.

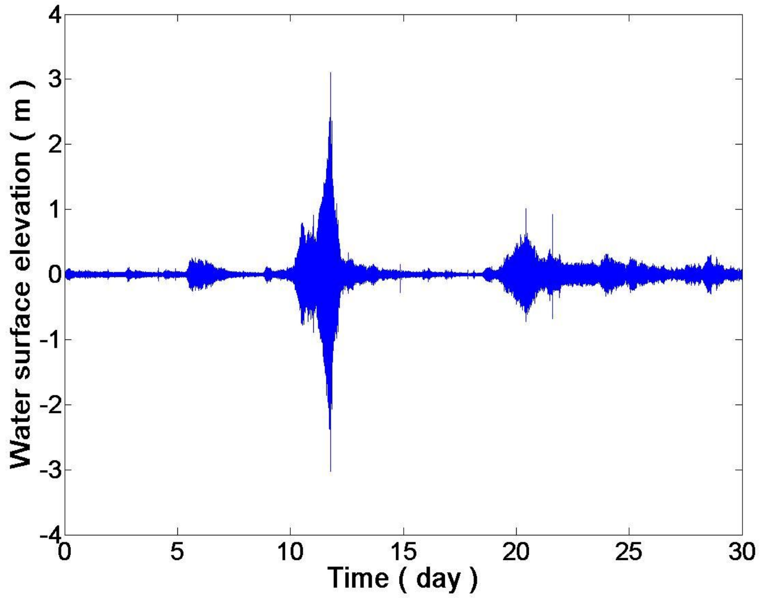


Fig. 8. Surface elevation by waves from Sep. 5, 2012 to Oct. 5, 2012.

Fig. 9 is obtained by graphical representation of the observed data of 2nd wave observation.

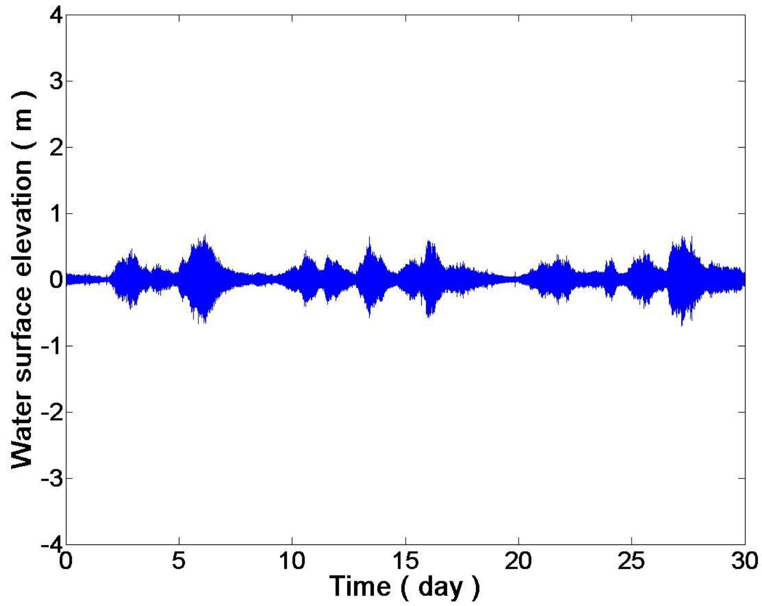


Fig. 9. Surface elevation by waves from Jan. 11, 2013 to Fed. 11, 2013.

2nd wave observation is in contrast with 1st. In the case of 2nd observation, it has wave height distribution averagely, because a strong wind is not blowing such as typhoon.

### 3.3 Wind data

As shown in the Fig. 10, that is wind speed at 31m. 48 and 70m height using MAT-mast. Wind speed per each height can check that there is no significant difference.

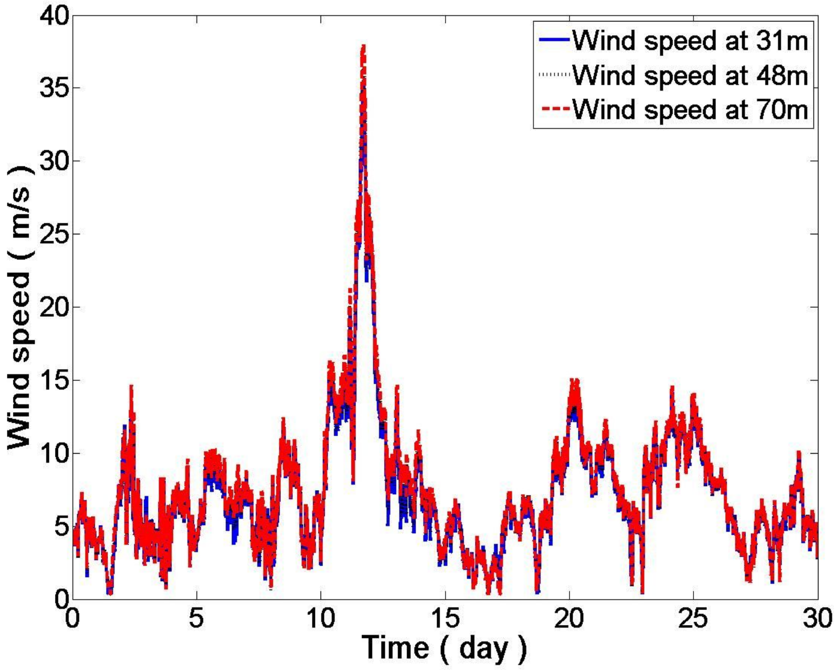


Fig. 10. The observation wind speed data on the northeastern Jeju island coastal.

In order to compare between wind speed in study area and Handong-ri, wind data was observed in Handong-ri at 10m, 30m, 40m. 58m during same time. And RMSE(Root Mean Square Error) value and correlation coefficient is calculated of per each height wind speed. The RMSE and correlation coefficient are given by

$$R.M.S.E = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y_i - f(X))} \qquad (15)$$

$$R = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \qquad (16)$$

Fig. 11.,. Fig. 12 and Fig. 13 are show to compare wind speed between in study area and in Handong-ri

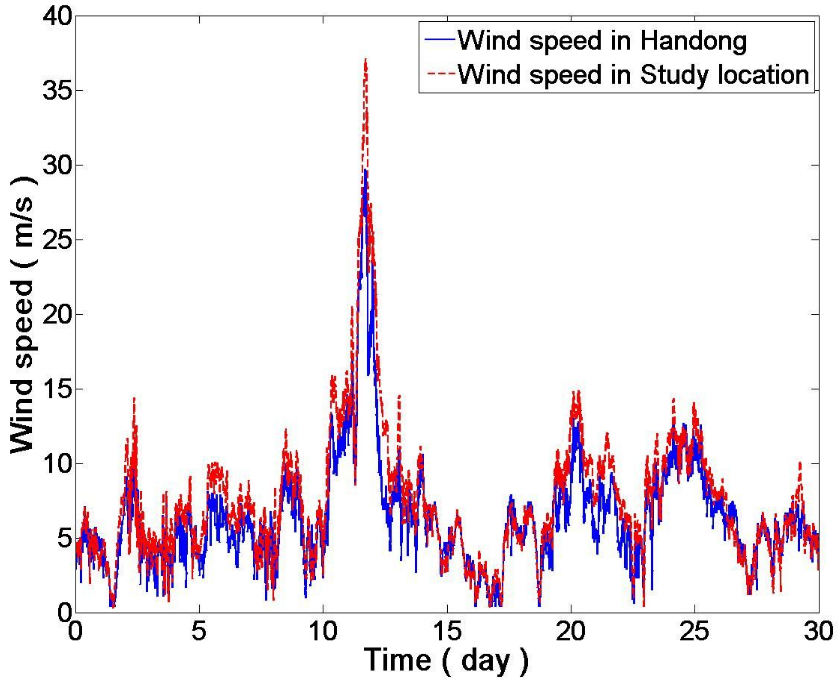


Fig. 11. Wind speed from Sep. 5, 2012 to Oct. 5, 2012 at (Handong=58m) and (Studied location=58m) height.

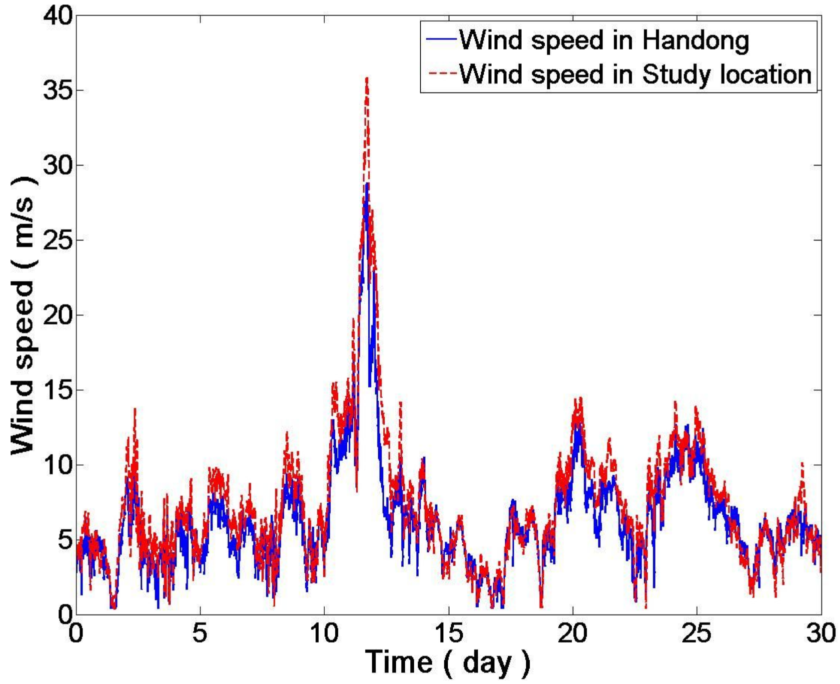


Fig. 12. Wind speed from Sep. 5, 2012 to Oct. 5, 2012 at (Handong=40m) and (Studied location=38m) height.

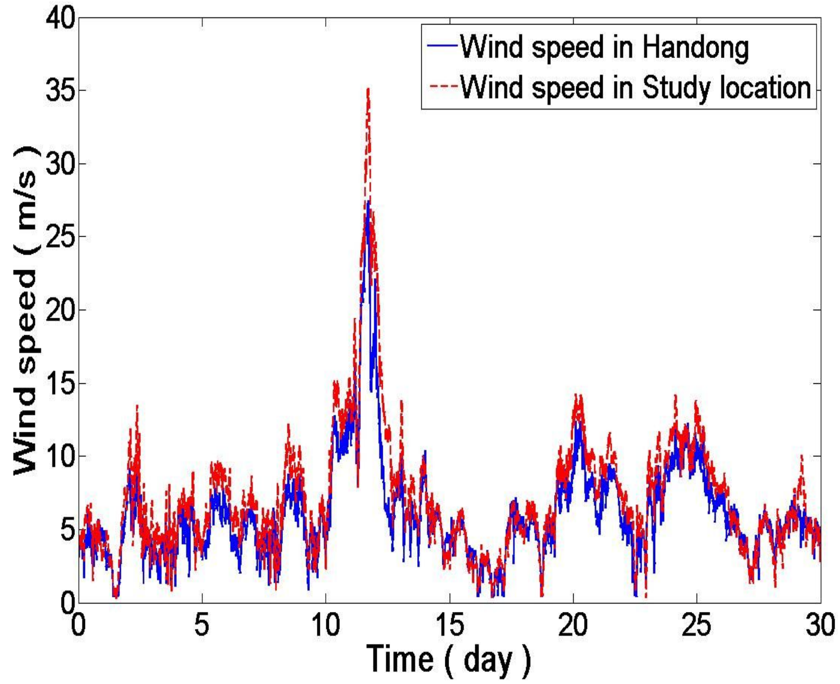


Fig. 13. Wind speed from Sep. 5, 2012 to Oct. 5, 2012 at (Handong=30m) and (Studied location=31m) height.

Table 4 is the result about RMSE value and correlation coefficient between wind speed in study area and Handong-ri.

Table 4. Comparison of wind speed between handong and study area.

| Height | Correlation coefficient. | RMSE value. |
|---|---|---|
| 58m and 58m | 0.947 | $6.46\times10^{-17}$ |
| 50m and 48m | 0.950 | $6.05\times10^{-17}$ |
| 30m and 31m | 0.948 | $6.43\times10^{-17}$ |

Looking at this result, Wind speed in study area and Handong-ri are almost the same. Therefore, the observed wind speed in Handong-ri was used instead of the observed wind speed in study area.

# CHAPTER 4

# The result of analysis

### 4.1 The analysis of wave data

Fig. 14 and Fig. 15 are result of significant wave height and maximum wave height that calculates observed wave data using zero up-cross method. When you look at the results that have been observed on 1st, The significant wave height and maximum wave height have large dynamic range because of the typhoon. Fig. 16 and 17 show the calculated number of wave by zero-upcross method.

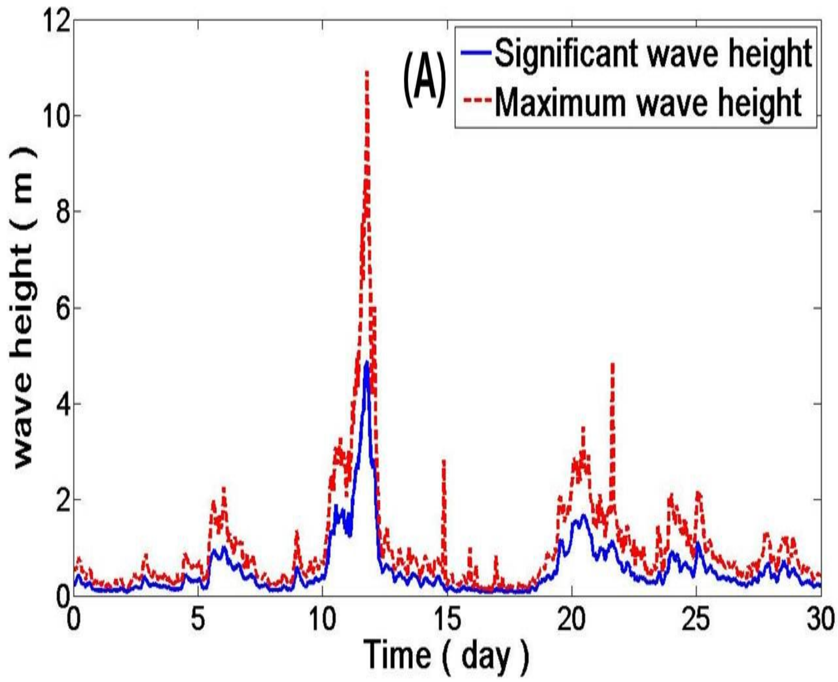


Fig. 14. Significant wave height and maximum wave height from Sep. 5, 2012 to Oct. 5, 2012.

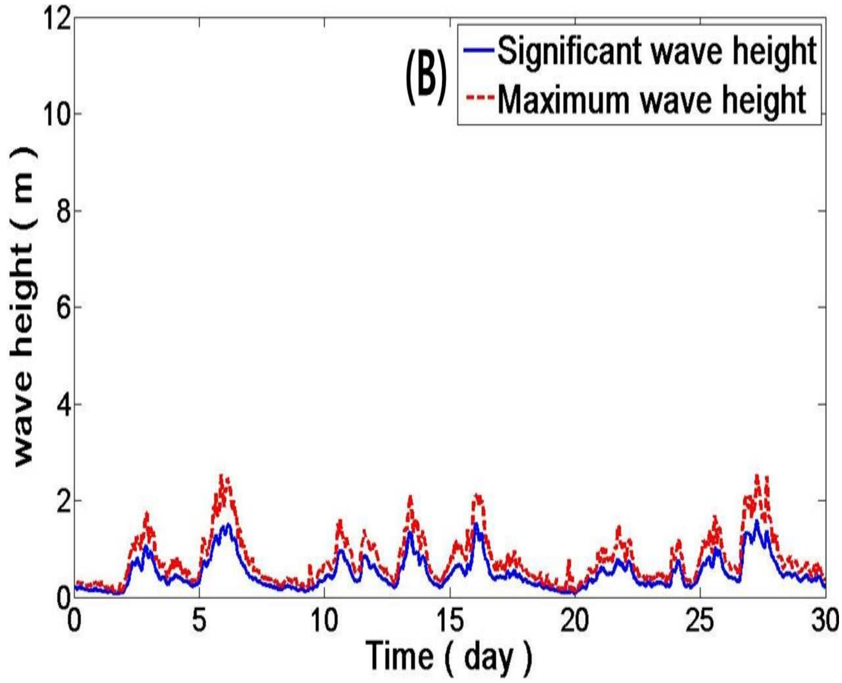


Fig. 15. Significant wave height and maximum wave height from Jan. 11, 2013 to Fed. 11, 2013.

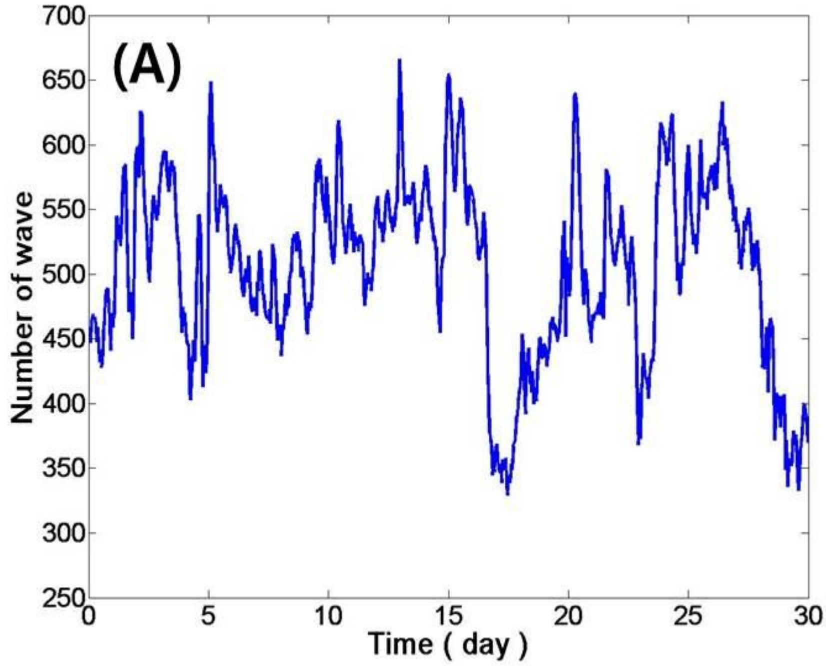


Fig. 16. Number of wave from Sep. 5, 2012 to Oct. 5, 2012.

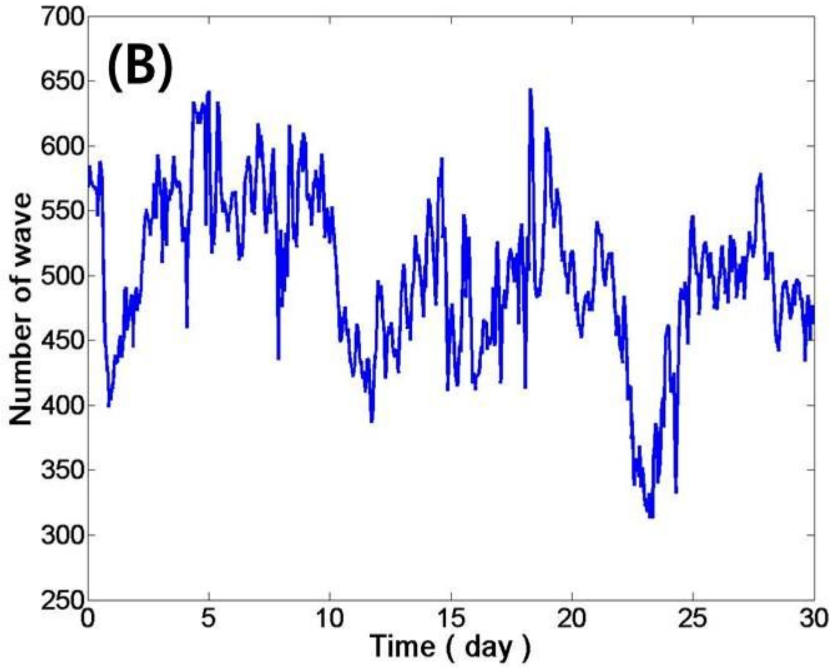


Fig. 17. Number of wave from Jan. 11, 2013 to Fed. 11, 2013.

Fig. 18 is the distribution of the 1st significant wave height and maximum wave height. Fig. 19 is the distribution of the 2nd significant wave height and maximum wave height. Henceforth, the the number of data is 720(720 hours = 30 days). The significant wave height was observed at almost 1m height. Fig. 20 shows the distribution of number of wave. The highest distribution of number of wave is 500 to 550.

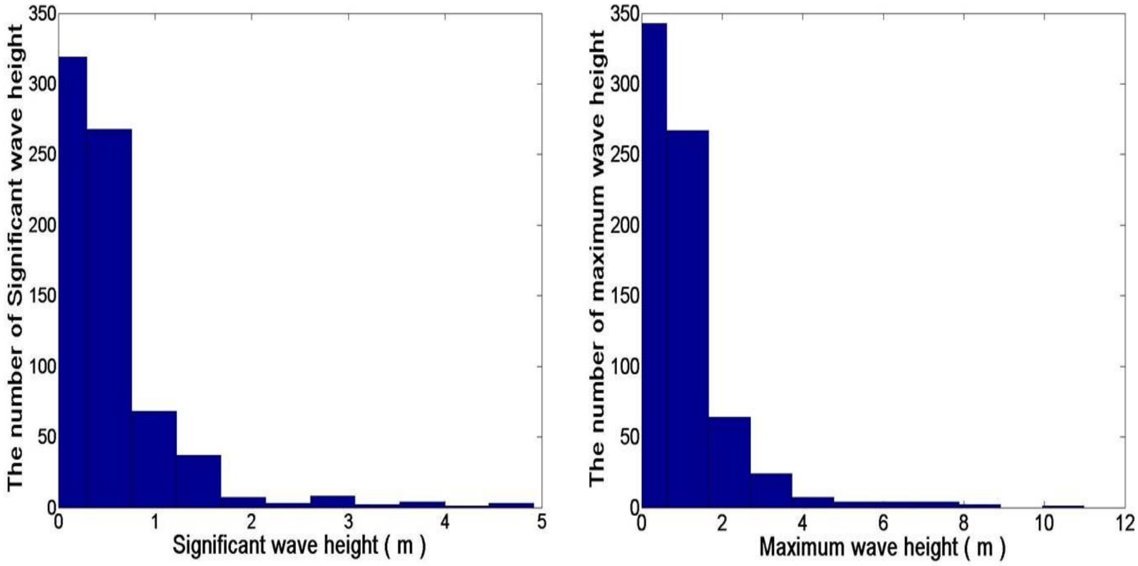


Fig 18. Distribution of significant wave height and maximum wave height from Sep. 5, 2012 to Oct. 5, 2012.

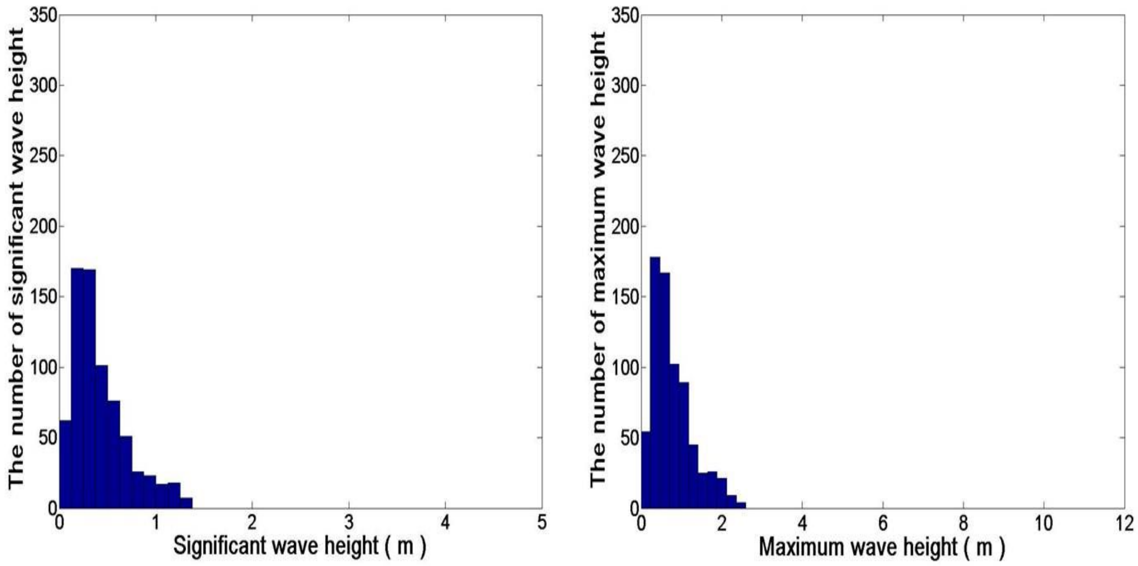


Fig 19. Distribution of significant wave height and maximum wave height from Jan. 11, 2013 to Fed. 11, 2013.

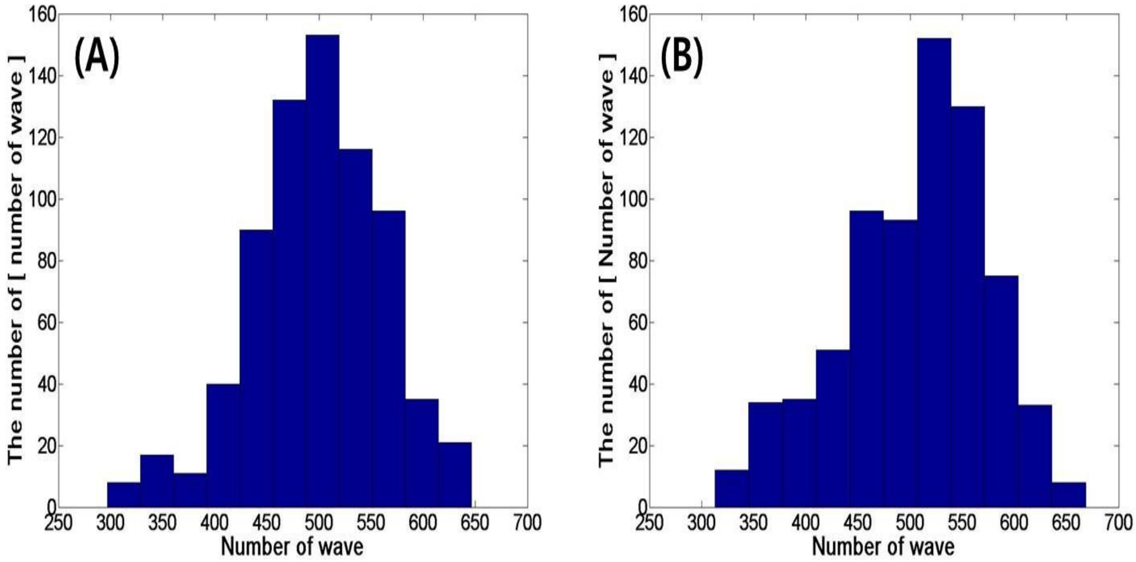


Fig. 20. distribution of wave number from A)Sep. 5, 2012 to Oct. 5, 2012 and B)Jan. 11, 2013 to Fed. 11, 2013.

Fig. 21 shows the calculation results of linear regression function using significant wave height and maximum wave height. In the case of 1st, the maximum wave height is $1.64H_s$ and 2nd, the maximum wave height is $1.63H_s$.

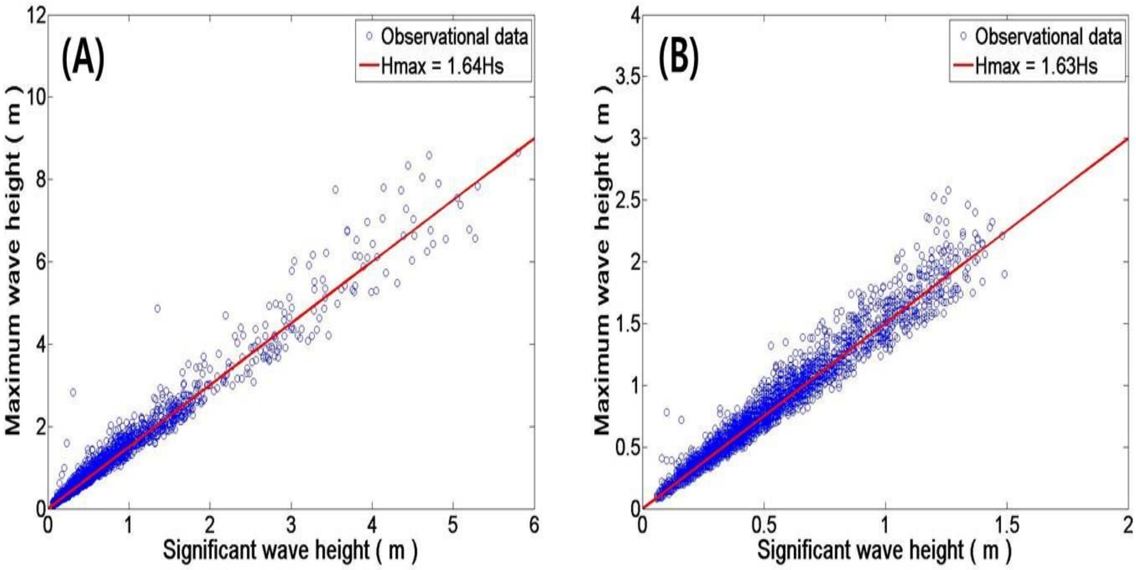


Fig. 21. The result of ratio of significant wave height and maximum wave height from A)Sep. 5, 2012 to Oct. 5, 2012 and B)Jan. 11, 2013 to Fed. 11, 2013.

Next, Fig. 22 shows the result of calculated peak frequency using Eq. 8 Peak frequency occurred among 0.08Hz to 0.2Hz every time.

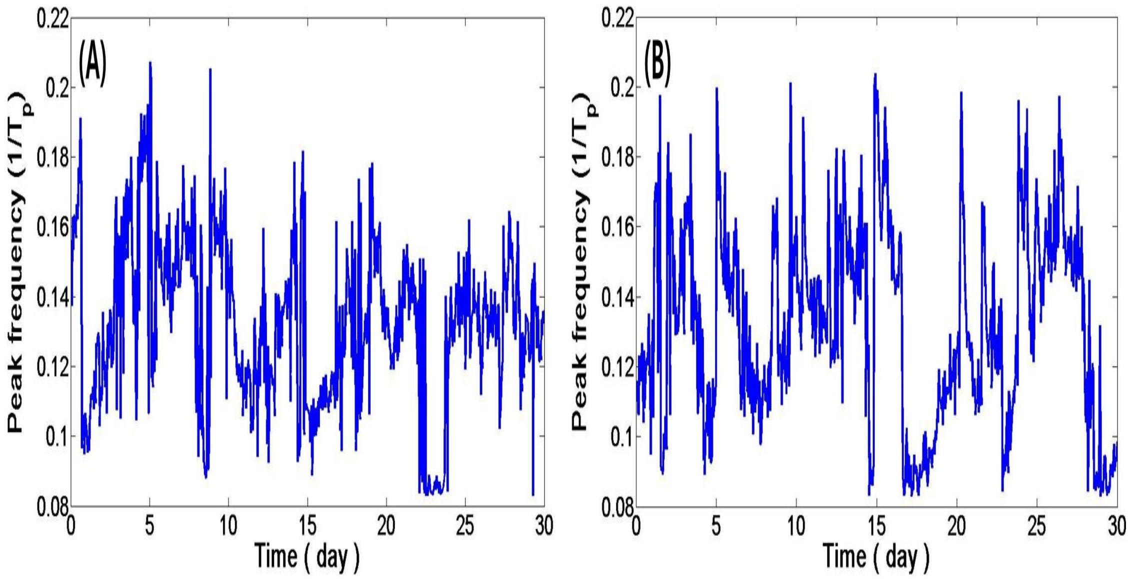


Fig. 22. Peak frequency from A)Sep. 5, 2012 to Oct. 5, 2012 and B)Jan. 11, 2013 to Fed. 11, 2013.

Each mean value of significant wave height and peak frequency is applied by frequency analysis to Eq. 12. As a result, $\gamma$ value able to be calculated. Fig. 23 shows the distribution of $\gamma$ value, and the average value is 2.72.

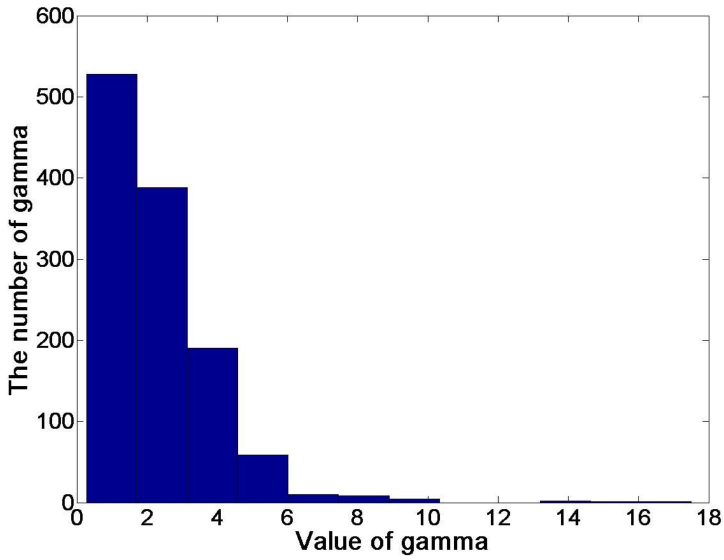


Fig. 23. Distribution of $\gamma$.

The reason for the difference between the $\gamma$ value of Suh, K. D(2010)'s study and the calculated $\gamma$ value is considered to be differences between shallow and deep-sea or the lack of observation data used in this study.

Fig. 24 shows comparison result between PSD and JONSWAP. (A) and (B) are the highest significant wave height and the lowest significant wave height from 1st observation data respectively. (C) and (D) are the highest significant wave height and the lowest significant wave height from 2nd observation data respectively. Results of the comparisons showed that $\gamma$ value by lowest significant wave height is lower than $\gamma$ value by highest significant wave height.

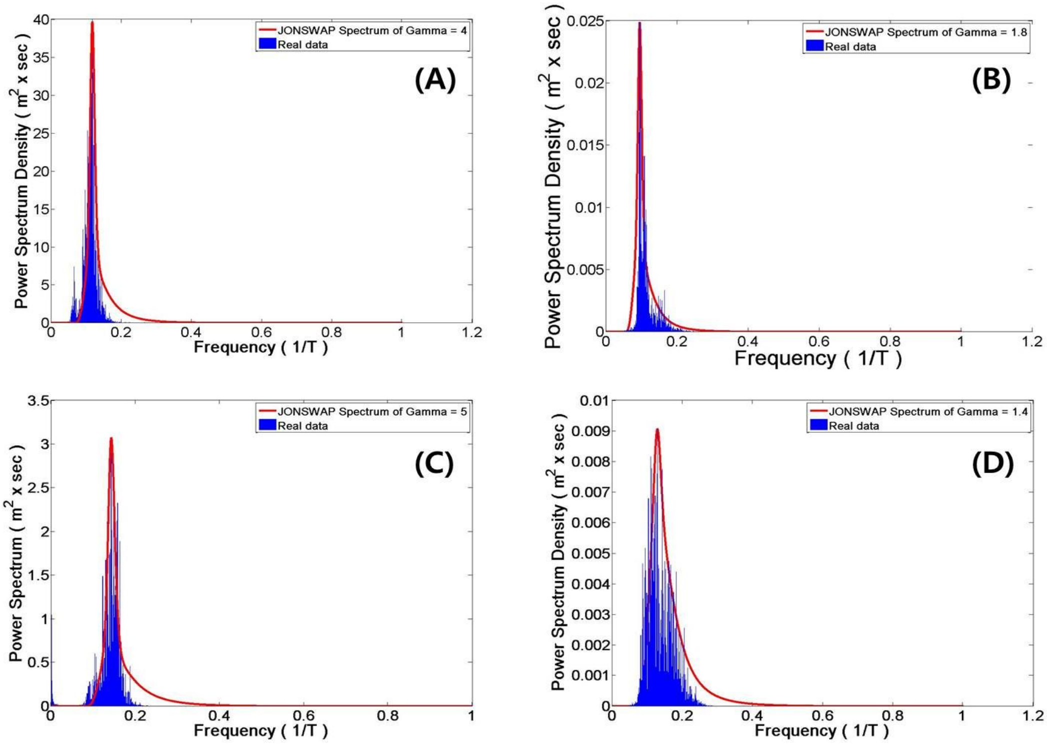


Fig. 24. Comparison of real sea wave spectrum and JONSWAP spectrum.

### 4.2 A comparison between the significant wave height and wind speed

1st regression function is calculated from relationship between significant wave height and wind speed. As a result, a and b values able to be obtained, a is 0.1625 and b is −0.2378, respectively. Fig. 25 shows the calculated simplified SMB method, SMB method, 1st regression function and measurement data. The fetch length in SMB method is 50km. In Fig 25, most observation significant wave heights are less than 1m and wind speeds are mostly 5 to 10 m/s. In the trend line by applying regression function, it has weakness that is simple, because wind speed and significant wave height are increased at the same time. Also, it predicts whole pattern better than the SMB method. However, The trend line by SMB method predicts more than 1st regression function in low wind speed, but overestimates significant wave height in high wind speed. Because of shallow-sea, because wave has limit to grow height.

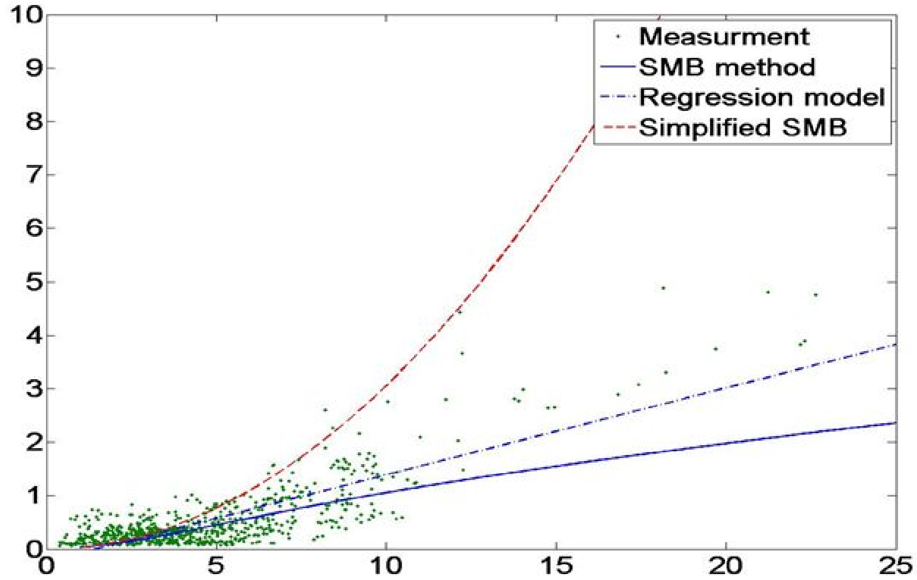


Fig. 25. A comparison of the measurement data and regression function and SMB method.

The measurement significant wave height is compared with each transformed function applied to the 1st observed wind data and the 2nd observed wind data. Fig. 26 and Fig. 27 show comparison between each applied result. And then confirmed the predicted significant wave height to the calculated significant wave height by observed wave data.

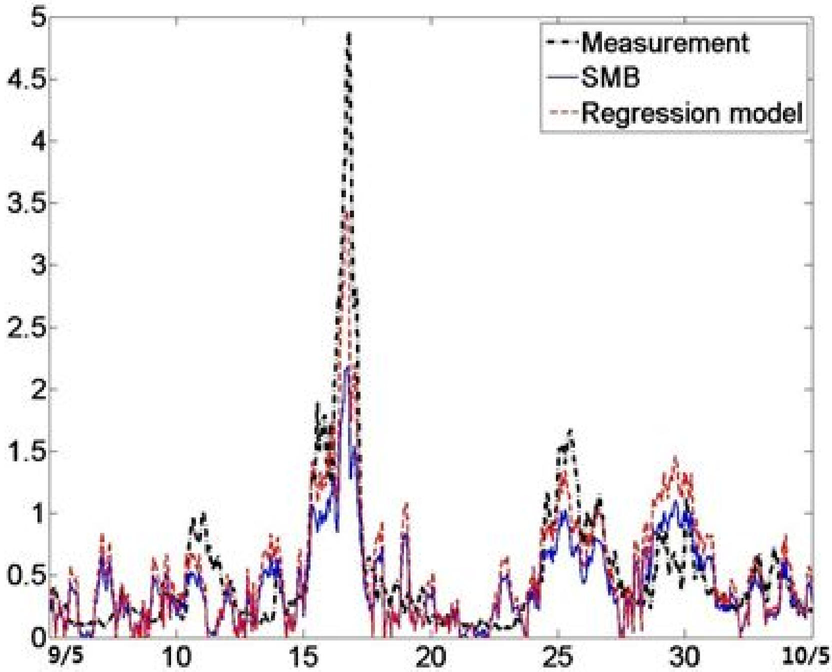


Fig. 26. A comparison of the 1st significant wave height and height and each transformed significant wave heigh.

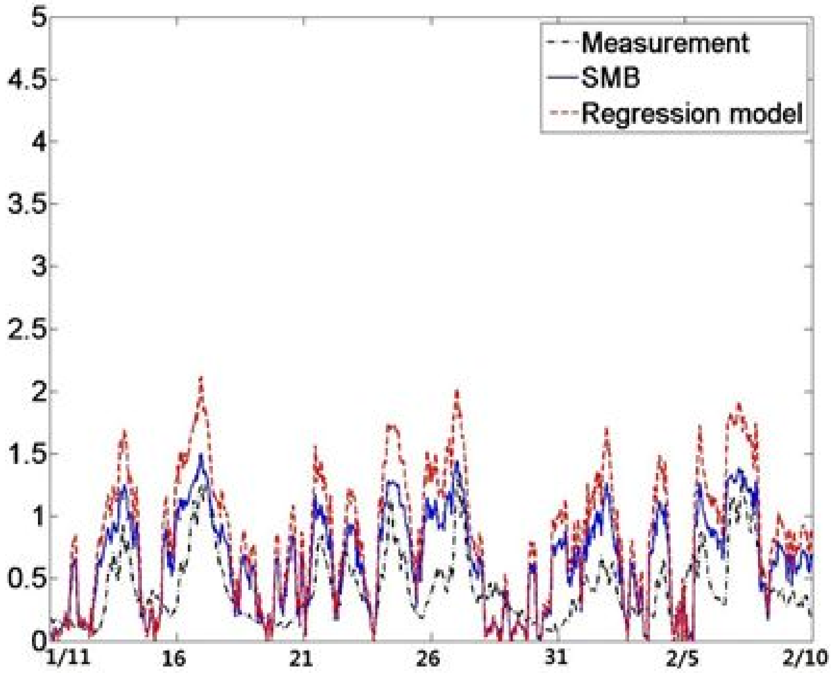


Fig. 27. A comparison of the 2nd significant wave height and height and each transformed significant wave heigh.

The JONSWAP spectrum is calculated using real significant wave height(real significant wave height using real observed wave data) and each predicted significant wave height by wind speed using 1st regression function and SMB method. Also, this study used peak frequency, peak period and $\gamma$ value, 0.13Hz, 7.7s and 2.72, respectively. Fig. 28 show the result of the JONSWAP spectrum using lowest predicted significant wave height by the 1st regression function, the SMB method and real significant wave height. Fig. 29 shows the result of JONSWAP spectrum using the highest significant wave height by the 1st regression function, the SMB method and real significant wave height. Looking at Figs. 28 and 29, it is found that the error of spectral moment of order 0 is small when the significant wave height is low. However, the value of the spectral moment of order 0 has many errors when using the predicted significant wave height using higher wind speed. Many difficulties are expected when significant wave height is predicted by strong wind such as in a Typhoon.

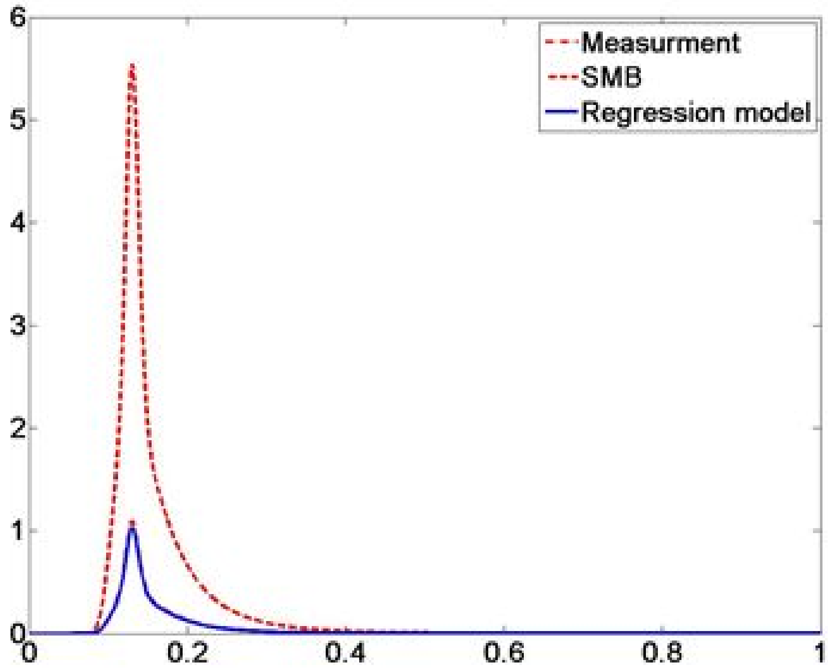


Fig. 28. Calculated JONSWAP spectrum using lowest significant wave height.

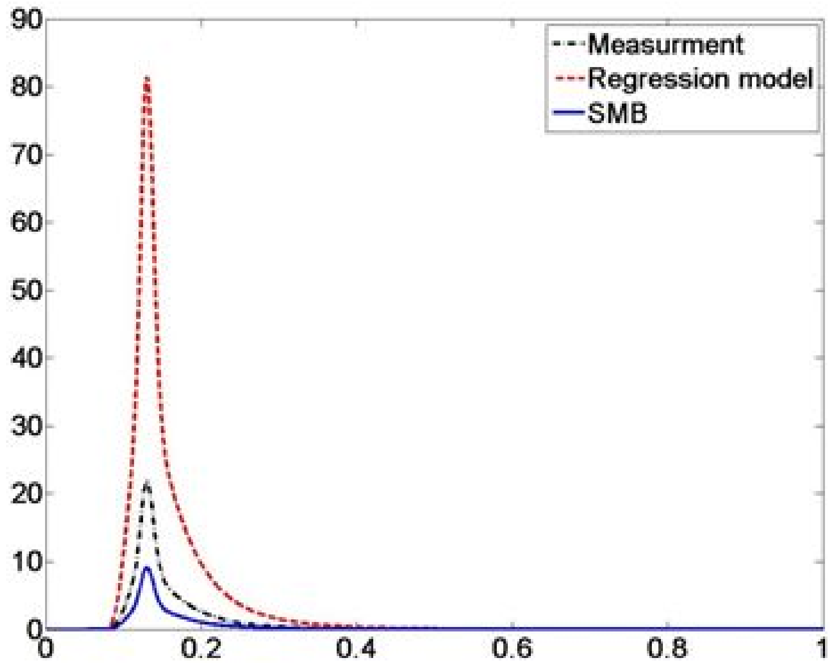


Fig. 29. Calculated JONSWAP spectrum using highest significant wave height.

The calculated spectral moment of order 0 of JONSWAP spectrum is compared by Eq. 4, and it is area of spectrum. Because, it is a value that is used when using the $H_s = 4.\sqrt{m_0}$ to calculate the significant wave height, it is an important value. As a result, Table 5 shows the result of comparison the spectral moment of order 0 of Fig. 20 and Table 6 shows the result of comparison of spectral moment of order 0 of Fig. 21.

Table 5 Comparison of Fig. 21's Spectral moment of order 0

| Mean value | | |
|---|---|---|
| $m_0$ of spectrum by $H_s$ | $m_0$ of spectrum by RM | $m_0$ of spectrum by SMB |
| 0.0502 | 0.0473 | 0.2551 |

Table 6 Comparison of Fig. 20's Spectral moment of order 0

| Mean value | | |
|---|---|---|
| $m_0$ of spectrum by $H_s$ | $m_0$ of spectrum by RM | $m_0$ of spectrum by SMB |
| 1.0054 | 0.4194 | 3.7499 |

Table 5 shows that spectral moment of order 0 of significant wave height by 1st regression function has an error of approximately $2.9 \times 10^3\, m^2$ and the SMB method has an error rate of approximately $0.21\, m^2$. Table 6 shows that spectral moment of order 0 of significant wave height by 1st regression function has an error of approximately $0.58\, m^2$ and the SMB method has an error rate of approximately $2.75\, m^2$.. The error rate increases with wind speed but when using the 1st regression function the error rate had a regular value. Table 7 shows that the RMSE and coefficient of determination between each calculated significant wave height and real significant wave height. The coefficient of determination is a statistical measure of how well the regression line approximates the real data points.

Table 7 RMSE and Correlation coefficient

| | | Regression function | SMB method |
|---|---|---|---|
| 1st | RMSE | 0.45 | 28.47 |
| | $R^2$ | 0.58 | 0.61 |
| 2ed | RMSE | 0.47 | 11.2 |
| | $R^2$ | 0.54 | 0.65 |

If RMSE value is near 0 it means it is exact about predicted significant wave height. Therefore, significant wave height by 1st regression function has a lower error than the significant wave height by SMB method. However, in the case of coefficient of determination of each predicted significant wave height, the SMB method showed better result than the 1st regression function.

# CHAPTER 5

### 5.1 Conclusions and Remarks

In this study, in order to predict irregular waves along the northeastern shore of Jeju Island using the 1st regression model, the SMB method, and the JONSWAP spectrum wave and wind data was observed from Sep. 5th, 2012 to Oct. 5th, 2012. First, wave characteristics and the JONSWAP spectrum model are evaluated. As a result, peak frequency, peak period and $\gamma$ value are obtained in the study area. Secondly, we compared each predicted significant wave height by wind speed using the 1st regression function( $H_s = 0.1625U - 0.2378$ ) and the SMB method.

The results of this study are the following.

1) The significant wave height is observed most frequently note that the wave height of below 1m. The first observed(from Spe. 5th, 2012 to Oct. 5th, 2012) significant wave height's mean was 0.523m and the second observed significant wave height's mean was 0.423m. Due to the influence of the typhoon that appeared from the Sep. 15th to Sep. 17th, a significant wave height mean of 4.8m occurred most frequently

2) The Study area has maximum wave height / significant wave height ratio of 1.64.

3) The peak frequency's mean occurred approximately 0.12 to 0.15Hz during observation time.

4) The $\gamma$ value of the JONSWAP spectrum in northeastern Jeju Island is 2.72. The reason for the difference between the $\gamma$ value of study of Suh, K. D(2010) and the calculated $\gamma$ value is considered to be differences between shallow and deep-sea.

5) Significant wave height by the 1st regression function has a lower error than significant wave height by the SMB method. In the case of the coefficient of determination of each predicted significant wave height, the SMB method showed better results than the 1st regression function. that is considered about a more suitable way of estimating irregular wave. In the end, the prediction of irregular waves are recommend using the 1st regression function rather than the SMB method in this area.

6) In the case of using lowest significant wave height, the spectral moment of order 0 of significant wave height by the 1st regression function has an error of approximately $2.9 \times 10^{3}\,m^2$ and with the SMB method approximately $0.21\,m^2$. In the case of using highest significant wave height, the spectral moment of order 0 of significant wave height by the 1st regression function has an error of approximately $0.58\,m^2$ and the SMB method has an error rate of approximately $2.75\,m^2$.

7) The 1st regression function($H_s = 0.1625U - 0.2378$) was made by using the 1st observed wave and wind data. Subsequently, predicted significant wave height by the 2nd observed wind speed. It had a similar error to calculate significant wave height by the 1st observed wind speed. Accept the calculated 1st regression function using September data can be used to predict the significant wave height by wind speed on same time five months later.

### 5.2 Future Works

The study fields, which need to be conduct in future, are listed below.

1. The present study does not include the water depth. In reality, the accuracy of the prediction of irregular waves be different in parameters number such as water depth, fetch length and so on. In further study, we should consider the various parameter.

2. In order to predict of irregular waves, various prediction method is necessary such as multiple regression analysis or Kalman filtering.

3. It is needed that the validity of analysis result by the observed wave and wind data on different area.

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# 감사의 글

지난 2년간의 시간을 되돌아보면 가장먼저 떠오르는 것은 잘못된 길로 빠지지 않고 석사과정을 무사히 마칠 수 있도록 격려해주고 무한한 관심을 주신 이병걸 교수님이 가장 먼저 떠오릅니다. 학생이 원하는 것이 있으면 그것을 가장 최우선으로 생각하며 이 생활에 적응할 수 있도록 도와주신점이 가장 큰 도움이라고 생각합니다. 또한 바쁘신 와중에 언제나 상담을 요청하면 모든일을 내팽겨치고 학생들 상담에 앞서시던 제주대학교 토목공학과 양성기 교수님, 박상렬 교수님, 김남형 교수님, 김상진 교수님, 이동욱 교수님께도 진심으로 감사드립니다. 토목공학이라는 범위안에서 해양공학을 공부하기엔 부족함이 많았던 저에게 많은 본인의 지도학생도 아닌 저에게 많은 가르침을 주셨던 제주대학교 해양시스템 공학과 조일형 교수님 그리고 유학관련해서 가장 많은 상담을 해주신 제주대학교 전기공학과 김호민 교수님, 항상 학생들에게 많은 해택이 가길 바라는 마음뿐인 풍력공학부 수장이신 기계공학과 허종철 교수님 마지막으로 학생들이 많은 경험을 쌓길 바라는 마음뿐이신 풍력공학부 고경남 교수님께 감사의 인사를 드립니다.

군대를 제대하고 대학생으로 복학을 하기 전 [앞으로 어떻게 먹고살지?] 라는 고민으로 우울한 삶을 지내던 중에 한줄기 빛처럼 다가와 주었던 사랑하는 고효심양 이제 결혼혼자 2달이 넘어가는데 석사생활 때문에 서울과 제주도를 오가며 내조를 해주는 당신 진심으로 감사하고 미안하고 사랑합니다. 만날 때마다 논문에 대한 얘기만 하고, 데이트할 때도 데이트에 집중하기보다 논문주제를 생각해야 한다던 나에게 화내기보다 함께 고민해주고, 격려해주고, 자료조사도 함께해주는 당신의 내조는 앞으로 평생 갚아야할 은혜라고 생각합니다. 우리 함께 유학가서도 알콩달콩 잘 지내자. 사랑해.

학부시절부터 대학원마칠 때까지 함께 혼나고, 함께 기뻐하던 연구실 동기 서정이와 지선이 그리고 회사다니며 공부를 병행하면서도 힘든내색없이 우리 동생들

을 위해 밝은모습만 보이던 창선이형 연구실에 가장 오래 있어서 우리들보다 많은 부분에서 월등히 뛰어나 연구실 일에 힘들 때마다 자기 일처럼 도와준 정우형에게 진심으로 고마움을 전합니다.

그리고 다른 연구실 이였지만 함께 연구에 대한 이야기를 하며 많은 아이디어를 얻을 수 있도록 도와준 순보형 대학원생활에 적응 못해 [그만둬야 하나?]고민할 때마다 옆에서 할 수 있다는 자신감을 불어주며 목표를 잃지 않도록 도와준 수민이형 동생이지만 1년 먼저 대학원에 들어와서 대학원 생활 노하우를 알려주는 고마운 동생 명진이 그리고 바쁜와중에도 연구에대한 조언을 아끼지 않았던 혁준이형, 복도에서 만날 때마다 웃으며 인사를 건내주던 우열이형, 원석이형, 용석이형, 준호형, 항상 연구는 이런 것이다 라고 보여준 경태형, 모자란 형을 잘 따라준 제훈이, 승은이, 보성이, 우리 부부에게 스킨스쿠버를 가르쳐 주고, 부부생활의 노하우도 재미있게 알려주신 승현이형, 모자란 회화실력으로 더듬더듬 말해도 항상 웃으며 같이 대화에 응했던 Kanac, 우리 사랑하는 제주대학교 풍력 대학원 3.5기 동기인 효정이누나, 지훈이, 정훈이형, 사일이형, 동우 모두가 있었기에 즐거운 대학원생활을 할 수 있었으며 모두가 하나같이 즐거운 추억을 가질 수 있도록 도와준 고마운 사람들입니다.

마지막으로, 대학원생활을 무사히 끝낼 수 있도록 뒤에서 묵묵히 지켜봐주시고 물심양면으로 용기를 주신 세상에서 가장 사랑하는 부모님 “안경란, 강명수” 항상 내 걱정을 많이 해주시고 어릴 적 바쁜 부모님을 대신해 나를 키워주신 경희, 은희 이모, 타지에 떨어져 고생하는 멀리 서울에서 내 사랑하는 반쪽 효심이까지 챙겨주시는 경혜이모 항상 미소로 반겨주시는 외 숙모 “이혜영”, 나보다 먼저 공부를 시작해 여러 가지 조언을 해 주었던 형과 형수“강동완, 오진아”, 귀여운 내 조카 라연이 못난 사위를 믿고 기다려 주시는 사랑하는 장모님과 처제, 형님 “문명혜, 고민지, 고경태”, 사랑하는 할머니 할아버지“양춘화, 강태옥”, 외 할머니 “김정순”, 그리고 우리 부부를 위해 고생해주신 외 삼촌 “안용석”, 하늘에 계신 외 할아버지와 외 삼촌 “안재만, 안용철” 모두 사랑합니다. 그리고 지켜봐주셔서 감사합니다. 우리 사촌동생들 태우, 진우, 수민이, 준호도 사랑한다.

List of Papers

◈ Refereed Journal Paper

① "Evaluation of Wave Characteristics and JONSWAP Spectrum Model in the Northeastern Jeju Island on Fall and Winter" Journal of the Korean Society for Marine Environment and Energy Vol. 17. No. 2. pp. 63-69. May 2014(in Korea)

◈Proceedings of Annual Conference

① "The Study on Assessment of Lograthmic Law and Power Law for Wind Power Density in Jeju Island" Proceeding of the Korean Annual Conference on Civil Engineering, 2012(in Korea)

② "A Study on The Range of Peak Frequency Using Spectrum Analysis Method for Northeastern Jeju Island" Proceeding of the Korean Annual Conference on Korean Society of Marine Environment & Safety, 2013(in Korea)

③ "The Study on the Charateristics of Ocean Wave using Wind Wave Spectrum for Northeastern Jeju" Proceeding of the Korean Annual Conference on Korean Society for Marine Environment and Energy, 2013(in Korea)

④ "The Relationship of Wind Speed and Significant Wave Height in the Northeastern" Proceeding of the Korean Annual Conference on Civil Engineering, 2013(in Korea)