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Propagation of abnormal waves on 25 April 2008 at the West Coast of South Korea

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ABSTRACT

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On 31 March 2007, abnormal waves suddenly hit the West Coast of South Korea, causing heavy casualties and huge economic loss. Since the cause of wave generation is unknown, we aim to study the direction of wave propagation by investigating the abnormal wave signal recorded in the tidal stations. To determine the propagation direction of abnormal waves, we analyzed tidal level observation data at 1-min intervals, provided by the Korea Hydrographic and Oceanographic Administration (KHOA). To remove tidal components, wavelet decomposition, which filters wave periods ranging from 2 to 60 min, was performed. If the daily maximum amplitude exceeding 95% confidence interval of the total daily maximum amplitudes appeared simultaneously at more than three tidal stations, the day was defined as the day when abnormal waves occurred. Because of nonstationarity and localized peak in the time domain, wavelet analysis can be suitable for analyzing the power spectrum and wave period of abnormal waves. The time when maximum total power spectrum of the decomposed time series appears for the first time is considered the arrival time of the abnormal wave. The distance of crest line propagated by the abnormal wave was calculated by considering the arrival time difference between stations and long wave speed. The abnormal wave is assumed to propagate along a tangent to a circle with radius equal to the distance which the abnormal waves moved. Based on these considerations, we found that the propagation direction of the abnormal waves on 31 March 2007 was from the northwestern corner of the West Sea to the West Coast of South Korea. Similarly, abnormal waves that occurred on 25 April 2008 were propagated from the northwestern corner of the West Sea to the east–southeast.

ADDITIONAL INDEX WORDS: *Abnormal waves, propagation, power spectrum, wavelet analysis, Proudman resonance, pressure jump.*

INTRODUCTION

The West Sea, a semi-closed sea bordered by the Korean Peninsula to the east and China to the north and west. The maximum depth is 103 m, and the average depth is about 40 m. Many islands and large intertidal zones are distributed along the coast. The mean spring tidal range is about 8 m, and the mean neap tidal range is about 5 m. It is a macrotidal coast greatly affected by tides.

On 31 March 2007, abnormal waves lashed the West Coast of South Korea, causing a number of casualties and property damage to Yeonggwang (YG), Gunsan (GS), and Wido (Wi) (Figure 1). In propagation process of abnormal waves, 7 people died or were hurt and ships were damaged.

Oh et al.(2007) assumed that the abnormal waves were caused by the sea surface oscillation generated by changes in atmospheric pressure, and Eom et al.(2012) found that the Proudman resonance between the shallow water waves and the atmospheric pressure jump caused the abnormal waves on the West Coast. Jadranka et al.(2012) proposed that this atmospheric pressure jump has a relatively long duration (at least 1–2 h) and is caused by an abrupt atmospheric pressure of at least 2–4 hPa over a period of 5–10 min. The atmospheric pressure jump creates the barotropic ocean wave,



Figure 1. The damage situations which abnormal waves caused at the West Coast of South Korea on 31 March 2007.

which in turn results in resonance with the speed of the atmospheric pressure jump at a certain depth and higher waves are generated. As these higher waves travel toward the shore, they are influenced by amplification factors such as harbor resonance, shoaling, refraction, and reflection. Consequently, the height of the waves increases greatly at the shore, causing unpredicted abnormal waves.

Knowledge of quantitative criteria is necessary to analyze abnormal waves. Accordingly, abnormal wave analysis methods in previous studies were taken into consideration. Rabinovich et al.(1996) selected as "Rissagas" (abnormal waves of Spain) all seiche events in the Ciutadella Inlet (Balearic Islands) with sea

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level changes exceeding 30 cm. Monserrat et al.(2006) applied this absolute criterion. However, as background noise varied with locations, the absolute criterion too varied with locations. As alternatives, a combined threshold criterion based on the 4-sigma value and the absolute criterion were applied. Eom et al.(2012) used wavelets to obtain the power spectrum of the sea surface data of the West Coast. When the confidence interval of the total daily maximum amplitudes of each tidal station exceeded 95% and occurred at three or more tidal stations at the same time, abnormal waves were determined to have occurred. In order to analyze abnormal waves, the method of Eom et al.(2012), which applied the criteria of power spectrum and propagation through wavelet analysis, was used.

When analyzing abnormal waves, wavelet analysis resolves the three weaknesses of the Fourier transform: 1) After tidal constituents are eliminated with harmonic analysis, the Fourier transform is used to estimate the power spectrum. But it is difficult to analyze the variation of the power spectrum in the time domain. As the abnormal waves are 2) non-stationary, and 3) appear as localized peaks in the time domain, it is difficult to analyze abnormal waves using the Fourier transform. However, the wavelet transform can be used to analyze the time series that contain non-stationary power at many different frequencies (Daubechies, 1990). Wavelet analysis is also a commonly used technique for analyzing localized variations of power within the time series. It decomposes a time series into time-frequency space, thus enabling determination of both the dominant modes of variability and of how those modes vary in times (Torrence and Compo, 1998).

This study focuses on the following points: 1) The propagation direction of the abnormal waves that occurred on 25 April 2008; 2) the comparison of the propagation direction of the abnormal waves on 25 April 2008 and 31 March 2007; and 3) the driving force of the abnormal waves estimated by comparing the two events.

METHODS

Study area and data

To estimate the propagation direction of abnormal waves, the tide level observation data at 1-min intervals, provided by the Korea Hydrographic and Oceanographic Administration (KHOA), were analyzed. The tide level data of 2008 were used; data from seven tidal stations of the West Coast—Anheung (AH), Boryeong (BR), Janghang (JH), Gunsan-Outer-Port (GS), Wido (Wi), Yeonggwang (YG) and Daeheuksando (DH)—were used (Figure 2).

Abnormal wave analysis

Abnormal waves can be filtered by wavelet decomposition, which functions similar to a band-pass filter. Because abnormal waves along the West Coast of South Korea have their own period, wavelet decomposition is used to analyze sea surface oscillation caused by abnormal waves. Tidal components and relatively long period waves are also removed in this process.

To filter abnormal waves, it is necessary to use the Morlet wavelet as the wavelet basis function. For the Morlet wavelet with w0 = 6, where w0 is the nondimensional frequency, $\lambda = 1.03s$, where λ is the Fourier period. This indicates that, for the Morlet wavelet, the wavelet scale is almost equal to the Fourier period (Torrence et al., 1997).

Period of the abnormal waves are determined to be 2–60 min. Since the observation data interval is 1 min, the minimum period is 2 min, which can be analyzed. As for the maximum period, the period range of abnormal waves was determined by analyzing the wavelet power spectrum at the time when the abnormal waves actually occurred. Then it is possible to decompose the time series of period ranging from 2 to 60 min.

In the decomposed time series, abnormal waves appear as localized peaks. To analyze the power spectrum of the localized peaks, the wavelet power spectrum analysis can be applied. Wavelet analysis is a technique commonly used for analyzing localized variations in power within the time series (Jadranka et al., 2012). Additionally, wavelet analysis is convenient for analyzing period that contain the power spectrum of the localized peaks and variations in the power spectrum in time domain.

Power spectrum and propagation

Among the decomposed time series, those values with the maximum amplitude become daily representative values. Then it is possible to obtain the standard deviations of daily representative values at each tidal station. Daily representative values in excess of the 95% confidence interval (2-sigma) at each tidal station will be classified as the occurrence date of abnormal waves in terms of the power spectrum. Abnormal waves do not oscillate locally at one location only, like harbor resonance, but tend to propagate to several locations. Accordingly, if abnormal waves occurred at more than three of the seven tidal stations at the same time, we concluded that abnormal waves occurred along the West Coast of South Korea in terms of wave propagation.

It is possible to determine the day when abnormal waves occurred, but it is not possible to find exact times when abnormal waves occurred. We define the exact time when abnormal waves arrived as the time when the total power spectrum over the entire

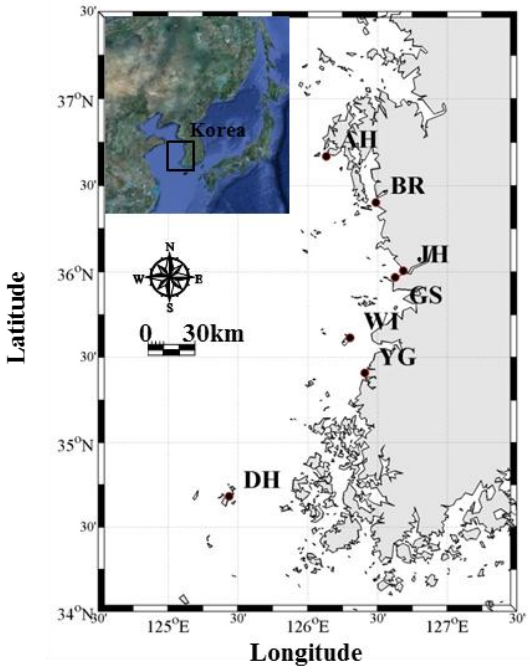


Figure 2. Map of the West Coast of South Korea with the position of 7 tidal stations (circles) : AH (Anheung), BR (Boryeong), JH (Janghang), GS (Gunsan-Outer-Port), Wi (Wido), YG (Yeonggwang), DH (Daeheuksando)

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period (2–60 min) was at the maximum. The total power spectrum at any given time is the sum of the power spectrum over periods of abnormal waves. In the total power spectrum of the abnormal waves, there is a dominant period of abnormal waves that have a maximum power spectrum.

Propagation direction estimation algorithm

The arrival time of abnormal waves was used to develop an algorithm for estimating the propagation direction. Firstly, if the times when the abnormal waves arrived at the two locations (P_1 and P_2) are t_1 and t_2, the time difference between the two locations can be said to be $dt_{21} = t_2 - t_1$. When passing P_1 where the abnormal waves occurred first, the direction of the long ocean waves will be determined by the following process. Here, the wave crest line of the long ocean waves is assumed to be a straight line.

1) The average depth (h_2) near P_2, the location the abnormal waves pass later, is used to calculate the propagation speed of the long ocean waves ($c_2 = \sqrt{gh_2}$)

2) The time difference (dt_{21}) between the two locations (P_1, P_2) and the propagation speed (c_2) in the waters near P_2 is used to calculate the travel distance of the long ocean waves in the waters near P_2 during dt_{21}.

3) The tangent line of the circle (O_2) with the travel distance (L_{21}) at P_2 during dt_{21} and P_1, the location where abnormal waves arrived first will be made.

By using the arrival times of abnormal waves which arrived next and the water depth of each location, the wave crest line and propagation direction of the long ocean waves at the time when the long ocean waves pass each location can be obtained.

PRELIMINARY RESULTS

Reconstructed time series

In the reconstructed time series (Figure 3), at AH, the period of waves ranging from 2 to 60 min oscillate with the wave height of 40 cm, ranging from a minimum 19.4 cm to a maximum 21.4 cm, and show the maximum peak at 21:09. At DH, waves with the period of abnormal waves oscillate with the wave height of 40.4 cm, ranging from a minimum of -22.8 cm to a maximum of 17.6 cm. At 21:26, the maximum peak appears. Lastly, at YG, the waves oscillate with the wave height of 53.4 cm ranging from minimum -27.9 cm to maximum 25.5 cm at 22:36. In the sequence of AH, DH, and YG, localized peaks with the maximum amplitude occur with a certain time lag.

Wavelet power spectrum

- **Anheung (AH)** - At first, around 14:00 on April 25, a disturbance with relatively small power spectrum oscillates weakly on waves with period ranging from 10 to 40 min (Figure 3). However, at 21:09, oscillations with the maximum total power spectrum (26,232 cm2) were observed with period ranging from 8 to 60 min. This oscillation lasts for about 5 h. When waves with the maximum total power spectrum oscillated on waves with the entire period (2–60 min), it is defined as the arrival time of abnormal waves.
- **Daeheuksando (DH)** - A weak disturbance similar to that of the disturbance that appeared around 14:00 on April 25 at AH also appeared around 14:00 with a small time lag. Oscillations with a relatively stronger total power spectrum (28,726 cm^2) than AH appeared at DH. Like AH, oscillations continued for about 5 h until 2:00 on April 26. Unlike AH, however, waves

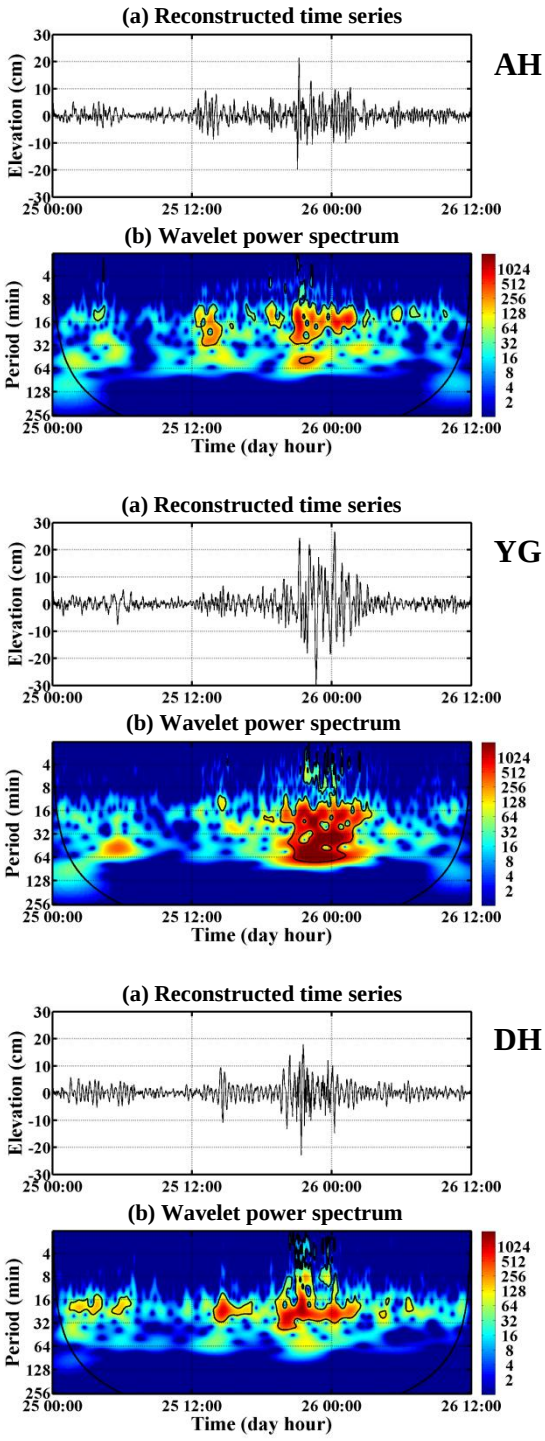


Figure 3. Reconstructed time series and wavelet power spectrum on April 25 2008 at AH, YG and DH; (a) The time series which is reconstructed by wavelet decomposition (upper); The left axis is water level elevation (cm). (b) Wavelet power spectrum (lower); The left axis is Fourier period (in min). The bottom axis is time (day and hour). The color bar is power spectrum ranging 2 cm^2 to 1,024 cm^2. The thick contour encloses the regions of greater than 99% confidence for power spectrum of abnormal waves during 36 hours. Hatched regions on either end indicate the "cone of influence", where edge effects become important.

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with relatively longer period (16–32 min) are gathered locally with a greater power spectrum.

- **Yeonggwang (YG) -** At 22:36 on April 25, abnormal waves with the greatest total power spectrum of 84,197 cm^2 oscillate with the entire period of waves. In particular, the dominant period at the maximum power spectrum of abnormal waves is longer than that of abnormal waves propagated from AH and YG. As the abnormal waves approach the West Coast, the maximum total power spectrum becomes stronger (Table 1).

Comparison between abnormal waves of March 31, 2007 and the abnormal waves of April 25, 2008

Figure 4 shows sea level variation of March 31, 2007 and April 25, 2008 at AH where abnormal waves arrived for the first time. There is a different propagation direction between the 2 abnormal waves, considering tidal phase. Tidal phase when abnormal waves arrived is completely opposite. Abnormal waves on 31 March 2007 during flood tide were able to make positive interference in terms of propagation direction of the abnormal waves and tide. But abnormal waves on 25 April 2008 during ebb tide were not able to positive interference because of out of phase with each propagation direction. The length of time abnormal waves lasted can be affected by the tidal phase difference.

However, there is a similar propagation direction between the 2 abnormal waves, considering the direction abnormal waves propagated. To estimate the direction abnormal waves propagated, we use propagation direction estimation algorithm. Abnormal waves on 25 April 2008 occurred at first at AH, and propagated from the northwestern corner of the West Sea toward the shore at DH and YG in that order (Figure 5). The abnormal waves on 31 March 2007 also propagated from the northwestern corner of the West Sea toward the shore at AH, DH, Wi, GS, and YG (Eom et al., 2012). The abnormal waves on 25 April 2008 and the abnormal waves on 31 March 2007 are closely related in terms of propagation direction of the abnormal waves.

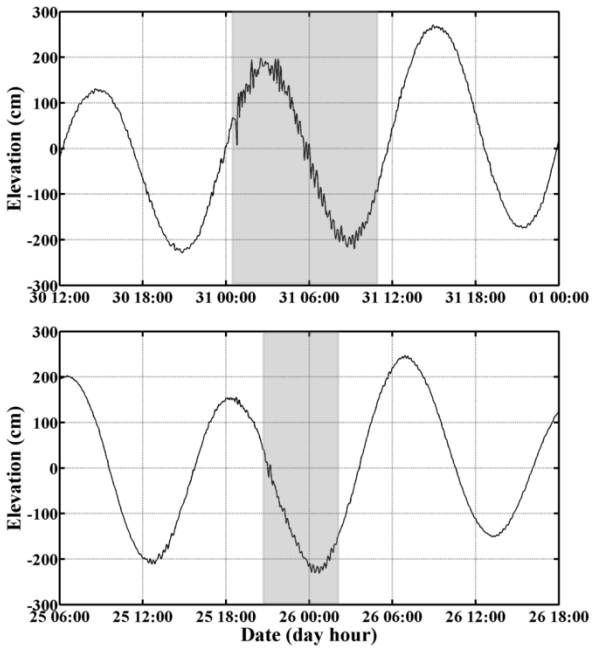


Figure 4. Comparison of sea level variation from 30 March 2007 to 31 March 2007 (upper) with sea level variation from 25 April 2008 to 26 April 2008 (lower) at AH (Anheung); The time series are linearly detrended. The size of the grey box indicates the length of time abnormal waves lasted.

Table 1. Maximum total power spectrum of the abnormal waves, arrived time of abnormal waves, maximum power spectrum and dominant period of abnormal waves.

Station	Max. Total Power Spectrum (cm^2)	Arrived Time	Max. Power Spectrum (cm^2)	Period (min)
AH	26,232	21:09	1,152	14.4
DH	28,726	21:26	1,659	21.8
YG	84,197	22:36	3,915	57.6

CONCLUDING REMARKS

The driving forces of abnormal waves propagated from the West Sea can be generated by earthquakes, storms, winds, and atmospheric pressure jumps. From about 21:00 on 25 April 2008 to about 2:00 on 25 April 2008, during which abnormal waves lasted (Figure 4.), there was no earthquake or storm in the West Sea. In the case of the abnormal waves of March 31, 2007, it was concluded that they were generated by the atmospheric pressure jump (Eom et al., 2012). Likewise, the driving force of the abnormal waves on 25 April 2008 was presumed to be pressure jumps in terms of the similarity of the propagation direction of the abnormal waves, if the impact of winds was negligible.

Literature indicates that Proudman resonance between atmospheric pressure jumps (13 ~ 27 m/s) and shallow water wave can occur when Froude number approximates to 1.0 (Choi et al., 2008). Propagated from to the West Sea, barotropic ocean waves derived from atmospheric pressure jumps generated Proudman resonance at a certain depth while moving together with the atmospheric pressure jumps. Figure 5 shows the velocity of abnormal waves which occurred from 30 m depth to 60 m depth.

In summary, the abnormal waves that occurred on 25 April 2008 were propagated from the northwestern corner of the West Sea to the east–southeast, similar to the propagation of the abnormal waves on 31 March 2007. It was concluded that the driving force of abnormal waves on 25 April 2008 was presumed to be atmospheric pressure jumps, and therefore, the abnormal waves were meteotsunami generated by atmospheric pressure jumps.

The propagation direction of abnormal waves, derived from this study, can be used to understand the movement of the atmosphere, which serves as an external force by means of, for example, variations in atmospheric pressure. Further, it is expected that it will be applied to two-dimensional numerical simulations, and more realistic results will be produced.

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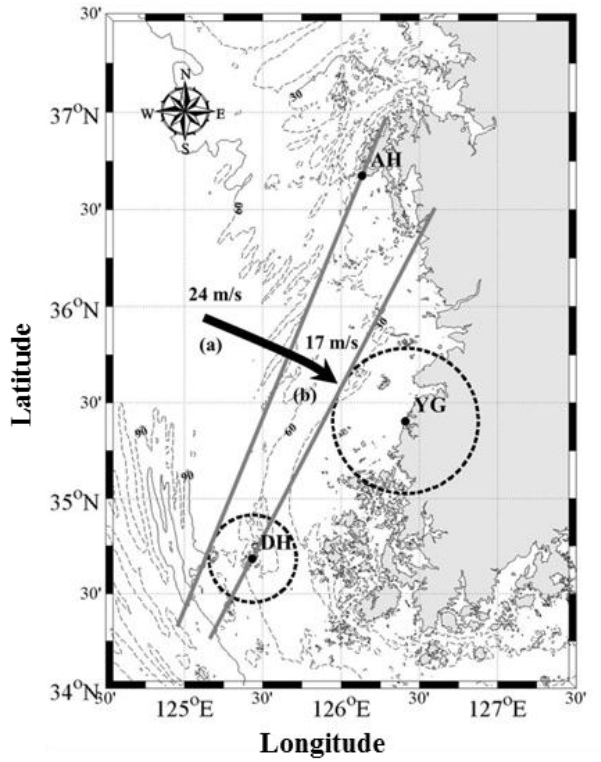


Figure 5. Propagation of abnormal waves on 25 April 2008; The thick grey line is wave crest line and the radius of each circle is the distance which abnormal waves moved derived from propagation direction algorithm. The dotted line is bathymetric contours. The velocity above the arrow is velocity of abnormal waves. (a) At first, abnormal waves were propagated to ESE direction from the north-western corner of the West Sea. (b) Then, approaching YG, the crest line tends to bend parallel to the shoreline.

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