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Typhoon Induced Swell

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Abstract

Waves that have propagated out of their generating fetch are called swell. Swell waves can significantly affect offshore structure designs, small boat operations and ship passages over harbor entrance, and surf forecasting. It is necessary and interesting to be studied on both scientific and practical purposes. There are several typhoons affect Taiwan every year. This paper estimates swell height by using a wind-sea and swell separation approach. The purpose of this paper is to understand the relationship between typhoon tracks and their generated swells. It is found that the value and occurrence time of maxima swell height are related to typhoon track. The maxima swell heights that generated by typhoons move westerly to Taiwan (track category I, III, V) is much larger than them generated by the typhoon moves from low to high latitude (track category VI). The maxima swell height estimated in this paper is up to 7 m. In addition, the maxima swell heights always occur after typhoon passing. In this study, it is also found that even the typhoon is far, the generated swell may have the same level as it generated by close typhoons. The results presented in this paper are obtained by analyzing the wave data from Taiwan coast ocean and may helpful on the prediction of typhoon swell.

Keywords: Swell; Typhoon; Data buoy

Introduction

Waves are generated by forces that disturb a body of water. They can result from a wide range of forces - the gravitational pull of the sun and the moon, underwater earthquakes and landslides, the movements of boats and swimmers. The vast majority of ocean waves, however, are generated by wind. Waves that are growing under the influence of the wind are called seas or wind waves. Waves that have propagated out of their generating fetch are called swell. Even on the calmest days, storms raging elsewhere on the ocean create rolling waves that radiate away from the storm. These are swells, and they can increase as storms intensify and near the coast. Swell waves are generated by tropical storms or typhoons at Taiwan waters. The coexisting of wind sea and swell can significantly affect sea-keeping safety, offshore structure designs, small boat operations and ship passages over harbor entrance, and surf forecasting (Earle, 1984). In addition, swell waves may also cause changes in the shape of a beach by moving sand from one end to the other.

The characteristic of swell is somewhat different with wind waves. Principally, swells are smoother, losing their rough appearance due to the disappearance of the multitude of small waves on top of the bigger ones and the whitecaps and spray. The motion of the swell is nearly irrotational and nonturbulent. When swell move away from the area where the wind is blowing, they sort themselves out into groups with similar speeds and form a regular pattern. As a result of swell, large waves may be seen breaking on the coast even on calm, sunny days in winter. The height of the swell will decrease the further the waves travel from the fetch. The height of swell waves on a usually calm leeward coast may vary between 1 m and 3 m, although occasionally they may be as high as 5 m.

The mixed seas affect the dynamics of near-surface processes. Therefore, studies on swell are many on the improvement of wave modeling. Wave forecasting by numerical model is an inherently difficult task, more so for swell (Komen et al., 1994; Kantha and Clayson, 2000), since inadequate or excessive decay of swell can lead to significant errors in the forecast. Kantha (2006) therefore derive an expression for the swell attenuation rate that is of potential use in wave forecast models. Alves (2006) presented a new technique for studying the contribution of ocean swell to the global wind-wave climate. However, identification and separation of wave components of wind sea and swell provide a more realistic depiction of sea state and is important and interest to both scientific and engineering applications.

Every year, there may be from three to ten typhoon events happened around Taiwan Waters, each lasting from one to four days. During typhoons, people quit oceanic activities; however it's an important issue to decide when to start the oceanic activities for safety reason. The purpose of this paper is to study the properties of swell generated by various typhoon tracks. A wind sea and swell separation method is applied to obtain typhoon swell height since it cannot be observed directly. The statistical results are summarized in this paper.

Swell Separation Method

The common method for separating the wind sea and swell from the wave components is to determinate a separation frequency f_s for a given wave spectrum. Wave components at frequencies higher than f_s are generated by local winds. On the contrary, the wave components at frequencies lower than f_s are from swell as shown in Figure 1. Earle (1984) proposes an empirical relation between the separation frequency and the local wind speed. A partitioning approach proposed by Hasselmann (1994) has been developed for identify wind sea and tracking storm source. Recently, this technique has been extended by Voorips (1997) for the assimilation of wave observation into the WAM model. Rodriguez and Guedes Sores (1999) proposed a method which uses an empirically determined width of the confidence intervals pf the spectral data to differentiate the legitimate energy peaks of wind sea and swell from the spectral irregularities. The method used in this study to compute the separation frequency was developed by Wang et al. (2001). The advantage of this method is to calculate the separation frequency without the need of wind and directional wave information.

The significant wave height and average wave period can be obtained from

$$H = 4\sqrt{m_0} \tag{1}$$

$$T = \sqrt{\frac{m_0}{m_2}} \tag{2}$$

Where m_0 and m_2 are spectral moments (Massel, 1996).

$S(f)$ is the wave spectrum. f_{max} is the upper-frequency limit of $S(f)$ and depends on the monitoring system. In this study the value of f_{max} is 0.4 H_z. For a given frequency f_* in the wave spectrum, the wave steepness is defined as the ratio between the significant wave height and wave length. It is expressed as

$$\alpha(f_*) = \frac{H_*}{L_*} = \frac{8\pi\left[\int_{f_*}^{f_{\max}} f^2 S(f)df\right]}{g\left[\int_{f_*}^{f_{\max}} S(f)df\right]^{0.5}} \tag{3}$$

Where L_* is the wave length which can be defined by using the linear dispersion relation. $\alpha(f_*)$ is called the steepness function. The peak frequency of the steepness function is defined as f_m.

Wang et al. (2001) simulate the steepness function for various wind speeds by using PM spectral model. Figure 2 is the curve-fitting result of the peak frequencies of steepness functions and wind speeds by regression analysis. The peak frequency of the steepness function decreases as the wind speed increase, which can be approximated by

$$U = a(f_m)^b \tag{4}$$

where U is the wind speed in m/sec. The two empirical constants are $a=0.379$ and $b=-1.746$ determined from the regression analysis.

The critical relationship between wave phase velocity (C_s) and wind speed (U) for wave to form swell is $C_S=U$. Using the deep water phase velocity the separation frequency is related to wind speed by

$$f_s = \frac{g}{2\pi U} \tag{5}$$

Substituting (4) into (5), we obtain

$$f_s = A(f_m)^B \tag{6}$$

Where $A=4.114$ and $B=1.746$. In other words, the reparation frequency f_s can be determined from the peak frequency of the steepness fm from the wave spectrum without the use of wind speed.

This method is applied to analyze typhoon waves. Figure 3 shows the wind and wave data measured at Longdong Buoy during typhoon NOCKEN, 2004. Figure 4 shows the wave spectra on several stages of typhoon period and their separation frequencies. Before the typhoon attacked Taiwan, the wave energy was small and the separation frequency was on the high frequency range. It means the sea condition dominates by swell before typhoon. As the typhoon moved close to Taiwan, the wave energy became large and the sea state transmitted to be dominated by wind seas.

In figure 3, the separated wind wave and swell heights are plotted. It is shown that before typhoon arrived (Oct. 25 06:00), swell occurred but they are small. When typhoon was very close to the field station, wind wave started to dominate the sea state because of the blowing of strong wind of typhoon. However, when typhoon started to leave, swell again dominated the sea state with very high energy. This is a topical example of the wind wave and swell transition during a typhoon.

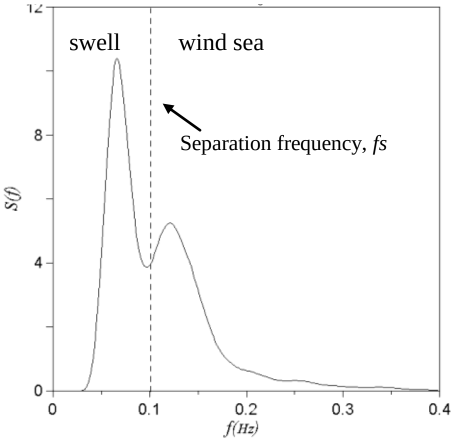

Figure 1 Diagram of separation of wind sea and swell

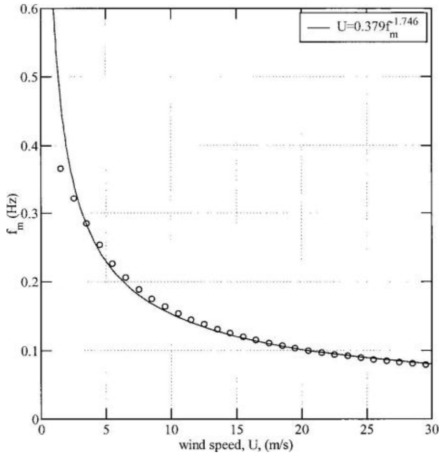

Figure 2 Wind speed vs peak frequency of the steepness function based on the PM spectral model. The line is the fitting result by regression analysis. (Wang et al., 2001)

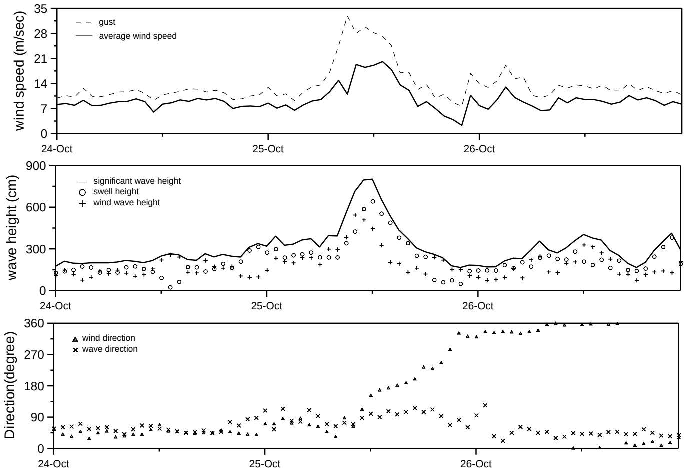

Figure 3 Example of the separation of wind sea and swell
(station Longdoong Bouy during typhoon NOCKTEN, 2004)

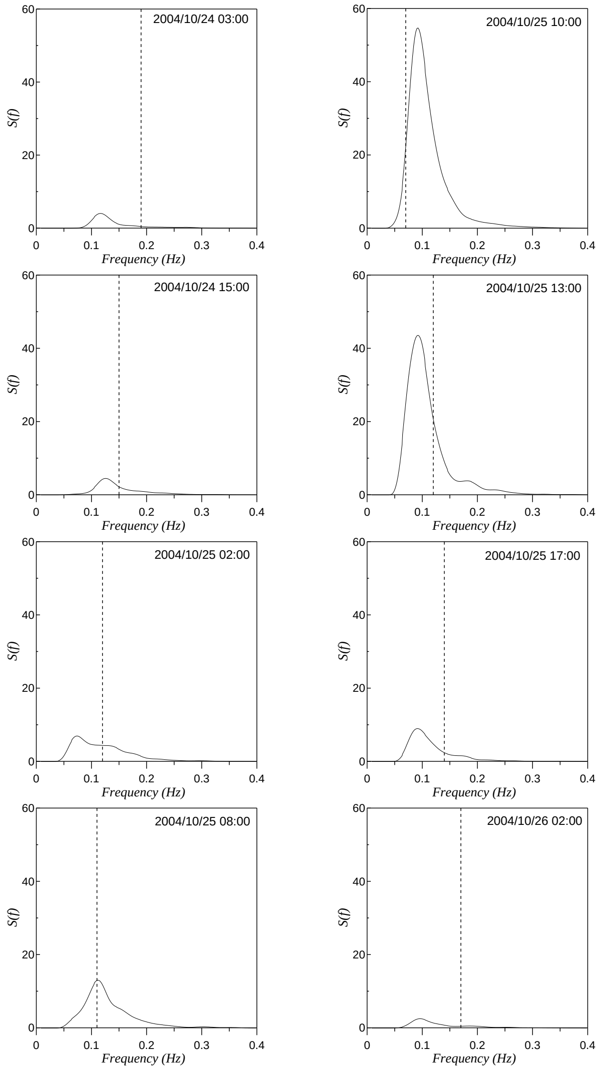

Figure 4 Separation of wind sea and swell on wave spectra
(station Longdoong Bouy during typhoon NOCKTEN, 2004)

Data

Natural hazard caused by severe marine climate are often happened at the coastal area of Taiwan. In response to the requirement of meteorological and oceanographic data, an enhanced monitoring network comprising buoys, pile stations and other automatic observation systems has been set-up around Taiwan by Coastal Ocean Monitoring Center (COMC) at National Cheng Kung University since 1997. This network provides real-time observations and archived records of coastal water (20~50m) wave characteristics, water temperature, water level and meteorological conditions (wind speed and direction, temperature, barometric pressure), as well as digital images of the nearshore ocean. The system is designed to provide real-time information to Central Weather Bureau and Water Resources Agency for marine weather forecasting and coastal hazard mitigation purposes, and long-term records of wave, weather conditions and shoreline response for use by the coastal scientific community.

Typhoon waves erode the beaches and penetrate farther into the land behind the beach causing flooding, erosion of sand dunes and destruction of coastal roads and buildings. Typhoon data are used in this paper. Central Weather Bureau classify the track of typhoons moving forward to Taiwan to nine categories. In this paper, typhoon wave data of four different tracks are selected. Table 1 shows the basic information of the selected typhoon cases.

The data are from station Longdong where locates at northern eastern Taiwan at a water depth of 23 m as shown in figure 5. The measurement instrument is a data buoy which is self-designed and operated by COMC. It is a 2.5 meter wave-following discus buoy. The buoy is equipped with a tri-axial accelerometer to measure surface wave particle movements for the estimation of directional wave spectrum to derive the significant wave height, period and direction. In addition, sea surface wind speed, direction, air and water temperatures, barometer pressure are also measured simultaneously.

Table 1 Basic data of typhoons used in this study

Typhoon name	Typhoon duration	Lowest pressure (hPa)	Max. wind speed (m/s)	R_7 (km)	R_{10} (km)	V_F (km/hr)	Track Category
SINLAKU	2002/09/04~09/08	950	43	250	100	15	I
RANANIM	2004/08/10~08/13	960	38	250	100	19	I
AERE	2004/08/23~08/26	960	38	200	150	12	I
MATSA	2005/08/03~08/06	955	40	250	80	14	I
BILIS	2000/08/21~08/23	930	53	300	120	22	II
TORAJI	2001/07/28~07/31	962	38	250	100	17	II
LONGWANG	2005/09/30~10/23	925	51	200	80	23	II
UTOR	2001/07/03~07/05	960	38	350	120	30	V
IMBUDO	2003/07/21~07/23	935	48	300	120	27	V
DUJUAN	2003/08/31~09/02	950	43	250	100	26	V
KAITAK	2000/07/06~7/10	965	35	150	50	25	VI
KUJIRA	2003/04/21~4/24	950	43	250	100	7	VI
SOUDELOR	2003/06/16~6/18	965	38	200	50	32	VI
CONSON	2004/06/07~6/09	970	33	150	50	25	VI

* R_7: Radius of 34 KT Winds (Beaufort Scale 7); R_{10}: Radius of 50 KT Winds (Beaufort Scale 10); V_F: moving speed of typhoon

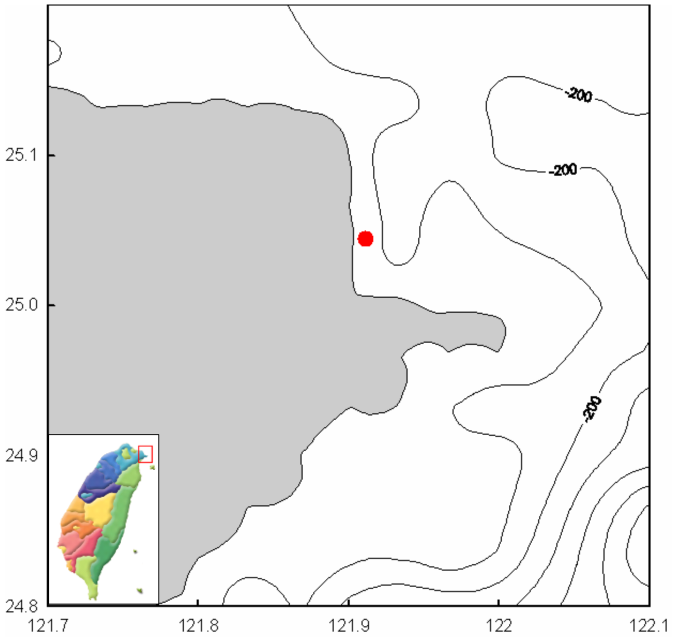

Figure 5 Location of the field station - Longdong Data Buoy

Typhoon Swell

In order to study typhoon phenomena, the Central Weather Bureau (CWB) of Taiwan classified the invaded typhoon to 9 tracks. In this paper, data from typhoons that classified in category I, III, V and VI are selected to study the swell wave properties. Typhoon track category I covers the typhoons that moving pass through northern Taiwan waters. Typhoon track category III includes the typhoons that passing across Taiwan Island. Typhoon track category V means the typhoons that moving pass trough southern Taiwan waters. The typhoons that moving from south to north at eastern Taiwan waters are classified as track category VI. In this section, time series of typhoon swell heights are estimated by the wind-sea and swell separation method. The in-situ data used is from Longdong Buoy. The objective of the discussion is to study the influence of swell height by various typhoon tracks

Track category I

In this study, four typhoons that classified in track category I are used. They are named SINLAKU, RANANIM, AERE and MATSA. The basic information of these typhoons is listed in Table 1. The track of typhoon SINLAKU is shown in Figure 6a. The typhoon was to move westward at a speed of 11~15 km per hour when it close to Taiwan. The radius of 50 KT Winds is about 100 km and the 34 KT Winds is about 300 km. Time series of typhoon swell height measured at Longdong Buoy is shown in Figure 6b. It is shown that the max. swell height is up to 5.4m and it occurs 4 hours before the typhoon arrived the closest position to the field station (-4 hr). When typhoon passed the field station, swell reduced at a very short time.

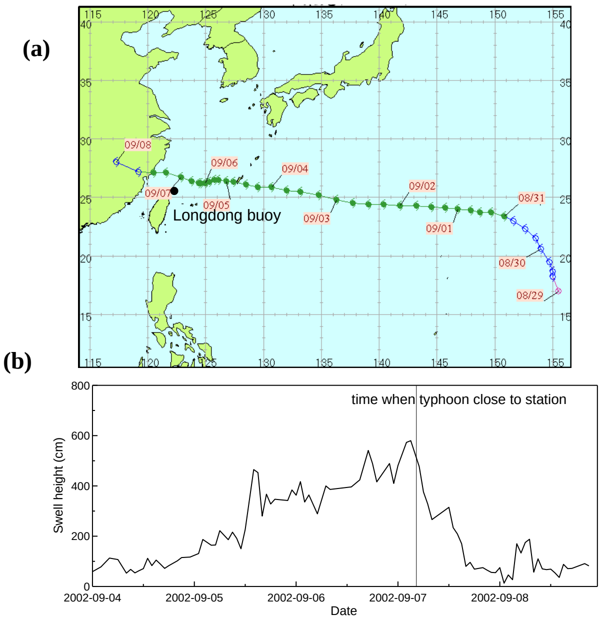

Figure 6 (a) Track of typhoon SINLAKU (2002) (b) Swell heights at Longdong

Typhoon track category III

Typhoon BILIS is classified in the track category III. The track is shown in Figure 7a. It was the most powerful storm to hit Taiwan in year 2000. This typhoon brought strong winds of 190 km per hour and very heavy rain destroyed homes and property, downed trees, and caused flash flooding, particularly in coastal areas. The radius of 50 KT Winds is 120 km and the radius of 34 KT Winds is up to 300 km which covers whole Taiwan when it landed at Taiwan. From the CWB report, the max. significant wave height induced by this typhoon is up to 11m at eastern Taiwan coast. By the analysis of this study, the max. swell height at Longdong is about 4.5 m as shown in Figure 7b. It is not expected high. One of the probable reasons is because of that the location of Longdong is at the north of typhoon eye and covered by land comparing to direct impact by typhoons such as above SINLAKU. The other season is that this typhoon was a fast movement one. Its moving speed is 22 km/hr which is almost twice of SINLAKU's. In addition, from figure 7b we see the max. swell wave height occurred half day (+12 hr) after typhoon arrive. When the max. swell height occurred, typhoon BILIS was already pass crossing Taiwan. In addition, after typhoon pass, the swell heights decay slowly.

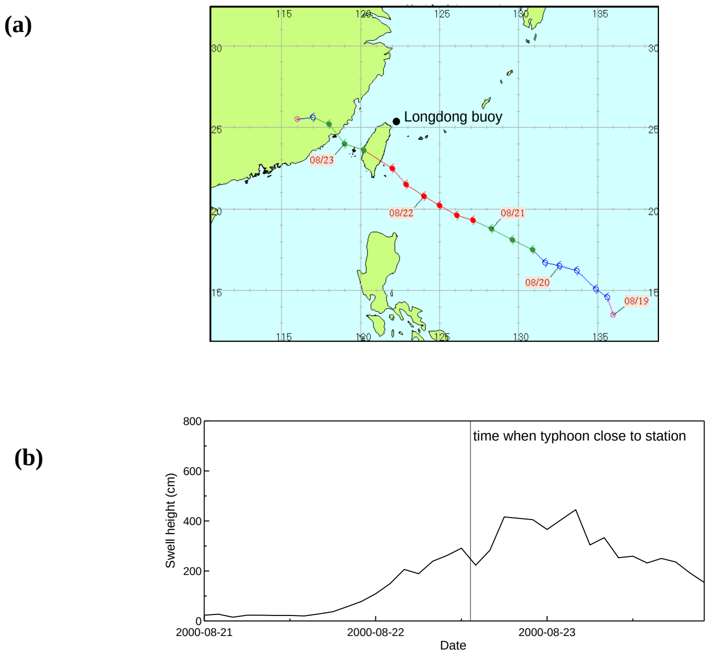

Figure 7 (a) Track of typhoon BILIS (2000) (b) Swell height at Longdong

Typhoon track category V

When typhoons move passing southern Taiwan waters, they are classified as track category V. In this study, three category V typhoons are analyzed. They are UTOR, IMBUDO and DUJUAN. These typhoons are far away from northern Taiwan where it sometimes still has clear sky. However, the induced swell waves are not small. Figure 8b shows the swell time series at Longdong of typhoon UTOR that has 600 km distance. The max. swell height is 4.6 m and it occurred at 8 hour later (+8 hr) when typhoon arrive the closest point with the field station. Like typhoons belong to category III, the swell heights induced by this category typhoons also decay slowly.

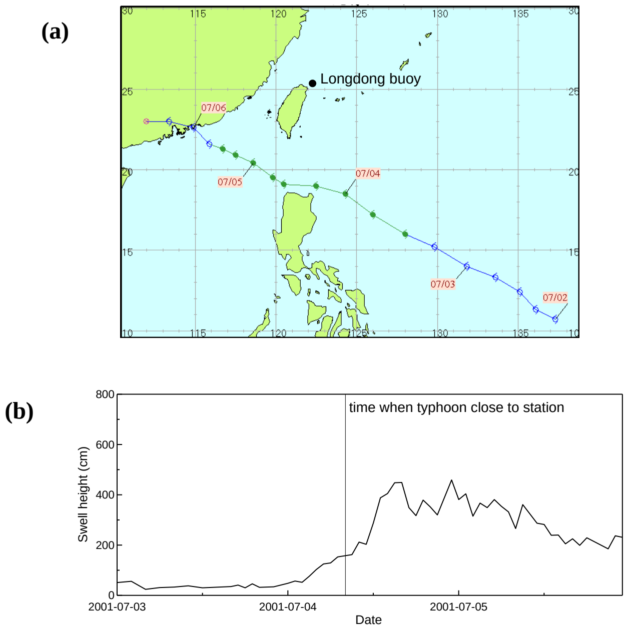

Figure 8 (a)Track of typhoon UTOR (2001) (b)Swell height at Longdong

Typhoon track category VI

In this study, typhoon SOUDELOR is used as the representation of track category VI. Three other typhoons are also analyzed for following statistics. Typhoon SOUDELOR straight moved from eastern Phillips waters to Japan. The distance between typhoon track with Taiwan Island is about 250 km. The max. swell height at Longdong Buoy during this typhoon period is about 2.2 m. It occurred at 2 hours when typhoon arrive the closest point to Longdong.

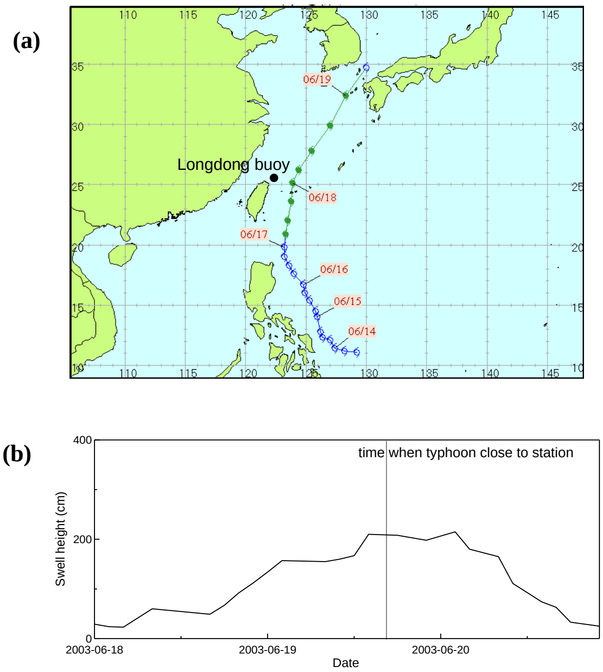

Figure 9 (a) Track of typhoon SOUDELOR (2003) (b) Swell height at Longdong

Waves in seas have many aspects to study. Coastal waves are complex in that wind waves and swells often co-exist and maybe come from different directions at the same time, especially during typhoons. In the above section, data from four different track typhoons are analyzed on swell height as examples. Table 2 shows the whole results. The "occur time" in the figure means the time of max. swell occurs. Symbol "-" means it occurs before typhoon arrive the closest distance to the research area, ie. the field station – Longdong Buoy. Symbol "+" means max. swell occurs after typhoon arrive the closest position. We find from the table that the max. swell wave heights always occur when typhoon pass the closest position to the interested filed station. It is out of expectation. In figure 10, the typhoon positions when the max. swell wave height measured at northeast Taiwan waters of various tracks are plotted. At the west Pacific region, typhoon always moves forward at a speed of 12~25 km/hr. Since the swell wave period is around 15 sec, the phase velocity of the swell is about 84 km/hr. The swell velocity is average 4.5 times of typhoon moving speed. Therefore, people knows the swell will arrive when typhoon is still thousand kilometer away. It is a fact. We could see in figures 6~9. The swells do occur before typhoon comes, however they are sometimes less than 1m. This paper is to focus on the study of the occurrence time of the max. value of swell waves. They always occur late during typhoon period. The reason is interesting to be further studied in order to forecast max. swell height induced by typhoons. Considering the value of swell heights, it is found that the typhoons of track category I, III, V generate large swells. The maxi. Swell height is up to 7m during typhoon Aere in year 2004. However, typhoons of track category VI which is the typhoon moving pass the eastern Taiwan waters generate small swell.

Table 2 Results of typhoon swell analysis

typhoon track	typhoon name	max. swell height (m)	occur time (hr)	average swell height (m)
I	SINLAKU	5.4	-4	1.8
	RANANIM	4.8	+6	1.0
	AERE	6.9	-7	1.8
	MATSA	4.9	+1	1.5
III	BILIS	4.5	+12	1.8
	TORAJI	2.6	+7	1.0
	LONGWANG	5.3	-1	1.4
V	UTOR	4.6	+8	2.1
	IMBUDO	2.4	+4	0.7
	DUJUAN	5.2	+10	1.0
VI	KAITAK	2.0	+5	1.0
	KUJIRA	2.3	+4	1.2
	SOUDELOR	2.2	+2	0.6
	CONSON	1.4	+8	0.5

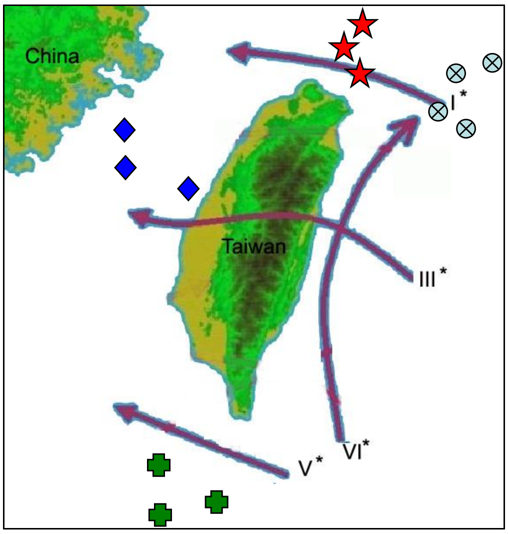

Figure 10 Typhoon positions when the max. swell wave height measured at northeast Taiwan waters under various typhoon track categories

Conclusions

People know typhoon generates huge waves. People also know typhoon generates long-period swell waves. However, how large are the swells within typhoon waves and do they effected by typhoon properties? These are uncertain but interesting issues. If they can be clearly studied, it is helpful on understand of swell and on swell forecasting. This study estimates the swell wave component of typhoon waves using a wind-sea and swell separation approach. By analyzing wave data from 14 typhoons that contain four kinds of track categories around Taiwan, conclusions are listed as follows.

(1) The value and occurrence time of max. swell height are related with typhoon properties, such as typhoon moving track.

(2) The maxima swell height generated by a typhoon always occurs after typhoon arrive the closest position to interested area (field station), or said when typhoon pass through the field station. It should be found more data to explain this phenomenon. This result is obtained by analyzing the wave data measured at Taiwan coast ocean area.

(3) If the typhoon moves westerly to Taiwan Island (track category I, III, V), the swell heights are estimated up to 5~6m at northern Taiwan coast. However, swell height is around 2m when the typhoon coming from south (track category VI).

(4) Even the typhoon is far away from the interesting point, the generated swell may have the same level as the one generated by close typhoon. However, the occurrence time may difference.

Acknowledgements

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References

Alves, Jose-Henrique G.M., 2006. Numerical Modeling of Ocean Swell Contributions to the Global Wind-Wave Climate, Ocean Modelling, Vol. 11, pp.98-122.

Earle, M.D., 1984. Development of algorithms for separation of sea and swell, National Data Buoy Center Tech. Rep. MEC-87-1, 53pp.

Hasselmann, S.K. Hasselmann, and C. Bruning, 1994. Extraction of wave spectra from SAR image spectra. Dynamics and Modelling of Waves, G. J. Kommen et al., Eds., Cambridge University Press, 391-401.

Hanson, J.L. and O.M. Philip, 2001, Automated analysis of ocean surface direction wave spectra, J. Atmos. Oceanic Technol., 18, 277-293.

Kantha, L., 2006. A Note o the Decay Rate of Swell, Ocean Modelling, Vol. 11, pp.167-173.

Kantha, L.H., Clayson, C.A., 2000. Small Scale Processes in Geophysical Fluid Flows. Academic Press, p.888.

Komen, G.J., Gavaleri, L., Donelan, M., Hasselman, K., Hasselman, S., Janssen, P.A.E.M., 1994. Dynamics and Modelling of Ocean Waves. Cambridge University Press, Cambridge, p.532.

Massel, S.R., 1996, Ocean surface waves: their physics and prediction, World scientific.

Voorrips, A.C., V. K. Makin, and S. Hasselmann, 1997, Assimilation of wave spectra from pitch-and-roll buoys in a North Sea wave model. J. Geophys. Res. 102, 5829-5849.

Wang, David W. and Paul A. Hwang, 2001, An operational method for separating wind sea and swell from ocean wave spectra, J. Atmos. Oceanic Technol., 18, 2052-2062.