

EXTREME WAVES GENERATED BY TYPHOON BOLAVEN(201215) IN SOUTHERN KOREAN WATERS

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ABSTRACT: Unusual extreme waves were generated by Typhoon Bolaven (201215) in the Southern Korean Waters (SKW) and gave destructive damages to the breakwaters of Seogwipo Harbor at Jeju Island. The waves were far exceeding the design wave height (H_{s50yrs} 9.3m) and their duration was 14hours. The duration is a very significant factor as much as the design wave height for breakwater armor stability in terms of cumulative damages. A significant increase in strong typhoon intensity and duration in North West Pacific (NWP) due to global warming has been reported and also in landfall typhoons on Korea/Japan in a recent decade. The frequency of typhoon passed SKW region had an inter-annual and also a decadal variation and decreased in recent years, but several strong typhoons were occurred. Bolaven was affected by high pressure distribution located above the warm eddy region to track toward NNW rather than NE as usual in August. The extreme waves were analyzed with respect to typhoon genesis, evolution of the waves through extensive measured data and model simulation. Numerical models of TC96 for the wind fields and WAM4.5.2 for the waves were used after calibration with measured data and correction of C_d in wave growth term. They produced reasonably good results. It was found that the extreme waves were evolved by combination of distant large swell and strong wind seas generated by consistent strong winds from front right quadrant of typhoon track for such a long time. The variation of those waves was relatively small as 1-2m, which might be due to limitation of wave growth for $U > 30m/s$ and bottom energy dissipation of long period waves in the region. It is essential to hindcast accurately the extreme waves for design of the breakwaters and also for assessment of coastal flooding and coastal erosion in a warming climate.

Keywords: Typhoon, extreme waves, breakwater damage, climate change

INTRODUCTION

It is important to analyze the characteristics of unusual extreme waves generated by a strong typhoon in a warming climate. When a typhoon (TY) generated deep-water significant wave heights in excess of 10 m, it is classified as 'extreme' on the Dolan and Davies (1992) scale for storm magnitude proposed for the Atlantic. The strong typhoon used to generate the extreme waves of very high wave height and long duration, which can cause destruction of armored layer of breakwaters, and also cause severe beach erosion in a coast (Allan and Komar 2002).

TY Bolaven (201215) classified category 4 passed the Southern Korean Waters (SKW) on August 2012. It generated unusual high waves ($H_{s,max}$ 11.3 m at Ieodo Ocean Research Station (IORS, <http://ieodo.khoa.go.kr/>) in deep-water, 11.8 m in shallow water near Seogwipo Harbor were observed on August 28, 2012 (KHOA 2012; Jeong et al. 2012) (Figs. 1 and 2). The waves exceeding 9.3 m (H_{s50yrs}) with 14 hrs of duration gave destructive damages to the breakwaters of Seogwipo Harbor located at the southern coast of Jeju Island Korea

(Park 2012). Long duration of design waves plays a significant role on the cumulative damage to breakwater armor layer (Van der Meer 1987; Suh et al. 2012). In coastal and harbor engineering practice the duration of a design wave is usually 3 hours (eg., $N_s=1000$ in Van de Meer formula) when the waves are generated by a TY passing SKW. The breakwaters were also experienced severe damages by TY Maemi in 2003 and repaired with referenced to revised H_{s50yrs} 9.3 m (DY Engineering, 2012). Such extreme waves have been occurred during typhoons in a recent decade and damaged to coastal infrastructures. Thus it has been requested to revise the design wave height considering climate change effects.

Most of strong landfall typhoons in Korea usually pass SKW that includes the sea in the vicinity of Ieodo and Jeju Island, and also southern coastal waters of Korean Peninsula as shown in Fig. 2. The water depth of SKW varies from 40 m to 120 m.

According to some recent studies there has been a significant increase in the destructive power of strong tropical cyclones (TCs) over the Western North Pacific (WNP) basin due to anthropogenic global warming

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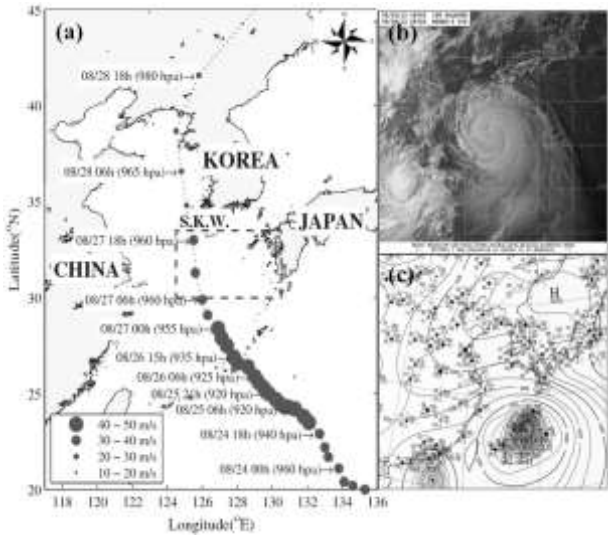


Fig. 1 The track of typhoon Bolaven: (a) locations, times, minimum pressures of its centers, and U_{max} , (b) Cheollian satellite image, (c) synoptic weather chart showing L-H pressures distribution.

(Emanuel 2005; Webster et al. 2005). Especially the strong intensity and longer duration of TCs have been occurred over Korean Peninsula and Japan (Oh and Suh 2011; Park et al. 2011). The TY tracks might be affected by strong high pressure distribution near Japan in the North Pacific with relation to large scale environments (Jin et al. 2012), which may result in the generation of higher waves than the earlier decade. The relative proportion of the most intense TCs (Category 4+) may increase in the future (Knutson et al. 2010) but there will be inter-annual and inter-decadal variations of landfall TCs in East Asia (Chan et al. 2009). General increase in significant wave height can be seen in North Pacific including Korea and Japan from Young et al. (2011).

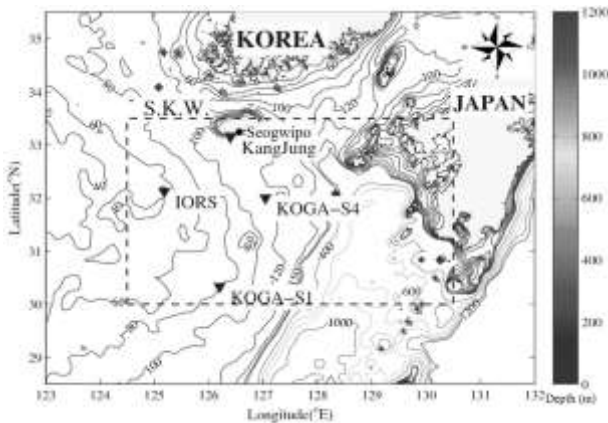


Fig. 2 Map showing the S.K.W region as dotted lines, bathymetry, and location of measurement stations and Seowipo Harbor

TYPHOON BOLAVEN (201215)

Genesis

Bolaven (201215) was the strongest TY in SKW since Maemi (200314) even though there were two more TYs of Kompasu (201007), and Muifa (201109) within a last 10 years (2003-2012) (refer to yearly typhoon track records from National Typhoon Centre <http://typ.kma.go.kr/>). Frequency of TYs passing SKW is plotted in Fig. 3 where it can be seen an inter-annual and decadal variations of TYs frequency in SKW. As shown in Fig. 3 the frequency decreased apparently in a recent decade, but the typhoon intensities and durations were increased (Park et al. 2011).

Following the best track of Bolaven, it developed as TS (Tropical Storm) on 06:00 Aug 20, 2012 at 570 km apart in the north-west of Guam, gradually became a small TY (U_{max} 34 m/s) on 12:00 Aug.21, and then medium TY (U_{max} 47 m/s) on 12:00 Aug. 24, and the strongest TY (U_{max} 53 m/s, 920 hPa) C4 on 00:00 Aug. 26 (Fig. 1(b)). Bolaven was fully developed and intensified ($U_{max} > 50$ m/s) during two days (06:00 Aug. 25–18:00 Aug. 26) in the mid-latitude region where warm eddies are to be well developed (eg., Park et al. 2011).

It progressed in the NW direction and turn to NNW-N from 06:00 Aug. 27, which might be influenced by high pressure distribution located above the warm eddy region as a counter balance in Fig. 1(c) (eg., Jin et al. 2012). It passed right on the IORS and then through the west coastal waters of Korean Peninsula, and made landfall on August 28, 2012.

Field Measurements of Winds and Waves

Measured data of winds and waves are more extensive and detailed than that for any previous typhoon in the SKW. Field measurements have been made at three stations in deep water and one in shallow water: Korea Hydrographic and Oceanographic Administration

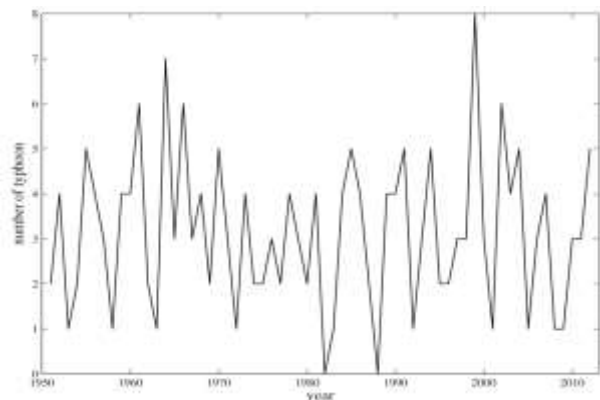


Fig. 3 Yearly frequency distribution of typhoon passed SKW region since 1950.

(KHOA) collected measurements at marine observation tower of IORS (Shim et al. 2005) and data buoys of KOGA S1 and S4 (KHOA 2012) in the water depth of 56 m, 81 m, and 115 m respectively. Korea Institute of Ocean Science and Technology (KIOST) collected measurement at coastal site Kangjeong in the water depth of 14.5 m (Jeong et al. 2012) near Seogwipo as shown in Fig. 2.

Waves were measured using radar MIROS mounted on the tower of IORS, and Datawell accelerometer MOSE-G1000 mounted on a corn-typed buoy of diameter 4.5 m moored with a length of steel chains for safety which can affect the maxima of the extreme wave heights. A pressure type wave gauge was used at coastal site. Water depth at the measuring site of IORS is a little shallow for the waves of period larger than 9 s might be experienced bottom frictional energy damping.

With the presence of several wave measurement stations the movement of Bolaven can be followed as it passed the SKW. The measured time series describe wave generation and propagation from deep water to coastal waters of Jeju Island in the SKW.

Extreme Waves at IORS

Atmospheric pressures, winds, waves measured at IORS are graphed in Fig. 4. Wind speeds began to increase steeply up to its maximum of 34 m/s in ESE direction on 08:00 August 27. However the significant wave height (H_s) increased a little slowly from 3 m to 6 m until 18:00 August 26, and then suddenly increased up to 10 m on 07:00 and 11.0 m at its maximum on 10:00 August 27. Such extreme waves exceeding 9.3 m of H_s 50yrs fluctuated in the range of 1-2 m and lasted for 14 hrs. Their significant wave periods were around 14 s and wave directions ESE. After that time wind speed and directions were changed abruptly to around 24 m/s SW-WSW, and then gradually decreased.

They are very unusual extreme waves generated by typhoon whose heights were larger than 10 m varied in a

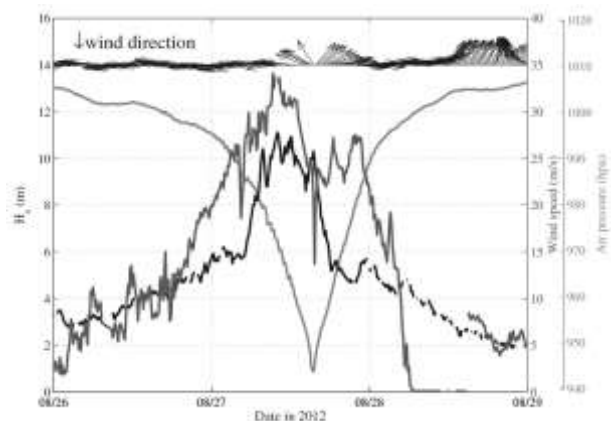


Fig. 4 Measured significant wave heights, winds, and air pressures at IORS

small range and stayed for such a long time. Three hours is used for the duration of design waves in coastal engineering practice in SKW region.

Breakwater damages

Maximum H_s measured at Kangjung was 11.8 m on 12:30 August 27, and waves of $H_s > 10$ m were occurred for 13 hrs. Bathymetry of the site is a little concaved. Hindcasted $H_{s,max}$ was 11.0 m, T_p 14.9 s at the breakwaters of Seogwipo Harbor. The extreme waves were larger than both wave height and duration of the design waves $H_{s,50yrs}$, and destructively damaged the breakwaters of Seogwipo Harbor as shown in Fig. 5

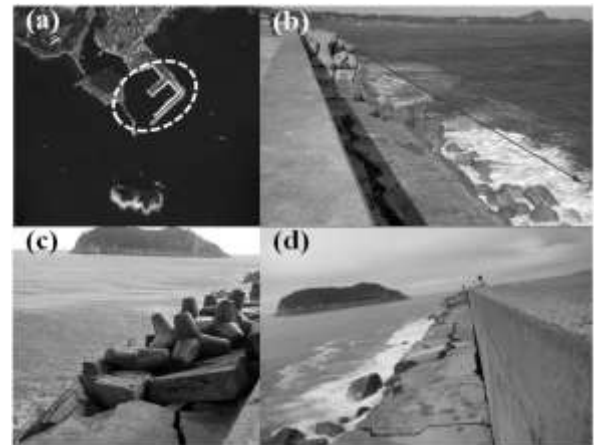


Fig. 5 (a) Layout of Seogwipo Harbor. Damaged breakwaters : (b) east breakwater, (c) left side and (d) right of south breakwater, TTPs of 72 ton were destructed and slid down, cap conc. cracked, and top conc. blocks were moved, which were placed for repair works after Maemi (2003)

SIMULATION OF THE EXTREME WAVES

Wave Model

Wave model WAM4.5.2 (Gunther 2005) is used for deep-water wave generation, which has been continuously improved due to better quality of the forcing wind fields (Komen et al. 1994). WAM is a third generation discrete spectral wave model solving the action balance equation including refraction and shoaling, and accounting for arbitrary water depth in source/sink term specification to compute the generation and dissipation of wave action (The WAMDI Group 1988). It uses an atmospheric input source term based on Janssen (1991) that includes the net impact surface roughness resulting from a growing wave field, with an upper limit where the dependency of frictional velocity becomes linear with the equivalent neutral stable marine exposure wind field at 10 m.

WAM was set up to define directional spectra in terms of 25 frequency bins of 1.1 times its frequency

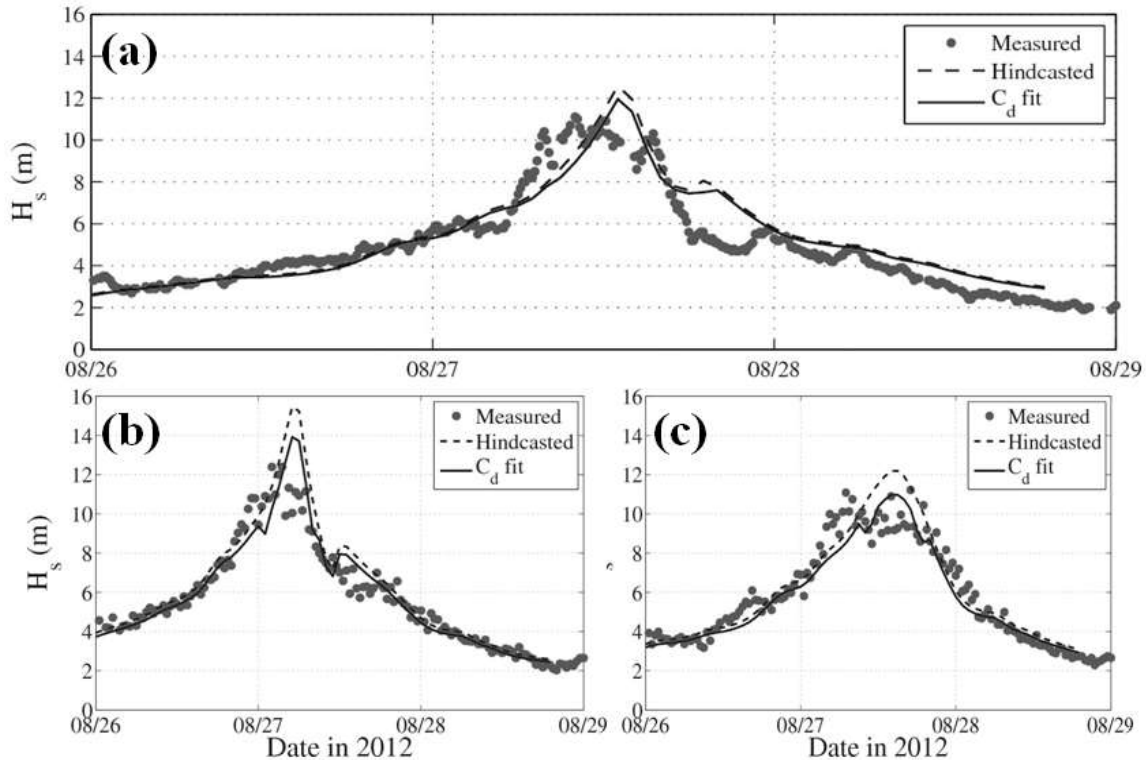


Fig. 6 Time series of measured and computed significant wave heights at (a) IORS, (b) KOGA-S1, and (c) KOGA-S4: measured values are shown with red dot; modeled results from WAM4.5.2 are shown with a dotted line and modified WAM4.5.2 with a thick line

width from 0.04-0.4 Hz, and 24 regularly spaced directional bins of 15° width. It was run at $1/12^\circ$ spatial resolution covering 20° - 50° N latitude and 117° - 143° E longitude (KORDI 2005) (refer to Fig. 1). Water depths were mainly obtained from General Bathymetric Chart (DEM) of KHOA. It was initiated on August 20, 2012 with the TY Bolaven winds generated by TC96 (Cox and Cardone 2000; Thompson and Cardone 1996) following JMA best track with the TY's intensity information.

Comparison to Measurements

The wind seas exhibit a slow response to changing wind conditions as shown in Fig. 4, and also WAM does similar behavior shown in Fig. 6. The hindcasted values are generally in good agreement with field measured wave heights even with some positive bias in peak values. As there is an important issue on the extreme waves, comparison to measurements is made mainly on the high waves in the data collected at IORS, which is more reliable than data at two buoy stations moored with a length of steel chains. Computed peak values are 1-2 m higher than the measured ones as shown in Fig. 6(a).

The overestimation might be attributed from the TC96 winds and wave growth source term of WAM. According to Cox and Cardone (2000) TC96 winds at the peak of a storm (Hurricane Floyd, 1999), a little overestimated when the wave height was greater than 9 m. And there was an examination of source behavior,

which shows that a cap on the atmospheric drag coefficient has a fairly positive impact on reducing wave height bias in the fully developed wind seas mainly due to strong wind speeds in excess of 30 m/s (Powell et al. 2003; Jensen et al. 2007; Dolean et al. 2004). Therefore the drag coefficient C_d in the wave generation source term of WAM4.5.2 is corrected to produce more realistic peak wave heights measured at three stations.

Evolution of the Extreme Waves

Bolaven generated waves with estimated H_s of 10-16 m in the northeast quadrant of typhoon (Fig. 8), where the winds were the strongest. These waves propagated as large swell and appeared early on August 27. Local winds were blowing from ENE and getting strongest to 34 m/s as shown in Fig. 4. Wave energy grew rapidly with strong winds over 30 m/s from the front right quadrant of typhoon and reached to the extreme wave when TY center was near KOGA S1 and sustained until it was on IORS. Those extreme waves were evolved with swell and fully developed wind seas as shown in Fig. 7 and lasted for around 14 hrs.

When the typhoon moved northward from mid latitude to SKW region, the TY generated waves were gradually decreased because TY intensity decreased and water depths became shallow. Therefore it might be some limitation on wave growth in SKW region. If such a strong typhoon as Bolaven tracked a little to right

bigger extreme waves could be occurred at the coastal waters of Jeju Island.

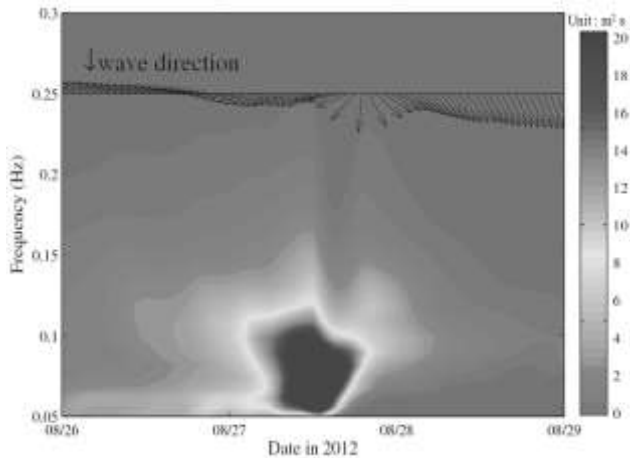


Fig. 7 Computed time series of frequency spectral densities and main wave directions at IORS during Typhoon Bolaven

CONCLUSION

A significant increase in the destructive power of strong TCs over the WNP seems to be due to global warming, and most intense TCs may increase in the future. The strong intensity and longer duration of TYs have been occurred during last decades even with less frequency in SKW. Bolaven track was affected by high pressure distribution and tracked to north in SKW region, which is unusual in late August. Consequently the stronger typhoon than Bolaven will generate higher extreme waves even with some periodical variations in the future.

Bolaven generated extreme waves which were higher

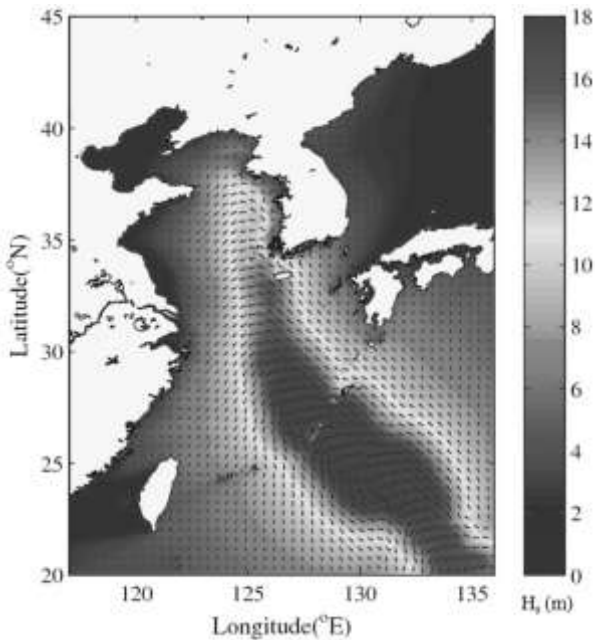


Fig. 8 Contours of maximum significant wave heights and vectors of wave directions during Typhoon Bolaven

than the design wave height, 9.3m for Seogwipo Harbor and lasted for a long time of 14hrs. They gave destructive damages to the breakwaters of the harbor. Hindcasting the extreme waves and analysis of their evolution were made using WAM4.5.2 and measured data. Computed extreme wave heights were overestimated by the model due to its inherent problem of C_d when wind speed is greater than 30m/s. Thus its wave growth term was corrected to produce more realistic extreme wave heights measured at three stations.

It was found that the extreme waves at IORS were evolved by combination of distant large swell and strong wind seas generated by consistent strong winds from front right quadrant in relation to Bolaven track toward NNW for such a long time. The variation of those waves was relatively small as 1-2m, which might be due to limitation of wave growth for $U > 30\text{m/s}$ and bottom energy dissipation of long period waves in considerably shallow water region. If TY tracked toward Jeju Island greater extreme waves could be generated in SKW.

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