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Estimation of Design Wave Height for the Waters around the Korean Peninsula

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Abstract – Long term wave climate of both extreme wave and operational wave height is essential for planning and designing coastal structures. Since the field wave data for the waters around Korean peninsula is not enough to provide reliable wave statistics, the wave climate information has been generated by means of long-term wave hindcasting using available meteorological data. Basic data base of hindcasted wave parameters such as significant wave height, peak period and direction has been established continuously for the period of 25 years starting from 1979 and for major 106 typhoons for the past 53 years since 1951 for each grid point of the North East Asia Regional Seas with grid size of 18 km. Wind field re-analyzed by European Center for Midrange Weather Forecasts (ECMWF) was used for the simulation of waves for the extra-tropical storms, while wind field calculated by typhoon wind model with typhoon parameters carefully analyzed using most of the available data was used for the simulation of typhoon waves. Design wave heights for the return period of 10, 20, 30, 50 and 100 years for 16 directions at each grid point have been estimated by means of extreme wave analysis using the wave simulation data. As in conventional methodsi of design criteria estimation, it is assumed that the climate is stationary and the statistics and extreme analysis using the long-term hindcasting data are used in the statistical prediction for the future. The method of extreme statistical analysis in handling the extreme events like typhoon Maemi in 2003 was evaluated for more stable results of design wave height estimation for the return periods of 30-50 years for the cost effective construction of coastal structures.

Key words – wave simulation, wave climate, design wave height, coastal structure

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1. Introduction

Accurate extreme and operational wave climate data are essential for various applications of coastal and ocean engineering such as coastal and marine planning, designing, management and operations. Design wave height is the basis for the safe and cost effective design of coastal and offshore structures. Since space and temporal coverage of wave measurement is limited for producing reliable long-term wave climates for all the area of the North East Asia Regional Seas, long-term wave climate is obtained by means long-term wave hindcasting using available meteorological data.

Design wave height had been estimated by sponsored projects of many agencies in Korea to support the port and harbor construction along the coast of Korea: Ministry of Construction (1971), Fisheries Administration (1974) and Agriculture Development Agency (1984, 1987). Systematic estimation of design wave height in Korea had been achieved by Korea Ocean Research and Development Institute (KORDI) in 1988 for 23 grid points with grid size of 54 km along the south and east coast of Korea following the request of Fisheries Administration (1988). The design wave height estimated by KORDI in 1988 has been used until recently for most of the coastal engineering works in Korea as the offshore boundary conditions of the shallow water wave models for the estimation of local shallow water design wave height. There has been a big demand by both government and industry for a revision of the design wave height through accurate long-term wave simulation using updated wave models and wind input and by making most of the field wave measurement data. The grid size needs to be more precise and design wave heights for many different wave directions are needed for many engineering applications.

In the past, one of the difficulties in long-term wave simulation was the specification of the proper wind fields required as an input of wave model. In early study of wave climate in Korea, wind field was estimated based on information from pressure field of surface weather maps. Synoptic weather maps published by Japanese Weather Association have been digitized together with surface air temperature field and 10 day mean water temperature for the period of 18 years from 1978 to produce input wind needed for wave simulation. Recently re-analyzed weather data is available to be used for wave simulation conveniently. One of these, and of the longest length is NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research); another is ECMWF (European Midrange Weather Forecasts) wind data. Many researchers conducted wave hindcasting using these re-analyzed wind data (Günther *et al.* (1998), Sterl *et al.* (1998), Hatada *et al.* (1998), Cox *et al.* (2001), Hatada *et al.* (2005)).

The Wave Measuring System in Korea had been established following the detailed design of the wave monitoring and prediction system proposed by Lee *et al.* (1986) based on the concept that long term wave statistics can be indirectly obtained by means of wave hindcasting by using up-to-date wave models and utilizing the wave data measured from a limited number of wave stations. The main objective of the system is the reliable estimation of long term wave climate for coastal waters of Korea. The first systematic production of the wave climate has been produced through the continuous simulation of the waves for 10 years from 1986, by using HYPA (HYbrid PArametrical wave prediction) Model (Hasselmann *et al.* 1976; Gunter *et al.* 1979) for the seas around the Korean peninsula with grid size of 1/4 degree (27 km). Wave climate had been synthesized and provided through an internet website (Jun *et al.* 2003). It has been updated to be able to produce continuous wave hindcast for 25 years from 1979 and wave hindcast for extreme cases of typhoon for 53 years since 1951, with grid size of 18 km. Through the extreme statistical analysis of the long-term wave hindcasting data, the design wave height have been estimated for the waters around the Korean peninsula to be used in the design of coastal and offshore structures.

There are many procedures in producing design waves such as typhoon analysis, long-term wind simulation, wave simulation and validation, statistical analysis of the hindcasting data and so on, which will be introduced elsewhere in detail. In this paper, the main procedures and results of design wave height estimation are shown and discussed.

2. Simulation of long-term waves for the waters around Korean peninsula

The bathymetry and grid system of the hindcasting model are shown in Fig. 1 and Fig. 2. The grid size is 1/6 degree (about 18 km) both in longitude and latitude direction and integration time is 20 minutes. Two different sets of long-term time series of wave for each grid point have been prepared: one with continuous wave simulation

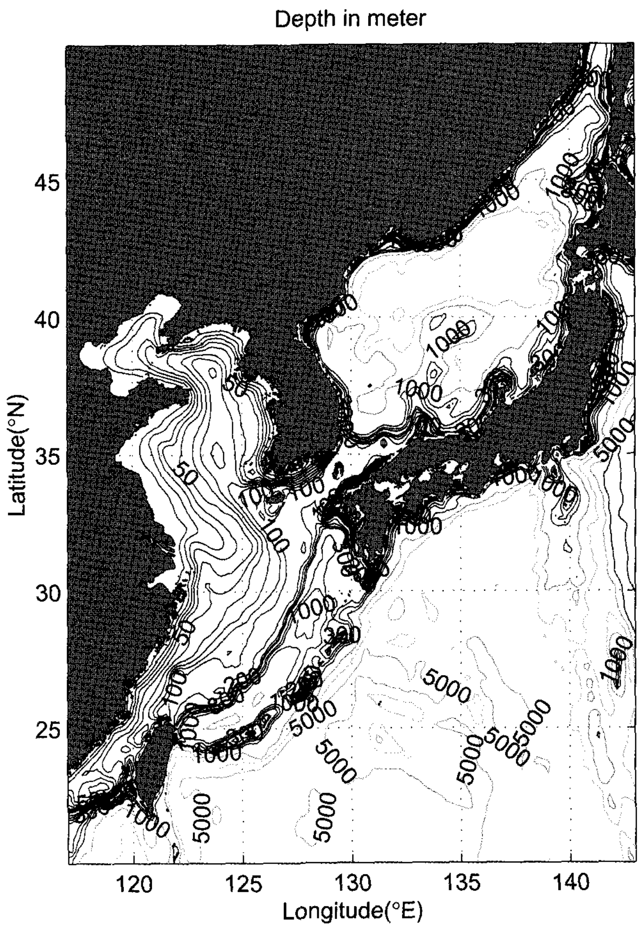

Fig. 1. Bathymetry of the wave model area.

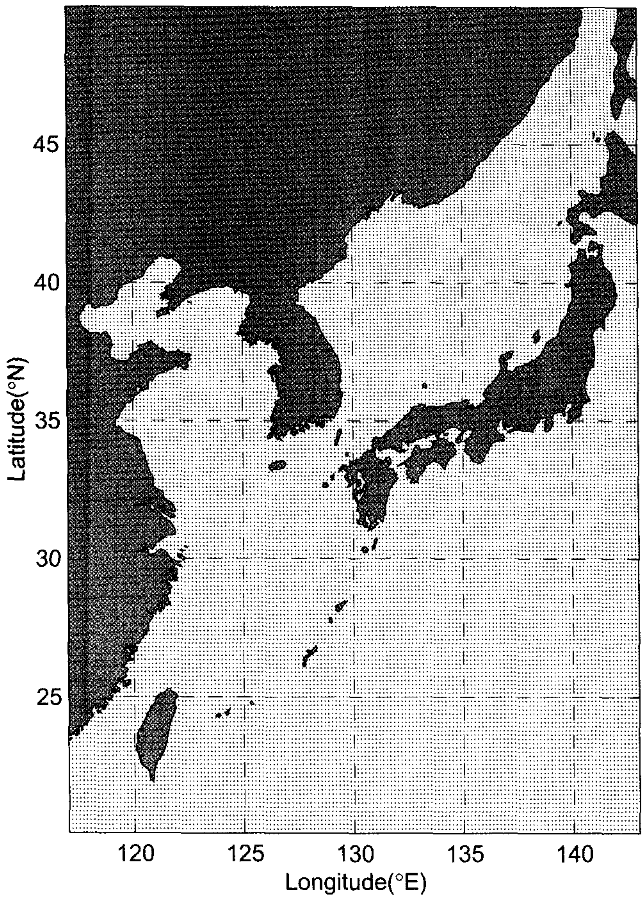

Fig. 2. Grid system for long-term wave simulation.

since 1979 and the other with wave simulation during the passage of severe typhoons since 1951.

High-quality wind fields are essential for the production of reliable wave hindcast. Errors in wind field produce corresponding errors in the computing wave field. It is well known that in most areas around Korea, strong winds are associated with two types of weather systems: one is strong winds caused by extra-tropical storms and the other is strong winds caused by tropical storms, or typhoons. The design waves are mostly determined by these two cases. The wind field used in the continuous wave simulation is the re-analyzed wind data conducted by European Midrange Weather Forecasts (ECMWF), which is interpolated to the grid points and time steps of the wave simulation model. Fourier transformation method was used in interpolation of the wind field for each time step of the wave model.

However, the advent of typhoon in this region is not so frequent, so continuous wave simulation for even as long as 25 years is not long enough for extreme value analysis to provide stable results for typhoon induced design waves. Winds induced by typhoons vary rapidly in space and time during the passage of the typhoon; which can not be properly modeled by large scale weather analysis program. So, the ECMWF re-analyzed wind data can not properly cover the space and time variation of typhoon winds. Considering these two characteristics, the simulation of the waves for typhoon has been separately carried out by using typhoon winds calculated by typhoon wind model for the 106 significant typhoons which affected Korea since 1951. Typhoon parameters needed for the typhoon wind model were analyzed using most of the available data in this region, such as observed surface air pressure, satellite remote sensing data, etc. That typhoon wind model solves, by numerical integration, the vertically averaged equations of motion that govern a boundary layer subject to horizontal and vertical shear stresses. The equations are resolved in a Cartesian coordinate system whose origin translates at constant velocity with the storm center of the pressure field associated with the cyclone. Thompson *et al.* (1996) and Cox *et al.* (2000) give detailed descriptions of the typhoon wind model used in this work.

Different types of wave model such as SMB, DSA-5, HYPA, WAM etc. have been tested and compared with wave data obtained from wave monitoring stations. For the regional seas around Korea, the hybrid parametric model (Hasselmann *et al.* 1979; Gunter *et al.* 1979) provided good results together with a third generation wave model WAM (WAMDI Group, 1988). The third generation wave model (WAM) avoids the use of the parameterizations and empirical results as much as possible and has been proved to give reliable results under a vast range of applications provided that the input wind source is of high quality (WAMDI Group 1988). The second generation wave model (HYPA) is considered to be economical since it can provide useful results for most of the cases with certain classes of wind fields with an accuracy comparable to third generation wave models, and it requires much shorter computer time compared to the third generation model. The second generation wave model, HYPA has been used in the continuous wave synthesis for the normal condition, while the third generation wave model, WAM has been used in the wave simulation for the extreme storm condition.

Continuous wave simulation had been carried out for 25 years since 1979, by using HYPA and WAM Models. The time series of wind wave data obtained from the continuous wave simulation are archived as a basic data base. The integration parameters such as significant wave height, period and direction have been recorded at all computation grid points, while the detailed wave spectral parameters have been recorded at 209 grid points along the coast of Korea and other major points. A versatile and interactive data base of hindcast wave data was built to handle large quantities of wave information and to provide comprehensive information on the long-term wave climate in the region. The field wave measurement and satellite remote sensing wave measurement are used for the evaluation of the wave climate synthesis.

3. Estimation of design wave height for the waters around Korean Peninsula

The design criteria can be estimated by means of extreme value analysis with the long-term data based on the assumption that the climate is stationary for a relatively short period of time compared to geological time scale. From a meteorological aspect, the area is affected by two distinct types of storm: typhoon and extra-tropical storm. Design wave height has been estimated by means of extreme wave analysis using the two types of long-term hindcasting data: continuous wave simulation for 25 years for extra-tropical storms and 53 years typhoon wave hindcasting. Since the extra-tropical storm and typhoon have different characteristics, the occurrences of these two different weather systems are considered independent of each other. Hence, the extreme value analysis is made independently. The design wave heights were calculated independently for both the extra tropical storm case and the tropical storm. The final value of design wave height for each grid point is determined by choosing the larger value wave height out of these two independent estimates.

The estimation of the return value can be achieved by the cumulative frequency distribution, the annual maxima or the peaks-over-threshold (POT) from a substantial data set. The design wave height can be estimated by means of fitting distribution function, such as the Gumbel distribution or the Weibull distribution, to the observed events and then extrapolating to estimate the required return values. The extreme value analysis with different distribution function were carried out and discussed by Jeong *et al.*(2004) with the earlier version of KORDI's simulation data where wave data for typhoon cases simulated with ECMWF wind, and also by Yamaguchi *et al.* (2005) with wave simulation data for the Northwestern Pacific Ocean. In the analysis with the wave data simulated with much accurate typhoon wind field the best fit distribution was not clearly decided; this depends on the weather system and location. In this study, Weibull the distribution that has been widely used in the estimation of design wave height in the past was used. For estimation of the design wave height, different methods of extreme wave analysis such as the Method of least square, Conventional method of moments, Method of probability weighted moments can be used. The difference between the analysis methods was found to be not so critical. A simple method of the least square was used for the estimation of parameters in the extreme analysis in this study (KORDI 2005).

In the case of annual maxima analyses, the sample data set is limited, while the peaks-over-threshold (POT) based analyses deals with sample with varying intervals. The extra-tropical storms occur rather regularly compared to typhoons. Hence, the extreme statistical analysis has been carried out using different number of extreme values for each year. The value estimated by choosing just annual maxima (1 per year) showed to be rather unstable compared to the values estimated using more numbers per year. In this analysis the values estimated by choosing two extremes per year are used. Through POT analyses, the extreme event value for each year varies quite a lot from year to year for typhoon cases. After test with different values of POT, the design wave height was calculated by choosing the value of POT to produce an average two typhoons per year, that is, total 106 typhoons for 53 years. The design value is selected by choosing the bigger value out of these two estimates of different weather systems. The grid points from which the design wave heights have been analyzed are shown in Fig. 3, where 106 points along the coast are marked with numbers for more detailed demonstration.

The method of extreme statistical analysis for considering the extreme event like typhoon Maemi in 2003 was evaluated for more stable results of design wave height estimation for the return periods of 30-50 years, which is commonly used in designing coastal structures. The

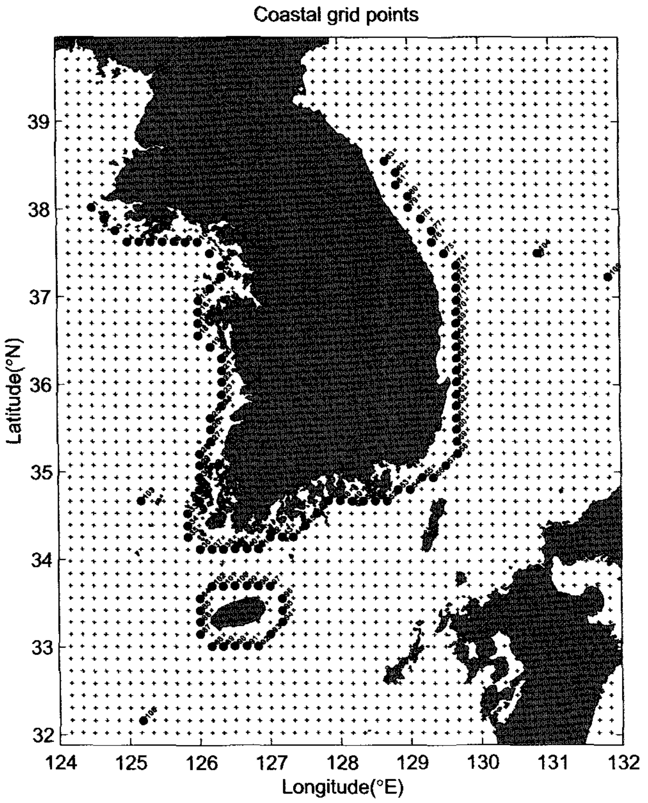

Fig. 3. Grid points for design wave height estimation.

inclusion of typhoon Maemi, which occurred in 2003, caused an abrupt increase of design wave height along the typhoon track. The 50 years return period design wave heights, as results of extreme analysis with and without inclusion of typhoon Maemi, are compared in Fig. 4 along the coastal grid points marked in Fig. 3. The design wave height estimated with inclusion of 2003's event is much higher along the south-eastern coast of Korea.

The abrupt increase of design wave height may cause many problems since it would require a considerable amount of budget for proper coastal hazard reduction measures based on such increased design wave height. Design wave height estimation excluding wave data induced by typhoon Maemi in 2003 is shown in Fig. 5 for a given grid point as an example. The maximum wave height during typhoon Maemi, marked □ in the figure is shown to be equivalent to design wave height for the return period of 120 years in this example. Equivalent return period of the typhoon Maemi induced wave heights along the grid points estimated from the extreme statistical analysis excluding wave data during typhoon Maemi in 2003 is shown in Fig. 6. The wave height for typhoon Maemi is shown to be equivalent to the design wave height for return period of more than 100 years for many grid points in the eastern part of the South Sea of Korea.

For more stable results of design wave height estimation for the return period of 30-50 years, the extreme statistical analysis is made using the simulation data up to year of 2002 to exclude the severe wave induced by typhoon Maemi in 2003. The design wave height for different return periods of 10, 20, 30, 50 and 100 years for each wave direction has been calculated. The users

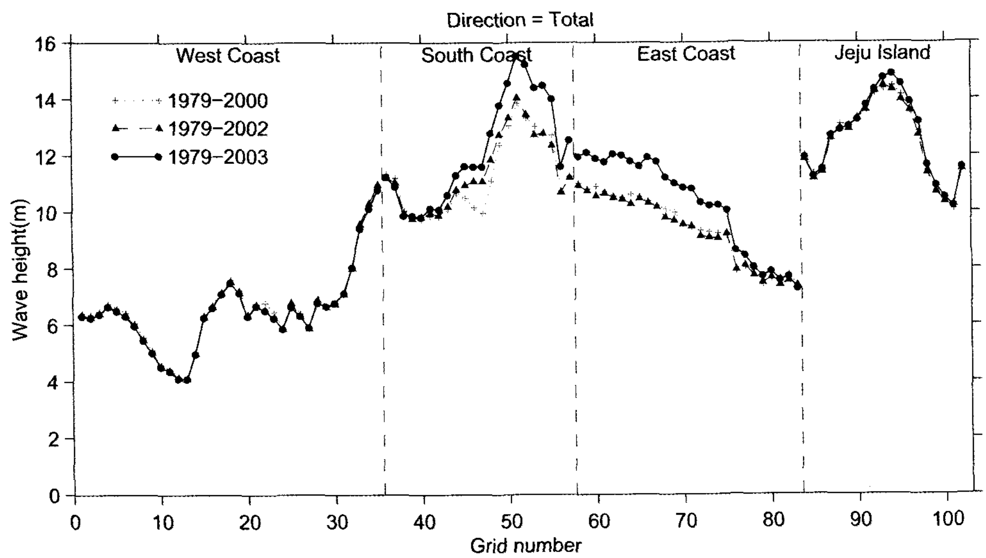

Fig. 4. Comparison of design wave height for return period of 50 years along the coastal grid points estimated for different period of hindcasting duration.

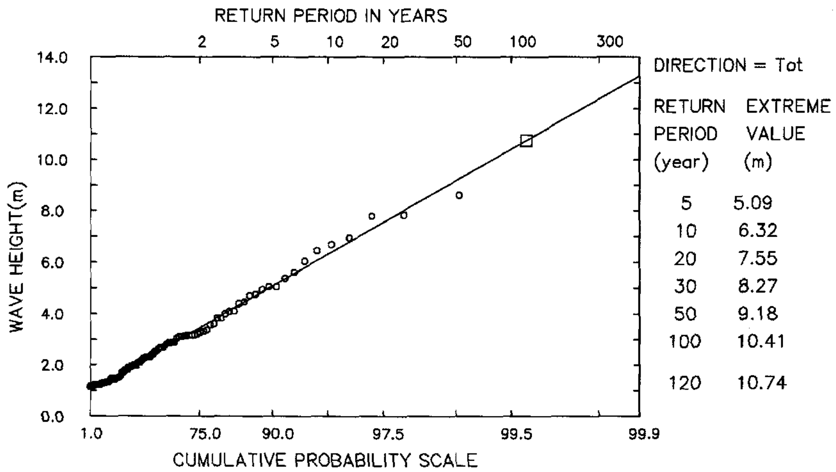

Fig. 5. Design wave height estimation excluding wave data during typhoon Maemi in 2003. (The maximum wave height during typhoon Maemi, marked □ in the figure, is shown to be equivalent to design wave height for return period of 120 years).

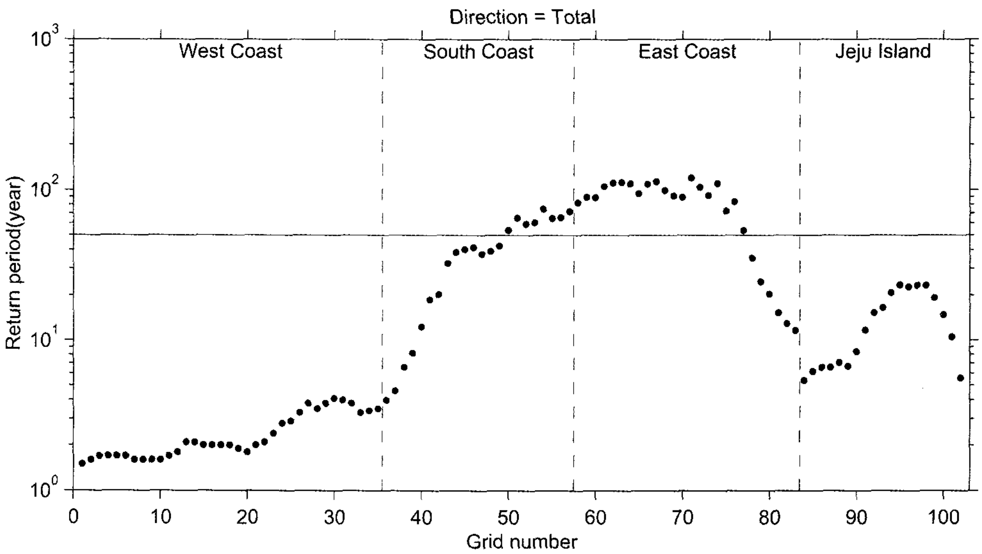

Fig. 6. Equivalent return period of the typhoon Maemi along the grid points estimated from the extreme statistical analysis excluding wave data during typhoon Maemi in 2003.

can retrieve the design wave information simply by inputting the location of interest either by grid number or by longitude and latitude from the data base. Examples of the space distribution of design wave height for a given return period and wave direction are shown in Fig. 7 and Fig. 8. The results of design wave analysis for the 106 points along the coast of Korea for the return period of 50 years are listed in Table 1.

4. Conclusion and Discussion

Wave hindcasting has been carried out for the waters around the Korean peninsula to produce a basic data base of time series of waves, with 1 hour interval, continuously for the period of 25 years and for major typhoons during 53 years for each grid point of North East Asia Regional Seas, with grid size of 18 km. Design wave height for each return period and direction at each grid point has been estimated by means of extreme wave analysis using the wave simulation data.

Verification of the simulated waves was done by using directional wave data measured by the wave monitoring system of Korea. Considering the safety of the buoy, the locations of some buoys are close to the land or to

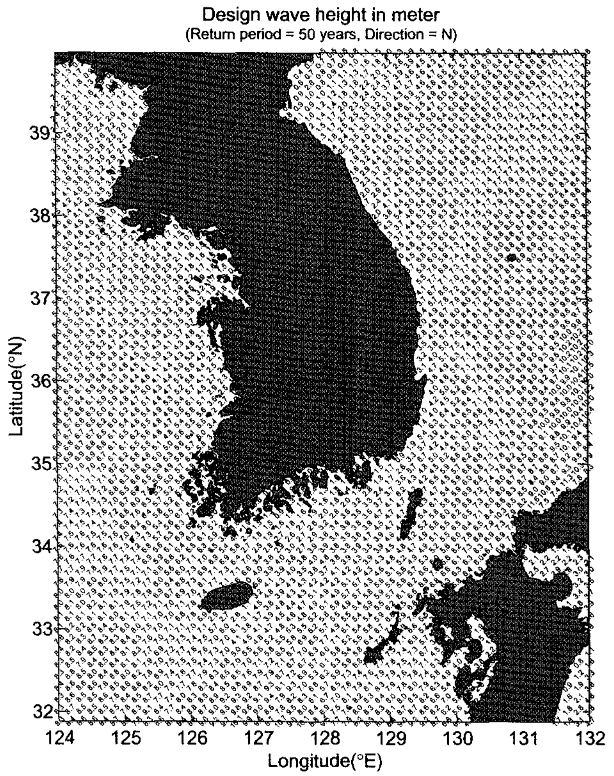

Fig. 7. Example of design wave height in meter for given return period and wave direction (in digital value).

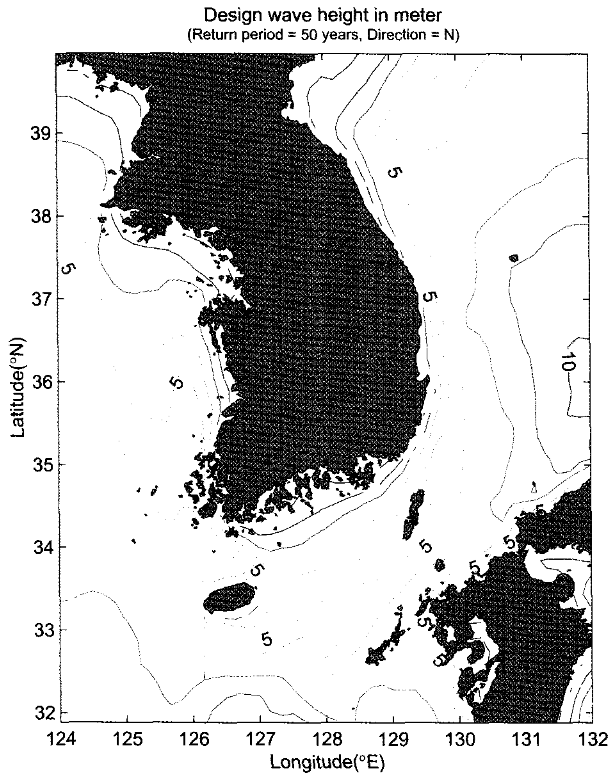

Fig. 8. Example of design wave height in meter for given return period and wave direction (in contour graphic).

islands, so that the wave observations are affected by local phenomena which can not be covered properly by regional scale wave simulation models. More intensive validation is needed by using all the available satellite remote sensing data for the offshore area of the region for more reliable estimate of the design wave height. The design wave height depends on the method of statistical analysis of the wave simulation data such as selection of sampling interval, extreme value, distribution function and inclusion and exclusion of highest value, etc. More intensive studies on the method of extreme statistical analysis are necessary to produce more reliable estimate of design wave height.

The assumption of stationary state used in the analysis of design wave height in this study may not be valid in the future due to the impact of global climate change. However, it is difficult to include the impact of global climate change at present because our knowledge on that is still poor. It is unlikely to secure tremendously large amount of budget to build coastal structures based on information with lots of uncertainty. New methods of estimation of design wave height need to be developed to cope with the impact of global climate change in the future. Research on the change of typhoon intensity related to the global climate change is essential to reduce the uncertainty in design wave height estimation to be used for practical applications.

The methods of extreme statistical analysis for considering extreme events like typhoon Maemi in 2003 were evaluated for cost effective construction of coastal structures. Coastal structures like breakwaters are different from offshore structures like oil platforms in the sense that the damage is mostly partial and can be recovered later, and that there is normally no life casualty. For more stable and cost effective design of coastal structures, it is suggested to use the design wave heights of the return period of 30 years or 50 years, analyzed with data excluding the extreme case of typhoon Maemi, which is considered to be equivalent to the value for the return period more than 100 years for the south eastern area of Korea. Because of the lack of information and technology to analyze the data, this can be tentatively used for the design of coastal structures like breakwaters along the coast of Korea for a certain period until more information can be obtained in the future. Intensive research on this is necessary for more reliable and cost effective construction of coastal facilities in the future.

Table 1. Design wave height in meter for return period of 50 years along the coastal grid points

No	Grid Point	Lat. (deg)	Lon. (deg)	Direction															
				N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
1	046101	38.02	124.50	4.33	2.49	2.49	3.55	3.38	4.92	5.85	6.20	6.29	4.78	4.81	3.63	4.66	4.94	4.81	5.03
2	047102	37.89	124.67	3.31	2.46	2.33	2.44	3.94	4.98	6.05	6.28	6.46	5.07	4.83	3.79	4.75	5.16	5.02	3.37
3	048103	37.76	124.83	2.26	2.50	2.65	2.51	3.91	5.17	6.15	6.12	6.79	5.03	4.62	3.96	4.60	5.36	5.15	2.74
4	049104	37.63	125.00	2.40	2.74	2.77	2.82	4.01	5.16	6.19	6.30	6.30	5.90	4.92	4.33	4.97	5.41	5.34	2.19
5	050104	37.63	125.17	2.37	2.65	2.75	2.75	3.68	4.92	5.72	6.41	6.19	6.22	5.13	4.30	5.45	5.25	3.18	2.16
6	051104	37.63	125.33	2.22	2.42	2.71	2.65	3.43	4.24	5.49	5.92	6.30	6.06	5.04	4.24	4.21	2.57	1.70	1.64
7	052104	37.63	125.50	2.13	2.27	2.63	2.57	3.11	3.93	4.96	5.86	6.13	6.33	5.20	4.10	3.99	2.44	2.15	1.99
8	053104	37.63	125.67	2.00	2.43	2.48	2.42	2.57	3.66	4.49	5.42	5.99	6.00	5.23	4.13	3.99	2.23	2.13	1.64
9	054104	37.63	125.83	1.79	1.94	2.32	2.26	2.43	3.40	4.19	4.76	5.56	5.27	5.09	4.14	3.87	2.16	1.82	1.72
10	055104	37.63	126.00	1.64	1.79	1.99	2.17	2.26	3.45	4.16	3.65	5.05	5.00	4.97	3.80	3.82	2.09	1.74	1.51
11	056105	37.50	126.17	1.64	1.80	2.06	2.24	2.21	2.99	3.48	4.00	4.85	5.09	4.94	3.69	3.68	2.57	2.29	2.00
12	057106	37.36	126.33	1.62	1.66	1.87	2.16	2.16	2.72	3.02	3.27	4.24	4.74	4.89	4.11	4.05	3.26	2.48	1.76
13	057107	37.23	126.33	1.74	1.77	1.91	2.18	2.26	2.62	3.00	3.41	3.27	4.32	4.81	4.31	4.22	4.21	3.76	2.25
14	056108	37.10	126.17	3.17	2.06	2.45	2.65	2.49	3.04	3.56	4.19	3.76	4.86	5.30	4.62	4.63	4.39	4.39	4.68
15	055109	36.96	126.00	4.58	2.55	2.97	3.14	3.03	3.62	4.27	5.14	5.83	6.58	6.21	4.82	4.74	5.10	4.71	4.68
16	055110	36.83	126.00	3.78	2.63	2.99	3.07	2.89	3.33	4.16	4.67	5.68	7.10	6.37	4.64	4.56	6.02	5.97	3.91
17	055111	36.70	126.00	3.71	2.66	2.81	3.37	3.04	3.52	4.37	5.45	6.42	7.32	5.65	4.67	4.74	5.88	5.70	4.18
18	055112	36.56	126.00	4.62	2.81	2.92	3.53	3.64	3.93	4.88	5.67	6.98	7.41	5.60	4.75	4.86	6.31	5.87	4.70
19	056113	36.43	126.17	3.69	2.57	2.53	2.77	3.34	3.50	3.89	5.08	6.05	6.98	7.00	4.45	4.92	6.09	5.14	4.58
20	057114	36.30	126.33	2.27	2.07	2.15	2.22	2.65	2.88	3.04	3.59	4.58	5.80	6.00	4.22	4.75	5.50	5.05	3.32
21	057115	36.16	126.33	2.53	2.35	2.39	2.56	2.79	3.02	3.36	3.91	4.71	5.74	6.39	4.77	4.96	5.57	5.05	3.98
22	057116	36.03	126.33	2.71	2.55	2.50	2.75	3.18	3.34	3.67	4.19	4.78	5.65	6.35	4.62	4.91	5.74	5.58	3.78
23	057117	35.89	126.33	2.89	2.77	2.51	2.70	3.30	3.62	3.52	3.99	4.62	5.72	5.95	4.64	5.00	5.88	5.47	3.60
24	057118	35.76	126.33	3.58	2.91	2.52	2.41	3.31	3.34	3.84	3.95	4.42	4.97	5.44	4.83	5.34	6.21	5.68	5.02
25	056119	35.62	126.17	5.57	3.55	2.90	3.19	4.20	4.64	4.54	5.06	5.56	6.12	6.35	4.66	5.44	6.67	6.90	4.99
26	056120	35.49	126.17	5.50	3.46	2.98	3.13	3.65	4.48	4.90	4.84	5.30	5.84	5.70	4.61	5.56	6.91	7.00	5.16
27	056121	35.35	126.17	5.96	3.47	2.98	2.91	3.34	3.91	4.64	5.13	5.06	5.14	5.31	4.65	5.62	6.95	7.11	5.40
28	055122	35.21	126.00	5.69	4.62	3.54	3.77	4.42	5.08	6.14	5.62	5.96	6.11	5.94	5.63	6.35	6.92	7.43	6.06
29	055123	35.08	126.00	6.21	3.89	3.49	3.77	4.11	4.91	5.57	6.20	5.86	5.97	5.66	5.17	6.18	6.97	7.54	6.33
30	055124	34.94	126.00	5.79	3.84	3.57	3.76	4.35	4.83	5.63	5.81	6.49	6.27	5.71	5.22	6.40	7.02	7.69	7.00
31	055125	34.80	126.00	5.90	4.11	3.71	3.89	4.22	4.92	5.25	6.22	6.80	7.06	5.87	5.34	6.81	6.97	7.77	7.33
32	055126	34.67	126.00	6.28	4.24	4.31	4.22	4.56	4.89	5.76	6.98	7.92	7.97	5.39	5.08	6.55	7.06	7.94	6.27
33	054127	34.53	125.83	6.13	5.22	5.39	5.35	5.91	6.14	7.66	9.55	9.42	7.66	4.99	4.76	7.05	7.17	8.04	7.47
34	054128	34.39	125.83	6.67	5.79	5.83	5.88	6.68	7.01	8.71	10.39	10.25	7.38	5.26	4.24	6.74	7.07	8.12	7.46
35	054129	34.26	125.83	6.27	6.37	6.26	6.20	7.17	7.95	9.95	11.24	10.59	8.01	5.35	4.65	6.89	7.11	8.15	7.78
36	055130	34.12	126.00	6.35	6.69	6.95	7.14	7.73	8.99	9.73	11.45	10.89	8.68	6.04	4.47	6.67	7.25	8.23	6.49
37	056130	34.12	126.17	6.06	6.42	7.11	6.94	7.26	9.11	9.90	10.57	10.85	9.28	6.33	5.33	5.81	8.13	8.01	5.18
38	057130	34.12	126.33	5.91	4.45	6.89	6.91	7.14	8.75	9.88	9.29	9.40	8.97	6.38	4.90	5.82	4.75	4.69	5.22
39	058130	34.12	126.50	3.53	3.37	3.81	5.73	7.16	8.96	9.57	8.91	8.67	8.45	5.65	5.16	4.67	4.66	5.20	2.23
40	059130	34.12	126.67	4.65	3.64	3.46	4.85	7.56	9.14	9.82	8.58	8.20	7.78	5.62	5.21	5.26	4.93	3.25	3.43
41	060130	34.12	126.83	2.26	3.63	4.04	5.19	7.67	9.44	9.51	8.79	7.45	7.42	5.75	5.39	4.78	3.79	2.13	2.17
42	061129	34.26	127.00	1.53	2.15	3.58	3.94	5.12	6.68	8.62	9.61	8.57	7.02	4.67	4.86	3.78	2.03	1.98	1.67
43	062129	34.26	127.17	1.50	2.18	3.41	3.83	5.29	7.16	9.24	9.77	8.04	6.65	4.00	4.33	3.12	2.73	1.87	1.87
44	063129	34.26	127.33	1.55	2.27	3.54	4.35	5.05	8.31	9.85	10.20	7.67	6.56	4.30	4.20	3.30	2.48	2.32	1.77
45	064128	34.39	127.50	1.41	2.04	2.78	3.60	4.66	6.98	10.20	9.93	7.10	5.36	3.82	4.84	2.53	1.08	1.12	0.99
46	065127	34.53	127.67	1.24	1.65	2.02	3.08	4.31	7.61	10.46	10.18	6.30	3.89	3.88	2.25	1.71	1.57	1.57	1.12
47	066126	34.67	127.83	1.36	1.42	2.10	2.98	4.25	9.12	11.09	10.28	5.46	3.40	2.85	2.32	1.57	0.95	0.89	0.80
48	067126	34.67	128.00	1.30	1.53	1.92	3.35	4.64	9.06	11.84	10.81	6.16	4.22	3.73	2.34	1.68	1.50	1.47	1.16
49	068126	34.67	128.17	1.34	1.63	2.82	4.11	4.99	8.61	11.39	12.40	9.38	5.25	4.15	3.02	2.37	2.08	2.03	1.38
50	069126	34.67	128.33	1.39	1.43	3.10	4.34	5.06	9.31	12.16	13.44	10.96	5.88	4.40	4.84	2.67	1.68	1.48	1.34
51	070126	34.67	128.50	1.27	1.03	3.63	4.47	5.09	10.44	12.31	14.17	11.11	6.27	4.48	4.10	3.06	1.67	1.49	1.26
52	071126	34.67	128.67	2.77	2.96	4.28	4.81	8.64	10.49	11.20	13.62	10.46	6.86	4.39	4.56	2.93	3.74	2.81	2.90
53	072125	34.80	128.83	1.85	2.02	4.35	5.45	8.54	10.40	12.02	12.47	9.63	6.12	3.40	1.65	1.36	1.59	1.36	1.22

(**Table 1.** Continue)

No	Grid Point	Lat. (deg)	Lon. (deg)	Direction															
				N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
54	073125	34.80	129.00	1.74	3.67	5.27	5.27	9.16	10.48	11.91	12.39	11.37	7.52	4.67	1.80	1.55	1.64	1.61	1.69
55	074124	34.94	129.17	2.59	3.27	5.88	5.77	8.39	10.56	11.21	12.25	9.91	7.02	4.11	3.27	2.06	2.08	2.74	2.66
56	075124	34.94	129.33	5.74	6.39	6.70	6.59	8.61	9.86	10.37	9.99	8.06	6.58	6.16	5.18	2.90	3.24	2.93	2.73
57	076123	35.08	129.50	6.71	6.55	6.94	6.48	8.04	10.18	10.21	10.76	9.28	6.51	5.60	3.69	2.83	3.21	3.39	3.21
58	077122	35.21	129.67	4.23	5.95	7.13	6.60	7.73	10.10	10.44	10.47	9.54	6.26	5.09	3.77	3.27	3.37	3.22	3.18
59	077121	35.35	129.67	3.91	5.67	6.87	6.61	7.94	9.96	9.50	10.37	8.39	6.21	4.32	2.95	3.31	3.83	3.45	3.68
60	077120	35.49	129.67	6.33	6.38	6.79	6.56	8.11	10.25	9.93	9.08	7.60	6.12	3.46	2.75	3.42	3.42	2.91	3.11
61	077119	35.62	129.67	4.04	6.31	6.49	6.37	8.60	9.76	9.55	8.45	7.86	5.50	2.66	2.72	2.56	1.86	2.41	2.62
62	077118	35.76	129.67	4.20	6.23	6.54	6.56	8.59	9.34	9.50	8.08	7.66	5.22	2.27	1.26	1.47	1.63	1.45	1.96
63	077117	35.89	129.67	4.03	6.19	6.58	7.59	9.19	9.26	8.12	8.23	7.54	4.70	2.26	1.50	1.23	1.57	1.63	1.48
64	077116	36.03	129.67	3.84	6.06	6.64	7.48	9.00	8.95	8.07	8.19	7.39	4.77	2.08	1.77	1.55	1.30	0.88	1.85
65	077115	36.16	129.67	4.70	6.10	6.54	8.65	9.20	8.93	7.92	8.29	7.35	5.06	2.25	0.91	1.62	1.90	1.65	1.77
66	077114	36.30	129.67	3.98	6.29	6.44	8.28	9.01	8.58	7.68	8.29	7.38	4.69	2.17	1.73	1.63	1.92	1.78	2.03
67	077113	36.43	129.67	3.84	6.03	6.24	8.37	8.66	6.42	7.94	8.18	7.33	4.91	2.17	1.72	1.71	1.86	1.91	1.74
68	077112	36.56	129.67	4.29	6.01	6.06	8.00	8.44	6.01	7.77	8.26	7.19	4.31	2.22	1.78	2.39	2.08	1.93	1.83
69	077111	36.70	129.67	4.92	6.05	6.47	7.83	8.18	6.08	7.57	8.42	7.29	3.93	2.39	1.89	1.75	2.00	1.90	1.84
70	077110	36.83	129.67	4.88	6.16	6.43	7.65	7.83	6.07	7.86	8.44	7.31	3.81	2.45	1.95	1.83	1.98	2.01	1.99
71	077109	36.96	129.67	5.73	6.20	7.01	7.19	7.58	5.77	7.92	8.43	7.08	3.72	2.37	1.93	1.90	2.07	2.14	2.06
72	077108	37.10	129.67	6.65	7.29	6.67	8.34	7.22	5.35	7.40	8.47	7.35	3.90	2.51	1.99	2.01	2.18	2.28	2.35
73	077107	37.23	129.67	7.70	6.95	6.36	8.41	6.94	5.87	7.86	8.47	7.68	4.06	2.81	2.12	2.06	2.06	3.75	4.11
74	077106	37.36	129.67	7.60	6.95	6.32	8.01	6.98	5.56	7.91	8.68	7.05	4.01	3.00	2.41	2.28	2.45	3.06	3.82
75	076105	37.50	129.50	6.62	7.63	6.25	7.28	7.10	5.83	8.20	9.26	6.62	3.43	2.92	2.35	2.22	2.26	2.74	3.46
76	075104	37.63	129.33	4.83	6.96	6.33	6.65	6.44	6.68	7.67	5.49	3.56	2.80	2.43	2.36	2.04	2.12	2.73	3.10
77	075103	37.76	129.33	4.72	6.18	6.08	6.27	6.27	6.63	7.88	6.81	4.11	3.06	2.91	2.63	2.45	2.35	3.23	3.76
78	074102	37.89	129.17	3.68	5.78	6.27	5.66	5.77	6.91	7.20	6.18	3.72	3.07	2.85	2.48	2.19	2.38	2.99	3.35
79	073101	38.02	129.00	3.75	5.12	6.33	5.56	5.53	7.01	6.84	4.84	3.05	2.89	2.59	2.38	1.92	2.23	2.70	2.53
80	073100	38.15	129.00	4.08	5.45	5.79	4.90	5.43	6.99	7.31	6.12	3.76	3.27	2.91	1.62	2.09	2.48	3.14	3.30
81	072099	38.28	128.83	2.86	5.16	6.11	5.18	5.40	6.89	7.22	4.76	3.16	2.48	1.42	1.43	1.84	2.20	2.61	2.30
82	072098	38.42	128.83	3.12	5.10	5.97	4.94	5.22	7.48	7.15	5.30	3.41	2.59	1.47	1.58	2.08	2.48	2.75	2.82
83	071097	38.55	128.67	2.85	4.93	6.03	5.30	6.23	6.81	7.40	4.43	2.86	1.34	1.37	1.59	1.91	2.08	2.10	1.71
84	055134	33.56	126.00	7.35	7.93	9.67	9.23	10.05	9.55	10.08	11.18	11.72	9.82	7.09	4.81	5.67	7.30	8.39	6.60
85	055135	33.42	126.00	7.60	8.43	8.41	8.20	8.08	8.46	9.27	11.01	11.33	9.73	6.71	4.91	5.95	7.39	8.46	7.39
86	055136	33.29	126.00	7.81	8.76	8.89	8.43	7.98	8.36	10.01	11.17	10.94	9.22	6.46	5.00	6.44	7.41	8.54	7.53
87	055137	33.15	126.00	7.80	8.54	10.18	10.27	10.31	10.93	11.22	11.28	10.70	8.69	6.84	5.18	6.34	7.54	8.67	8.67
88	056138	33.01	126.17	7.15	9.23	10.48	10.36	10.98	11.67	11.53	11.21	10.72	8.77	6.60	5.80	5.88	7.51	8.62	6.19
89	057138	33.01	126.33	5.74	6.15	7.87	8.82	9.80	12.53	11.48	10.97	10.98	8.84	6.45	4.84	6.92	8.92	8.69	5.55
90	058138	33.01	126.50	5.97	4.98	6.75	9.29	9.88	12.94	12.01	10.59	10.64	8.20	6.46	5.09	5.58	4.62	4.83	5.43
91	059138	33.01	126.67	6.11	4.67	6.36	9.98	10.81	12.88	12.26	10.35	10.35	8.41	6.63	5.12	6.04	3.69	5.35	5.45
92	060138	33.01	126.83	3.80	5.20	7.32	11.24	12.17	12.79	12.16	11.03	10.09	8.47	6.79	6.00	6.38	4.01	4.07	3.63
93	061137	33.15	127.00	3.70	4.95	8.59	11.60	12.80	12.33	11.55	11.94	9.94	8.97	6.58	5.17	3.96	3.34	3.50	3.71
94	062136	33.29	127.17	3.77	5.09	8.23	12.00	12.99	12.74	12.58	11.77	9.59	8.54	5.78	3.65	3.70	3.12	3.58	3.61
95	062135	33.42	127.17	4.76	5.05	7.97	11.28	12.43	13.06	11.93	11.13	9.69	6.72	5.62	3.91	3.58	3.87	5.98	4.51
96	062134	33.56	127.17	4.13	5.62	7.17	10.88	12.16	12.61	10.97	11.05	9.53	6.71	5.25	6.39	4.79	6.53	7.78	5.53
97	061133	33.70	127.00	4.00	4.91	6.63	9.64	12.47	12.37	10.71	10.11	8.35	6.31	5.13	4.57	5.31	5.75	5.90	6.90
98	060133	33.70	126.83	6.62	7.10	7.24	10.72	11.28	10.07	8.48	7.09	5.25	5.28	5.12	4.95	5.17	5.66	5.12	5.95
99	059133	33.70	126.67	7.13	5.75	9.06	10.29	10.02	9.48	7.26	5.77	5.64	5.77	5.70	5.73	5.61	5.80	5.12	5.64
100	058133	33.70	126.50	7.29	7.61	9.06	9.69	9.67	8.73	6.62	5.99	5.51	6.34	6.24	4.80	5.85	8.35	8.46	5.91
101	057133	33.70	126.33	7.10	7.81	8.67	9.46	9.67	8.75	6.73	6.82	7.00	7.28	6.75	4.88	6.01	7.72	8.23	5.93
102	056133	33.70	126.17	6.90	7.71	8.67	8.98	9.75	9.26	10.01	10.21	10.97	9.79	6.75	4.85	6.57	7.61	8.36	6.12
103	050126	34.67	125.17	6.72	5.05	6.96	6.94	7.86	9.11	9.00	9.30	9.54	7.21	4.73	4.72	6.52	7.01	7.69	7.62
104	084105	37.50	130.83	9.06	8.58	6.57	7.06	9.97	9.92	7.82	6.85	6.86	6.89	4.51	4.32	7.53	6.05	6.51	7.05
105	090107	37.23	131.83	9.30	7.54	6.35	6.17	7.41	9.75	11.30	11.30	9.76	7.13	6.62	6.57	7.40	7.44	7.55	9.13
106	050144	32.16	125.17	8.53	7.65	9.54	10.74	10.55	10.40	11.34	10.29	9.47	7.97	6.82	5.36	6.00	7.65	8.46	9.09

The impact of the design wave height determination is great. If the value is under-estimated, this may result in failure of coastal and port facilities, which will cause lots of damage, while the over-estimated results will cost significant amount of budget. The estimation of the design wave height needs to be improved with more information available and needs to be updated reqularly. Intensive wave observation during the passage of severe typhoons is essential in upgrading the design wave height. Northeast Asia is one of the areas in the world with severe impacts of tropical cyclones. The design criteria of coastal and harbor facilities in the region are mostly determined by the typhoon induced waves. Regional cooperation among the neighboring countries of the region is necessary to cope with the common problem of coastal and harbor hazard with increase of typhoon intensity in the future.

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