Wave Propagation Modeling for Pusan New Harbor

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Abstract

For the basic design of Pusan New Harbor that will be the third largest container hub-port in the world, extensive wave measurements and wave propagation modeling were made. They are mainly for estimating shallow-water design wave height and determining breakwater alignment to acquire harbor tranquility. The directionality of short crested waves is proved to be very important when they propagate through the waterway. Bounded long-period waves with a small amplification were observed in the shallow water area, which might cause horizontal motions of the container ship moored at a berth aligned to the south. Modified and extended numerical wave models are found to be reasonably good at simulating the measured wave propagation phenomena. Hybrid modeling was made to evaluate harbor tranquility combining numerical and physical modeling results.

Introduction

With the rapid economic growth in the region of North-East Asia, Pusan New Harbor, which is located at the south-east end of the Korean Peninsula, is to be developed in order to cope with massive annual increase of trading goods (51 million tons in 1995). Then it will be the third largest container hub-port in the world and handle nine million TEUs per year (Ministry of Maritime and Fisheries, 1996). The proposed harbor site is located at the area of very shallow water of depth less than 5 m in which tidal flat is well developed due to the sediments from the Nakdong river as shown in Figure 1. The harbor basin and approaching channel are to be dredged up to 15 m below the chart datum.

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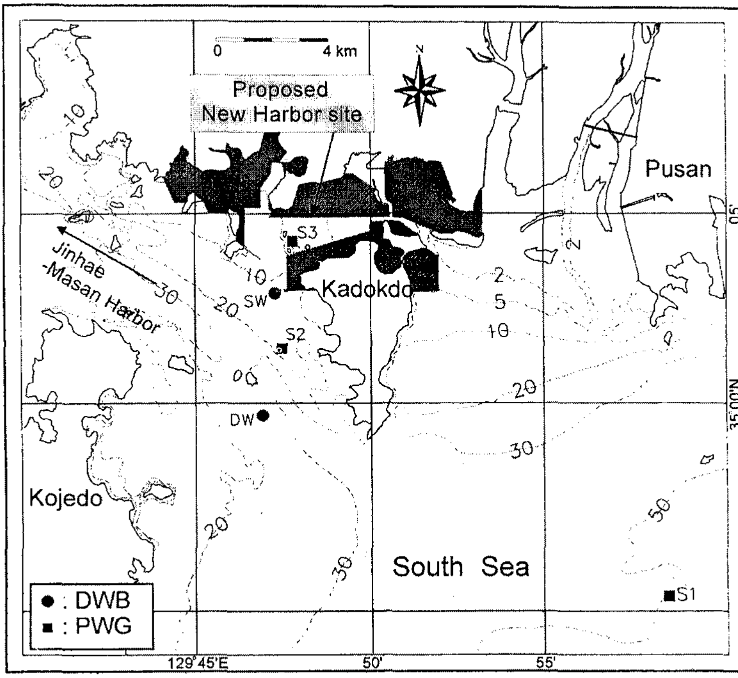

Figure 1. Measuring Stations around Pusan New Harbor.

Even though the site is sheltered from typhoon attacks in summer, both the waves coming from the south and long-period waves bounded in swell waves can penetrate into the harbor. The short-period waves might be strongly influenced by the complex bottom topography, reflections by the irregular coastal line and small islands, and tidal currents. Numerical modeling of the waves propagating through the waterway and penetrating into the harbor is essential for the determination of breakwater alignment which guarantees a harbor tranquility.

The concerned area is so large that it was divided into three regions for the numerical analysis. Short-period wave models were chosen to calculate effectively the irregular wave propagation because of their computational accuracy and efficiency. Hybrid modeling was done for the harbor tranquility analysis in combination with numerical and physical modeling results. The modified Chen's model (Jeong et al., 1996) was used for the long-period harbor oscillation. Extensive field measurements of short- and long-period waves were made in order to analyze wave propagation and statistical characteristics.

Field Measurement and Data Analysis

In order to analyze irregular wave propagations, the relationship between short- and long-period waves and harbor oscillations, extensive field measurements were carried out at five reference stations for three months as shown in Figure 1. Using two Datawell directional waverider buoys, short-period waves were measured at Sts. DW and SW for about 27 min. at every hour. Long-period waves were also measured simultaneously at Sts. S1～S3 for three months at the interval of 5 s.

Directional frequency spectra of the short-period waves were obtained using the maximum entropy method (Kobune and Hashimoto, 1986). After filtering low frequeney waves using the Butterworth high-pass filter, spectral analyses were made for each record of 16,384 data points (about 22.8 hours) using the standard FFT method. The spectrum was obtained by averaging over 64 raw harmonics.

Significant wave heights at St. SW were 40～60% of those at St. DW as shown in Figure 2. But the wave periods are almost the same each other at the two stations. Waves are narrow-banded at St. DW while waves are broad-banded and have non-negligible reflection components at St. SW. More details of the spectral changes can be seen in Figures 3～5. The frequency spectra have a very narrow-banded and single sharp peak, which is a typical shape of swell waves (see Figure 3). Even though swell waves, which have a narrow-banded spectrum, propagated through the waterway of about 8 km in the main direction (SSE), its significant wave height reduced half in average.

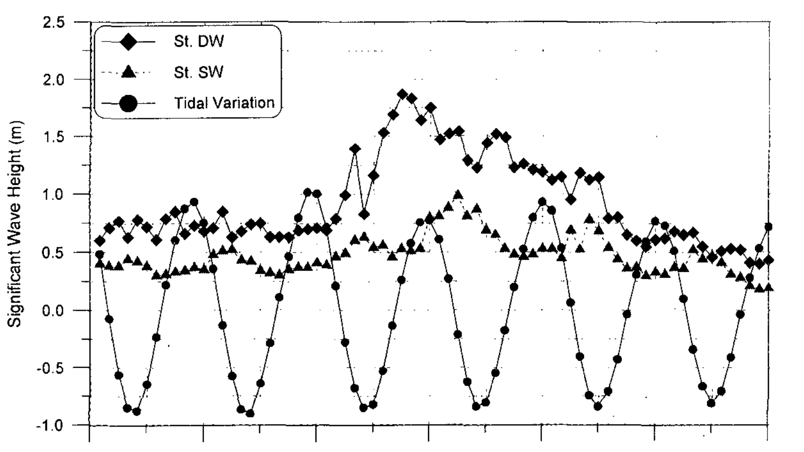

Figure 2. Variation of Significant Wave Height (H_s) at Stations DW and SW.

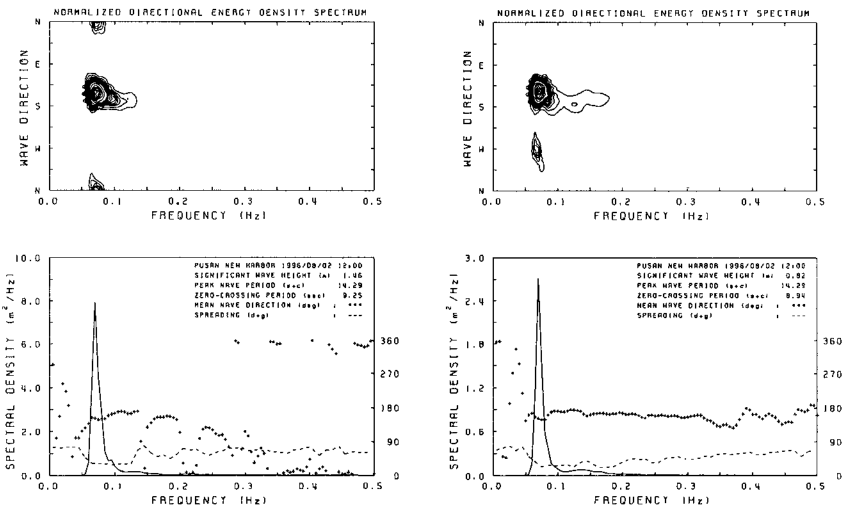

Figure 3. Frequency and Directional Wave Spectra Measured at Stations DW (Left) and SW (Right) (12:00~12:27, Aug. 2, 1996).

When the waves propagated from St. DW to St. SW, they were also affected by the tidal currents. The maximum current speed was about 60 cm/s. At high water (no current) spectral shape change was very small but energy level was decreased by half mainly due to refraction (Figure 3). However, in the following current condition, spectrum became wide in both direction and frequency bands, and wave height decreased by 60%. In the opposing current condition (Figure 4), the spectrum were less broad-banded than one in the following current (Figure 5). Significant wave height at St. DW decreased at St. SW by 40%. Reflected wave components were appeared, which might be due to currents or mooring line

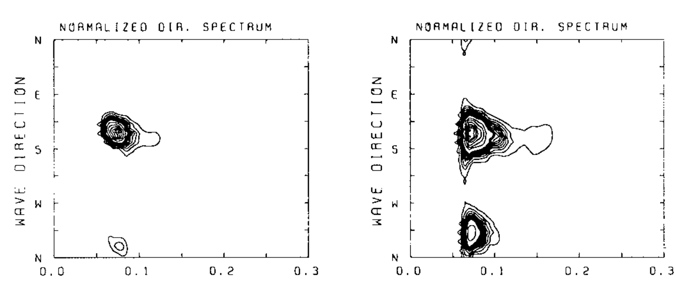

Figure 4. Directional Wave Spectra Measured at Stations DW (Left) and SW (Right) (14:00~14:27, Aug. 2, 1996).

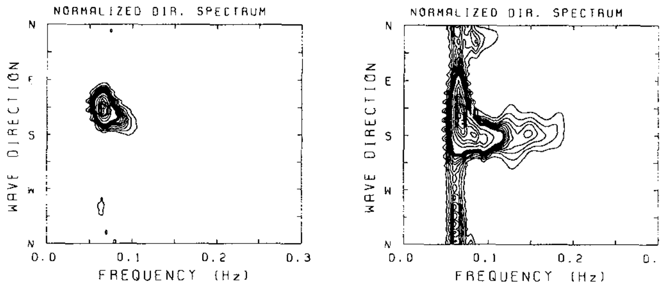

Figure 5. Directional Wave Spectra Measured at Stations DW (Left) and SW (Right) (08:00~08:27, Aug. 2, 1996).

system of the buoy. The mooring line was slightly modified by substituting a part of the polypropylene rope with thin steel wire of 10 m long in order to prevent the rope from cutting by fishing activities.

From this analysis it can be said that the wave height increased about 10% by the opposing current effects. The major factor on the wave transformation through the channel is the refraction of waves due to its bathymetry. To some extent current is responsible. Therefore consideration of directional distribution of the waves is most important for the refraction in the calculation of the wave propagation through the channel.

It is shown that long-period waves were observed at St. S1 and slightly amplified at St. S3. As shown in Figure 6 the spectrum has major peak in the short-period band and bounded waves are in the periods of 60 s to 150 s. The long-period waves were slightly amplified at St. S3 in shallow water area. Those waves might induce the ship moored at the berth to surge and sway because the periods are close to those of resonant modes of the ship and mooring system.

Short-Period Wave Propagation Modeling

As the modeling area of 49 km × 31 km shown in Figure 7 is so large that it was divided into three regions depending on the phenomena of wave transformation and the limitation of wave propagation models. With given deep-water wave height H_s and frequency-directional spectrum $S(f, \theta)$ the irregular waves at the input boundary can be generated (Goda, 1985). Additional wave growth was ignored during their propagation in the modeling area. The wave model was used to calculate 286 discrete spectral components. The total wave height can be obtained by adding each components.

For the calculation of wave propagation in the large offshore region in Figure 7, the RCPWAVE model (Ebersole et al., 1986) was used because of its

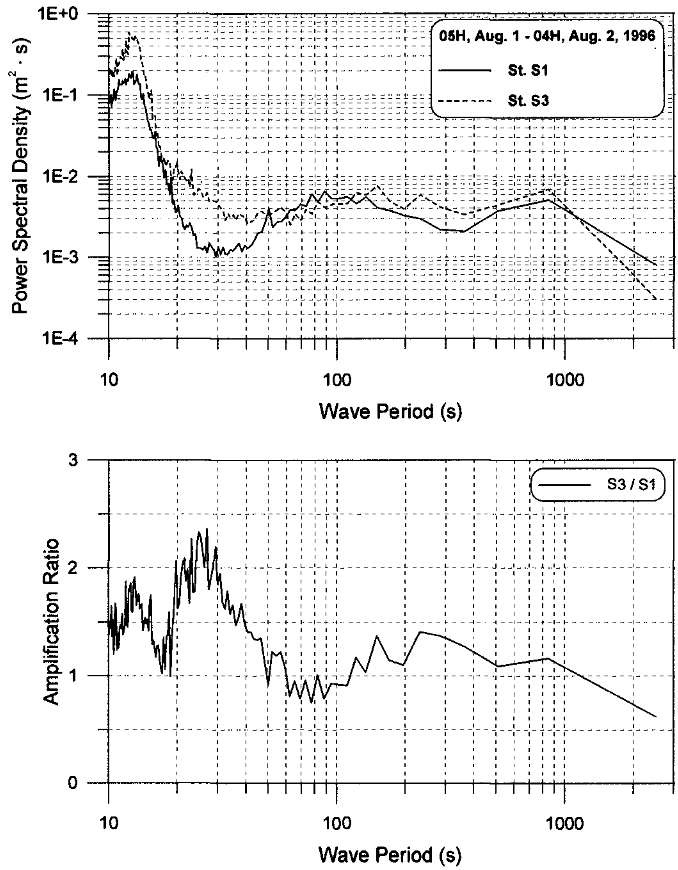

Figure 6. Spectra Obtained from Pressure Data at Sts. S1 and S3 and their Amplification Ratios.

computational efficiency and sufficient accuracy. The area was divided into 195 × 124 rectangular cells and the grid size was 250 m.

Estimation of Shallow-Water Design Wave Height for Breakwater

For the calculation of short-crested wave propagating in the complex coastal waterway (subregion A) and penetrating into the harbor (subregion B), a hyperbolic-type wave model HCORD (eg. Copeland, 1985) based on the mild-slope equation was used.

The HCORD is modified in order to simulate partial wave reflection by

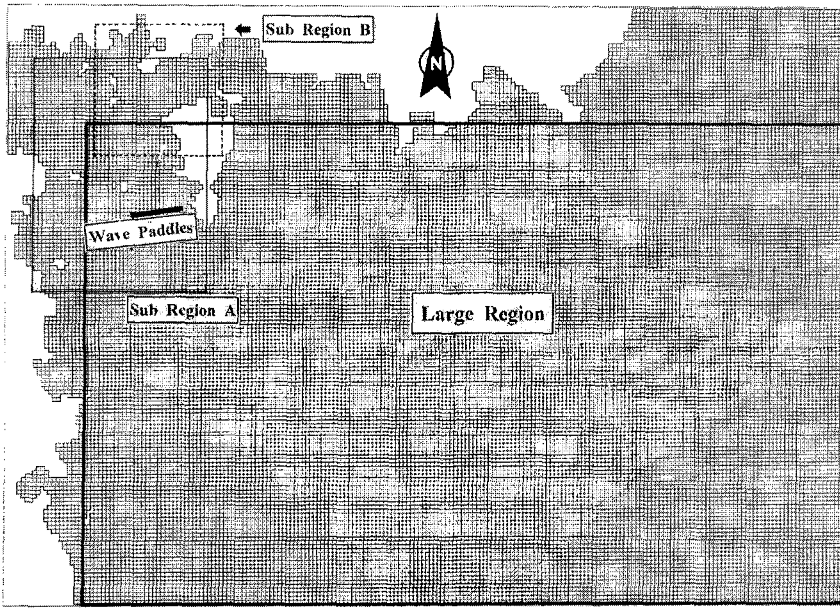

Figure 7. Map Showing Computational Domains for Short-Period Wave Propagation Modeling, and Location of Wave Paddles in the Physical Modelling.

absorbing wave energy normal to the solid boundary. The method is not correct in theory but gives numerical results within 10% error compared with the field data (Jeong et al., 1997).

Input wave conditions were provided at the boundary of the subregion B by the RCPWAVE results. The HCORD was applied to 5 discrete directional components ($\Delta\theta = 22.5°$) with a representative frequency of the waves (Goda, 1985). It is mainly because of the grid size limitation (herein 1/10 wavelength) and computational capacity of engineering workstation. The subregion A was divided into 1,650,000 grids and the size is 10 m×10 m. It took about 6 hours for computing one irregular wave propagation by engineering workstation.

The computation results agree well with the measured data in terms of wave height and direction. They were also compared with the data obtained from three-dimensional hydraulic model tests which used a JONSWAP (multi-frequency) spectrum with one direction. The physical model produced larger waves than the field data and it was tuned with the data. One of the calculation results is shown in Figure 8, where shallow water design wave heights were obtained for various breakwater alignments.

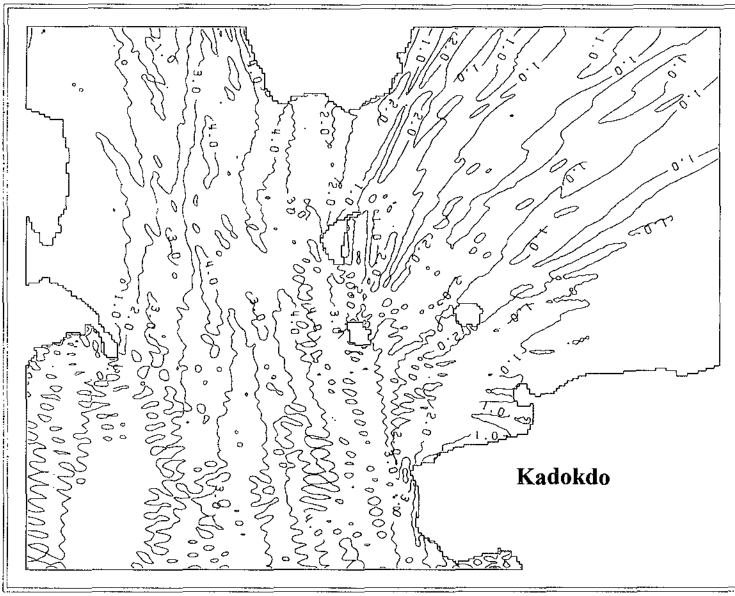

Figure 8. Calculated Significant Wave Heights around Pusan New Harbor (Incident Deep-Water Wave Height = 10 m, Period = 15 s, Direction = S10 ° W, Present State).

Harbor Tranquility Analysis

Harbor tranquility is essentially to reduce motions of ships moored at anchorage or along a wharf. Even though physical factors are involved for the analysis of harbor tranquility (Goda, 1985), a practical approach of wave height evaluation was used for simplicity in the designing stage. Harbor tranquility should be maintained above a certain level of harbor operation rate (95~97.5% in Korea) in order to have feasibility with respect to safety of loading/unloading and operational efficiency. Combined numerical and physical modeling results were used in order to estimate wave height distribution in the harbor. The limiting wave height criteria for loading/unloading were chosen as 0.3 m for small vessel, 0.5 m for general cargo, and 0.3 m for north and south container ship terminals.

Four-year data of six hourly hindcasted waves at deepwater were used, which are in the form of the joint distribution of significant wave height, period and direction. They were further reanalyzed to know the days of exceedance of the significant wave height above certain levels during a year at the container and cargo terminals in the harbor. Among the data set 12 cases of waves were chosen for the calculation because only limited number of directional wave components can propagate into the harbor. Those waves are in the direction of SSW, S and SSE with periods of 7 s, 9 s, 12 s, and 15 s.

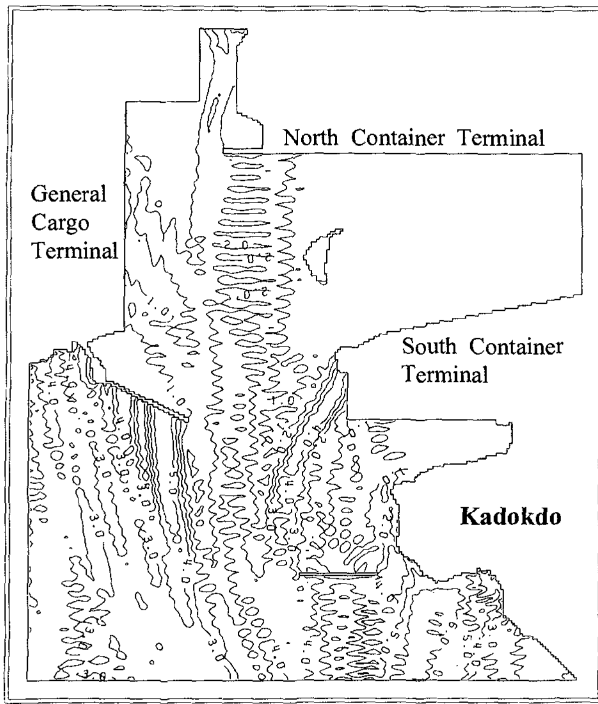

Figure 9. Calculated Wave Heights around Pusan New Harbor (Incident Deep-Water Wave Height = 10.1 m, Period = 14 s, Direction = S, Final Layout).

Two wave models of RCPWAVE and HCORD were used to calculate the wave propagation from deep water (large region) to shallow water (subregions A, B) shown in Figure 7. One of the computational results is shown in Figure 9, which is the wave heights in meter at the final harbor layout for the design wave condition. Hydraulic modeling results were adopted to estimate the wave heights inside the harbor depending on the wave condition at the entrance of the harbor given by HCORD. In order to reduce the strong wave reflection from the vertical wall with right angle to the north end of the general cargo terminal a beach with 1/3 slope was applied. As shown in Table 1 harbor operation rates were evaluated for small vessel, general cargo, and container terminals. Mean annual rate of the harbor operation is estimated at 98.7 %.

Table 1. Numbers of Waves Exceeding a Criteria and Harbor Operation Rate.

Terminal \ Wave		SSW				S				SSE				Total	Harbor Operation Rate (%)
		7s	9s	12s	15s	7s	9s	12s	15s	7s	9s	12s	15s		
General Cargo		0	32	9	6	5	6	13	11	17	5	2	2	108	98.2
Small Vessel		0	65	13	12	32	16	21	22	30	8	6	9	234	96.0
North Container	W*	0	49	9	9	12	10	17	16	24	7	3	4	160	97.3
	C*	0	8	3	2	0	3	4	1	4	1	0	0	26	99.6
	E*	0	3	1	0	0	0	2	0	1	0	0	0	7	99.9
South Container	W*	0	20	7	3	2	4	8	5	5	3	0	1	58	99.0
	C*	0	6	3	2	1	3	4	1	4	1	0	0	25	99.6
	E*	0	3	1	1	0	1	2	0	2	1	0	0	11	99.8

* W : West, C : Center, E : East part of the Terminal.

Long-Period Wave Modeling

Long-period wave oscillations in a harbor may cause unacceptable vessel motions, excessive mooring forces and fender reactions leading to the breaking of mooring lines and fender system. The typical natural periods of a reasonable harbor or moored vessel are of the order of magnitude of minutes (Nagai et al., 1994). One of the sources that generate the offshore long-period waves of 2~3 minutes is the wave set-down traveling with the wave group velocity.

For the analysis of harbor oscillations a long-period wave model HOMETA was developed, which is similar to Chen (1986)'s HARBD but improved with the extended mild-slope equation (Massel, 1992). Some details of the model equations and calculation method are given in Jeong et al. (1996). The model application to new harbor oscillation is focused herein.

The modified model was applied to calculate the wave amplification due to group bounded and free long waves, which were generated during the storm wave condition and resonated in the new harbor. The calculation area was taken large enough to cover offshore measurement station S1 as shown in Figure 1. The water depth of the far-field area (analytic solution region in HARBD model) is assumed to be constant. Reflection coefficients vary from 0.95 (natural beach) to 0.99 (vertical sea wall) and also vary depending on the magnitude of frequency (i.e., from 0.4 for 15 s to 0.98 for 180 s waves at energy absorbing boundary). The numbers of triangular elements are 22,222 and its size is small enough to resolve 30 s period wave in the water of 15 m depth. Numerical computation has been made for the 54 component waves of period ranging from 60 s to 1,400 s and comparisons were made with experimental data. The amplification ratio is $\sqrt{S_i(f)/S(f)}$, where $S_i(f)$ is the spectral density at the i-th point in the domain and $S(f)$ at offshore station.

The model was validated with the measured data, and then it was applied to predict harbor amplification by dominant frequency wave components observed at St. S1. Figures 10 and 11 show the amplification ratios at Sts. C12 (south), C13 (center), and C14 (north) of general cargo terminal, and Sts. C26 (west), C28 (center), and C30 (east) of north container terminal. First and second modes of the harbor oscillations are expected to be amplified but their energy levels are so low that they can not generate large water level variation and strong current. However the bounded waves of period from 100 s to 200 s will be amplified at St. C12 in the general cargo terminal. As the waves might be critical for the surging motion of ship sized several 10,000 DWG, this should be considered for the mooring line and fender system in the detail design stage.

Conclusion

From the field measured directional wave spectra and numerical modeling, the directionality of short crested waves is proved to be very important when they

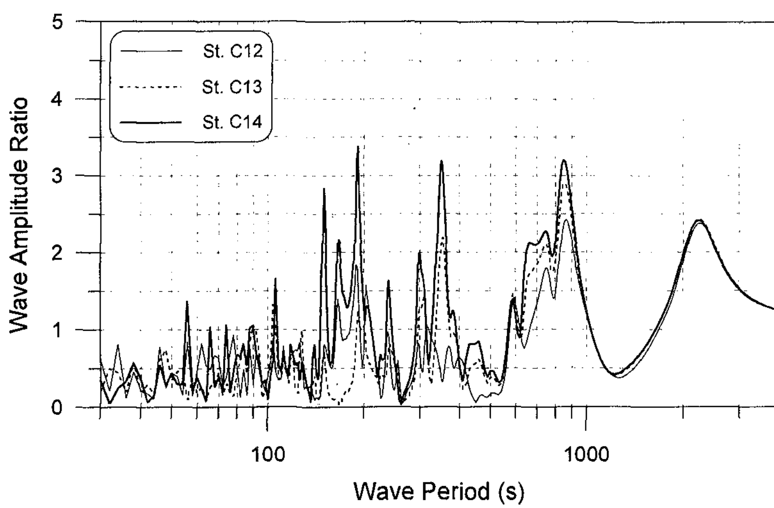

Figure 10. Computed Amplification Ratios for Wave Periods of 30 to 4,000 seconds at Stations C12, C13 and C14 of General Cargo Terminal.

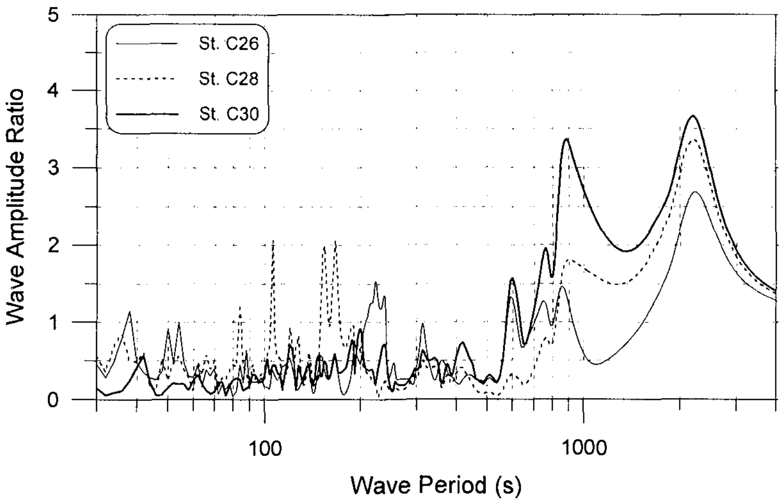

Figure 11. Computed Amplification Ratios for Wave Periods of 30 to 4,000 seconds at Stations C26, C28 and C30 of North Container Terminal.

propagate through the complex coastal waters. Bounded long-period waves were observed in the shallow water area with a small amplification. These might cause horizontal motions of a container ship moored at a berth aligned to the south. Both the modified and extended numerical wave models are accurate enough to simulate the measured wave propagation phenomena. Based on the computational results of short/long-period waves, proper counter-measures were recommended.

Acknowledgements

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