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A Practical Application of Multiple Wave Models to the Small Fishery Harbor Entrance

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Abstract : *Samchunpo(Sin Hyang) Harbor is located in the bay of Sa Chun, the central south coast of Korean peninsula. The harbor and coastal boundaries have been protecting by natural coastal islands and shoals. Currently, The Sin Hyang harbor needs maintenance and renovation of the sheltered structures against the weather deterioration and typhoon damages. Consequently to support this, the calculation of accurate design wave through the typhoon wave attack is necessary. In this study, calculation of incident wave condition is simulated using steady state spectrum energy wave model (wide area wave model) from 50 years return wave condition. And this simulation results in wide offshore area were used for the input of the extended mild slope wave model at the narrow coastal area. Finally, the calculation of design wave at Sin Hyang harbor entrance was induced by Boussinesq wave model (detail area wave model) simulation. The numerical model system was able to simulate wave transformations from generation scale to shoreline or harbor impact. We hope these results will be helpful to the engineers doing placement, design, orientation, and evaluation of a wide range of potential solutions in this area.*

Key words : *Steady state spectrum energy wave model, Extended mild slope wave model, Boussinesq equation, Design wave condition*

1. Introduction

Wave prediction in the complicate shoreline is a very important factor in the coastal engineering design. Due to the highly irregular nearshore bathymetry and the complicated structural configuration, the Boussinesq wave equation model might be a possible tool for the reasonable solution at this domain. This model is capable of reproducing the combined effects on most wave phenomena of interest in coastal and harbor engineering, including shoaling, refraction, diffraction, and reflection of irregular short-crested and long-crested finite amplitude waves propagating over complex bathymetries. In addition, phenomena such as wave grouping, generation of bound sub-harmonics and near resonant triad interactions, are also available. The Boussinesq wave modeling was geared at identifying all the physical processes in the immediate study region, with particular focus on the wave-structure interactions. This paper describes about numerical model application in order to investigate the wave disturbance problems at the Sin-Hyang harbor.

The region of Sin-Hyang harbor, which is located adjacent to Sa-Chun Bay main waterway, is a small fishery port which has coastal boundaries sheltering the port water area. This harbor is going to be renovated by expansion of mooring facility and breakwaters, because mooring problems have been experienced at the narrow berthing area. However, as the impact of waves on nearshore processes and bottom change is highly dependent on the offshore wave climate, we need to get the information of waves propagating to the inner coastal boundaries. It is necessary to have a complex modeling system starting from a generation scale basis to the practical design area.

In many cases, a single design wave condition is selected and/or minimal wave model simulation is preformed to design and construct coastal structures. In this study, we tried to show a successful application of multiple wave models to arrive at the reliable solution on a practical coastal engineering problem. In order to predict design wave conditions in Sin-Hyang harbor we formulated three different wave models. First of all, calculation of incident wave condition was done by steady state spectrum energy wave model (wide area wave model) from 50 years return wave condition. And the simulation results in wide offshore

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area were introduced for the input of the extended mild-slope wave model at the narrow coastal area. The nearshore wave model, extended mild-slope wave model, is to be utilized to evaluate the nearshore processes such as wave reflection, wave-induced currents, wave dispersion, nearshore wave refraction and diffraction, etc. This method has been successfully applied to various wave propagation situations in the context of finite element model.

Once calibrated, the Boussinesq model was applied to the harbor area adopting the average annual directional conditions for the same set of conditions developed for the nearshore wave modeling. This model includes shoaling, refraction, diffraction, wave breaking, bottom friction, partial reflection and transmission, non-linear wave-wave interaction, frequency spreading, and direction spreading. Phenomena, such as wave grouping, surf beats, generation of bound sub-harmonics and super-harmonics, and near-resonant triad interactions, can also be coupled using this model. Thus, details like the generation and release of low-frequency oscillations due to primary wave transformation are well described in the model. In these cases, mild-slope wave model spectral results were passed to the open boundary of the Boussinesq model.

2. Multiple Wave Model System

2.1 Generation scale to the nearshore zone model

The Steady-state spectrum wave model was used to transform the data from the generation scale results into the nearshore environment and to provide input into the local wave model. Steady-state spectrum wave model is based on a form of the wave action balance equation of Jonsson (1990).

$$\frac{\partial E}{\partial t}+(C_{ga})_i\frac{\partial}{\partial x_i}\frac{C_a C_{ga}\cos(\mu-\alpha)}{\omega_r}=\sum\frac{S}{\omega_r} \tag{1}$$

where, E = wave energy density divided by $(\rho_w g)$, ρ_w is density of water, $C(x,y)$ = phase velocity = σ/k, σ = wave frequency under consideration (in radians/second), through the linear dispersion relation, $C_{ga}(x,y)$ = absolute wave group velocity(= $\frac{\partial\sigma}{\partial k}=nC$) with $n=\frac{1}{2}\left(1+\frac{2kd}{\sinh 2kd}\right)$, $k(x,y)$ = wave number (= 2π/L), related to the local depth $d(x,y)$, S = energy source and sink terms. $\omega_r^2=kg\tanh kd$, where ω_r = relative angular frequency, g = gravitational acceleration. The detail information refers to Holthuijsen & Booij (1986), Resio and Perrie (1991).

2.2 Nearshore to harbor zone model

The Steady-state spectrum wave model results identify the regional wave transformations; however, due to the complex bathymetry in the vicinity of the intended site, the nearshore islands, the jetties, and a number of complex conditions need a higher resolution model, encompassing additional wave processes. Two-dimensional spectral output from spectral energy wave model was used as input into the local, nearshore wave model. The physics embodied in extended mild-slope wave model, to include the effects of frictional dissipation and wave breaking, are based on solving the two-dimensional elliptic mild-slope equation Berkhoff(1976).

$$\nabla\cdot\left(CC_g\nabla\hat{\eta}\right)+\left(\frac{C_g}{C}\sigma^2+i\sigma w+iC_g\sigma\gamma\right)\hat{\eta}=0 \tag{2}$$

where $\hat{\eta}(x,y)$ = complex surface elevation function, from which the wave height can be estimated, w = a friction factor, and γ = the wave breaking parameter. The detail information necessary refers to Chen & Houston (1987), and Demirbilek (1994).

2.3 Complex coastal and harbor zone model

The Boussinesq wave model (two horizontal space co-ordinates) solves the enhanced Boussinesq equations by an implicit finite difference technique with variables defined on a space-staggered rectangular grid. The model is capable of reproducing the combined effects of most wave phenomena of interest in harbor and coastal engineering. This is of significant important for harbor resonance, seiching, and coastal processes.

Continuity : $n\frac{\partial\zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=0$ (3)

X-momentum :

$$n\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{p\cdot q}{h}\right)+n^2gh\frac{\partial\zeta}{\partial x}$$
$$+n^2p\left[\alpha+\beta\frac{\sqrt{p^2+q^2}}{h}\right]+\frac{gp\sqrt{p^2+q^2}}{h^2C^2}-\Omega q+n\psi_1=0 \tag{4}$$

Y-momentum :

$$n\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{p\cdot q}{h}\right)+n^2gh\frac{\partial\zeta}{\partial y}$$
$$+n^2q\left[\alpha+\beta\frac{\sqrt{p^2+q^2}}{h}\right]+\frac{gp\sqrt{p^2+q^2}}{h^2C^2}-\Omega p+n\psi_2=0 \tag{5}$$

where the Boussinesq dispersion terms ψ_1, ψ_2 are defined by :

$$\psi_1 = -\left(B+\frac{1}{3}\right)d^2\left[P_{xxt}+q_{xyt}\right]-nBgd^3\left[\xi_{xxx}+\xi_{xyy}\right]$$
$$-dd_x\left(\frac{1}{3}p_{xt}+\frac{1}{6}q_{yt}+nBgd\left[2\xi_{xx}+\xi_{yy}\right]\right)$$
$$-dd_y\left(\frac{1}{6}q_{xt}+nBgd\xi_{xy}\right) \quad (6)$$

$$\psi_2 = -\left(B+\frac{1}{3}\right)d^2\left[q_{yyt}+p_{xyt}\right]-nBgd^3\left[\xi_{yyy}+\xi_{xxy}\right]$$
$$-dd_y\left(\frac{1}{3}q_{yt}+\frac{1}{6}p_{xt}+nBgd\left[2\xi_{yy}+\xi_{xx}\right]\right)$$
$$-dd_x\left(\frac{1}{6}p_{yt}+nBgd\xi_{xy}\right) \quad (7)$$

Subscripts x, y, and t denote partial differentiation with respect to space and time, respectively.

P = flux density in the x-direction, $m^3/m/s$, q = flux density in the y-direction, $m^3/m/s$, B = Boussinesq dispersion factor, F_x = Horizontal stress term in x-direction, F_y = Horizontal stress term in y-direction, x, y = Cartesian co-ordinates, m, t = time, sec, h = total water depth ($= d+\xi$), m, d = still water depth, m, g = gravitational acceleration ($= 9.81 m/s^2$), n = porosity, C = Chezy resistance number, $m^{0.5}/s$, α = resistance coefficient for laminar flow in porous media, β = resistance coefficient for turbulent flow in porous media, ξ = water surface level above datum, m, $\Omega(x,y)$ = Coliolis parameter. The detail information might be referred to Madsen (1983, 1991, 1992, 1997), Sørensen(1997a, b), Sørensen and Schäffer(2004).

3. Model Setup and Result

3.1 Generation scale to the nearshore zone

Incident wave condition on the extended mild-slope wave model which is the middle zone wave model was calculated from the state spectrum energy model in the generating zone. As the extended mild-slope wave model used two input conditions. These input were of 50 years return wave characteristics with wave height of 9.38m, period of 14.43sec, wave direction of S, and wave height of 13.44m, period of 16.79m, wave direction of SSE. Numerical simulation area is 18.8km × 20.0km and the grid interval is 20m, total grid number is 940,000 with 940 × 1,000. The area of study and the limit of open boundaries for each model are indicated in Fig. 1. Table 1 presents the storm scenarios simulated together with the grid system for model setup and the result of simulation is shown in Table 2. Fig. 2 and Fig. 3 present two energy spectrum input for this model. Simulation results of wave height are in Fig. 4 and Fig. 5. The color map corresponds to the distribution of significant wave height (m) throughout the model domain. Cool colors indicate a higher wave height, while warm colors indicate a reduced wave height. The result for the input into the nearshore wave model shows that a wave height of 2.4m, a period of 14.3sec, and wave direction S11°E for S wave, and the wave height of 3.09m, period of 16.7sec, and wave direction of S20°E for SSE wave, respectively.

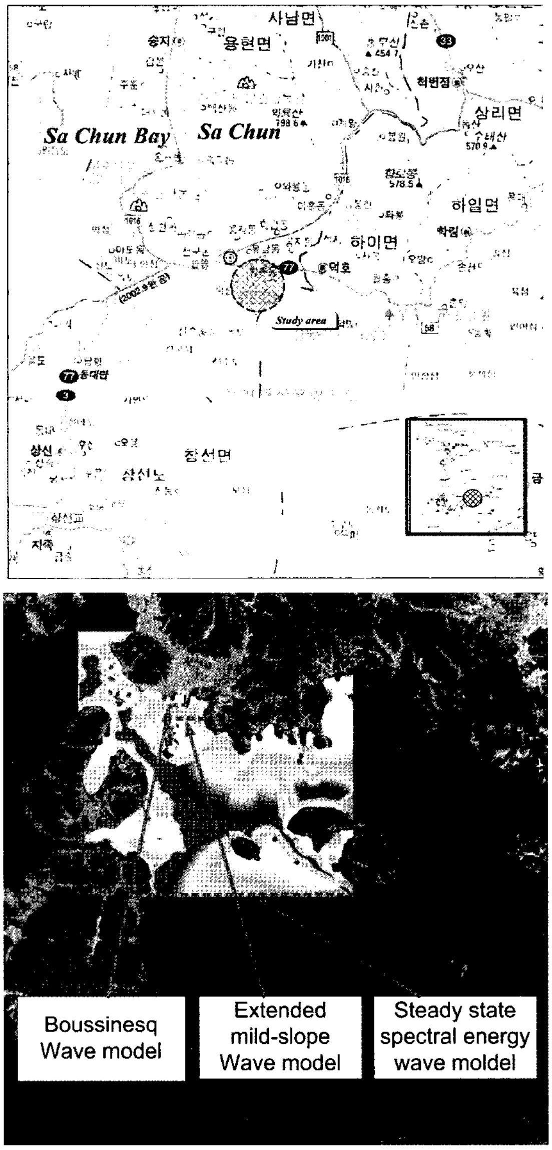

Fig. 1 Location of Sin-Hyang Harbor, Sa-Chun Bay, Korea and limit of open boundaries for model input

Table 1 Incident wave condition of steady-state spectrum wave model

Menu	**contents**		
Calculation model	**steady-state spectrum wave model (regular wave)**		
Grid	Calculation area : 18.8 km×20.0 km Grid space : 20 m×20 m Grid number : 940×1,000 = 940,000		
Incident wave (50 year return wave)	**Wave height(m)**	**Wave period(sec)**	**Wave direction**
	9.38	14.43	S
	13.44	16.79	SSE

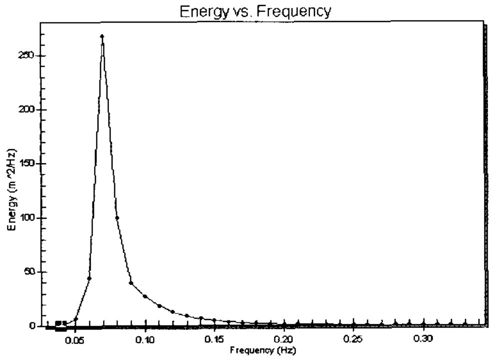

Fig. 2 Energy vs. frequency of model

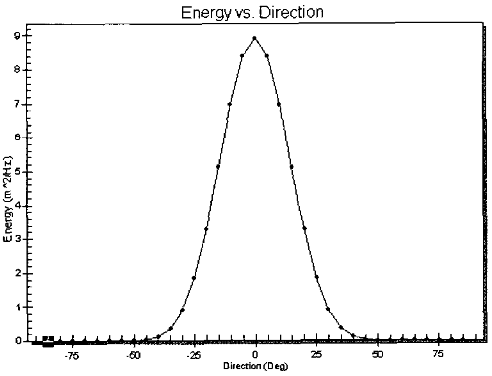

Fig. 3 Energy vs. direction of model

Fig. 4 Wave height of direction S

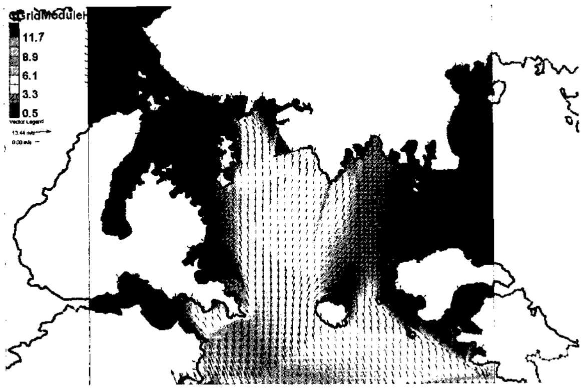

Fig. 5 Wave height of direction SSE

Table 2 Result for the input of Nearshore model by Steady state spectrum energy wave model

Wave direction	**Simulation result(Steady state spectrum energy wave model)**		
	Wave height (m)	**Wave period (sec)**	**Wave direction (°)**
S	2.4	14.3	S11°E
SSE	3.09	16.7	S20°E

3.2 Nearshore to harbor zone

Table 3 Incident wave condition of extended mild-slope wave model

Menu	**contents**
Calculation model	**extended mild-slope wave model (irregular wave)**
Element	Calculation area : 3.3 km×2.0 km element space : 10m ~ 20m element number : 4,643

Mild-slope equation wave model can incorporate the effect of diffraction and reflections caused by bathymetric features and structures. The result of steady state spectrum energy wave model is able to use incident wave condition of extended mild-slope wave model. Wave conditions of this model are showed in Table 3. Numerical simulation area is 3.3km × 2.0 km, element interval is 10~20m, total element number is 4,643, and incident wave conditions are same to result of steady state energy model in Table 2. The water depth of study area is in Fig. 6 and the finite element mesh is shown in Fig. 7.

Fig. 8 and Fig. 9 show the predicted wave heights in case of waves coming from S11°E and S20°E direction. Dark blue lines represent higher wave height, while the light yellow represents lower wave height. The results of simulation are summarized in Table 4. S11°E direction wave is consist of wave height 2.2m, period 14.3sec, wave direction S5°E and S20°E direction is wave height 2.60m, period 16.7sec, wave direction S5°E. Generally, S20°E direction wave is higher than S11°E direction wave, because of the S20°E direction wave period longer than S11°E direction wave. However, S11°E direction wave height is higher than S20°E direction wave at Sin-Hyang harbor entrance. Simulation result of wave height S11°E and S20°E is showed in Fig. 8, Fig. 9. Selected comparison points at Sin-Hyang harbor are showed in Fig. 8. P1 is inside the harbor, P2 the entrance of the harbor, and P3 is in front of the south breakwater.

The result in this simulation will be compared with the results of the Boussinesq wave model. St.1 through St.4 shown in Fig. 8 are the input stations of Boussinesq wave model from the result by the nearshore model simulation and these inputs are shown in Fig. 10 and Fig. 11. The significant wave results of each point are summarized in Table 4.

Table 4 Result of extended mild-slope wave model

Wave direction	**Significant wave height (m) (extended-mild slope wave model)**		
	P1	**P2**	**P3**
S11°E	0.44	1.34	1.43
S20°E	0.44	1.01	1.80

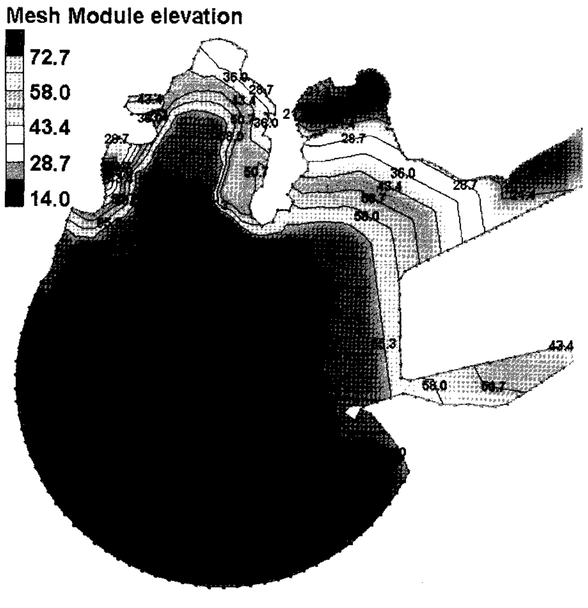

Fig. 6 Water depth of study area

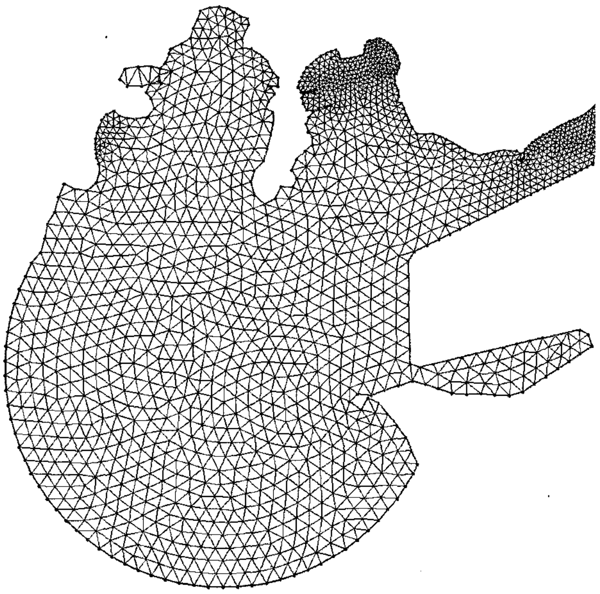

Fig. 7 FE mesh of study area

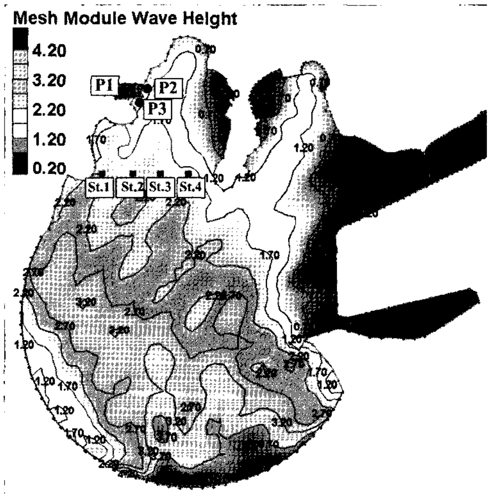

Fig. 8 Wave height of direction S11°E

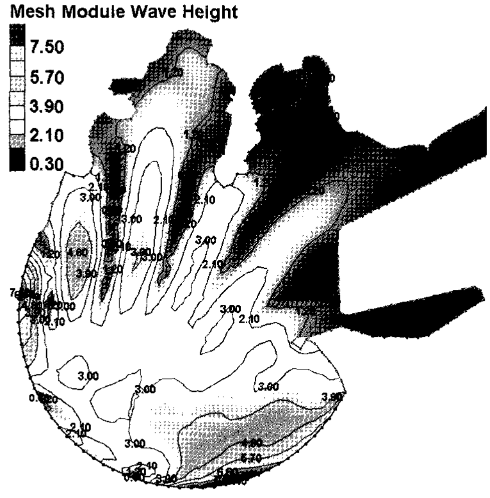

Fig. 9 Wave height of direction S20°E

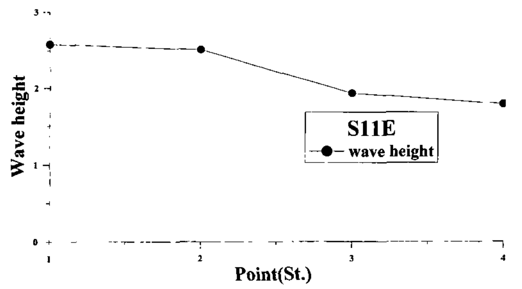

Fig. 10 Wave height at selected points (S11°E)

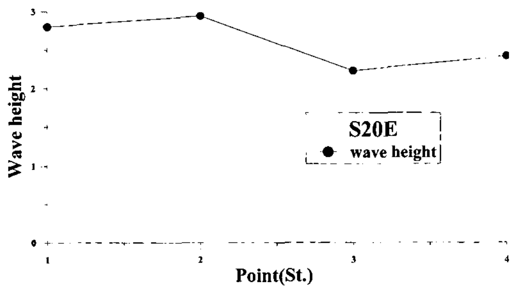

Fig. 11 Wave height at selected points (S20°E)

3.3 Complex coastal and harbor zone

Boussinesq wave model held an excellent capability of simulating wave breaking, shoaling, refraction, and diffraction. Boussinesq wave model applied here solves the Boussinesq equations using a flux formulation with the linear dispersion. The final numerical simulation area was chosen for 1.0km × 1.0 km, which includes the Sin-Hyang harbor. The grid extends from the shoreline to the selected stations St.1 through St.4. The grid consists of 333 cells across the shore and 333 cells along the shore with a resolution of 3 meters. The bathymetric grid and water depth of this model is shown in Fig. 12. Finally, the design wave conditions in Sin-Hyang harbor entrance are calculated by the formulated wave model. Incident wave condition of Boussinesq wave model is shown in Table 5 and the reflection coefficient is presented in Table 6. Fig. 13 shows the energy-frequency of model and Fig. 14 shows the energy-direction of this simulation, respectively.

Table 5 Incident wave condition of Boussinesq wave model

menu	contents		
Calculation model	steady-state spectrum wave model (irregular wave)		
Grid	Calculation area : 1.0 km×1.0 km Grid interval : 3m×3m, Grid number : 333×333 = 110,889		
Incident wave	Wave height(m)	Wave period(sec)	Wave direction
	2.6	16.7	S5°E

As a result, the responses at the three points chosen for calculation of design wave are shown in Fig. 15 through Fig. 17. Wave height calculated was 2.0m at the front of south breakwaters (P3). P1 and P2 shows under 0.5m of wave height. The 3D water level and simulated snapshot are shown in Fig. 18. Significant wave height and relative response (Hs/Hi, Significant wave height/Incident wave height) are represented in Fig. 19 and Fig. 20. Fig. 21 and Fig. 22 are the time series plot data at each point. Significant wave heights at P1 and P2, where inside the harbor, showed below 0.5m. In this plot, CG.W means the extended mild-slope wave model and BW is for the Boussinesq wave model.

Significant wave height at P3, in front of the southern breakwaters, shows 2.3m. Generally, the results of Boussinesq wave model were a little higher than the result by the extended mild-slope equation model at P1, P3. However, the result by the extended mild-slope equation model at P2 is higher than Boussinesq equation model. Significant wave direction is showed in Fig. 23. The wave direction of 255° is distinguished. Spectral density is showed in Fig. 24.

Table 6 Applied reflection coefficient

formation	Reflection coefficient
Wall(Crest on SWL)	0.7 ~ 1.0
Wall(Crest under SWL)	0.5 ~ 0.7
Rubble(1:2~3 slope)	0.3 ~ 0.6
heteromorphy bloke	0.3 ~ 0.5
Natural coastal	0.05 ~ 0.2

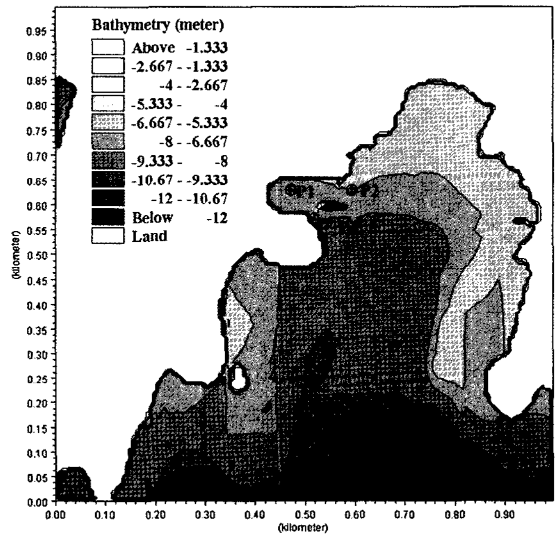

Fig. 12 Water depth of study area

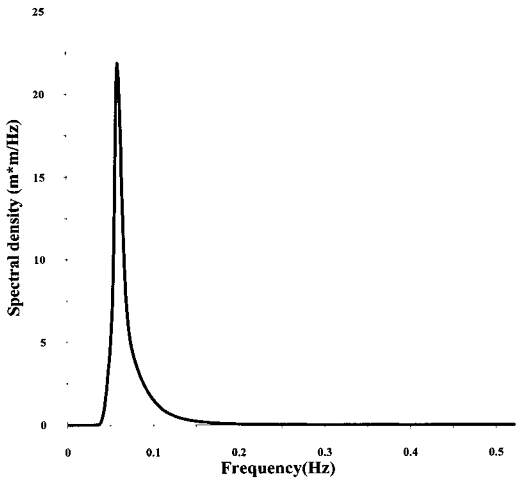

Fig. 13 Energy vs. frequency of model

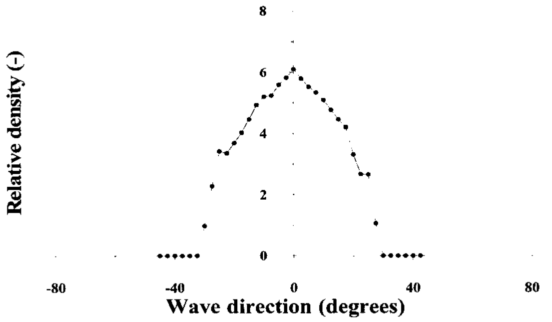

Fig. 14 Energy vs. direction of model

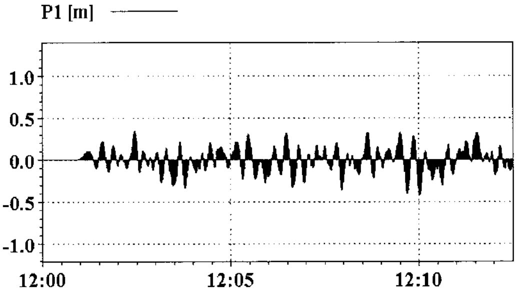

Fig. 15 Time series of respond at P1(10min)

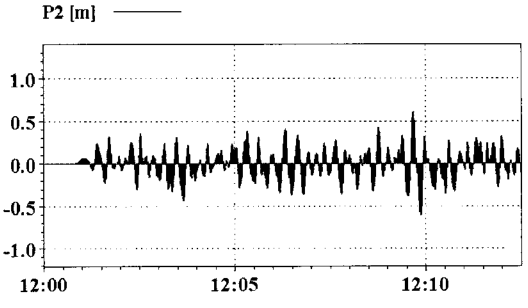

Fig. 16 Time series of respond at P2(10min)

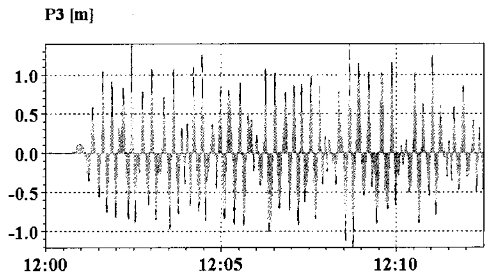

Fig. 17 Time series of respond at P3(10min)

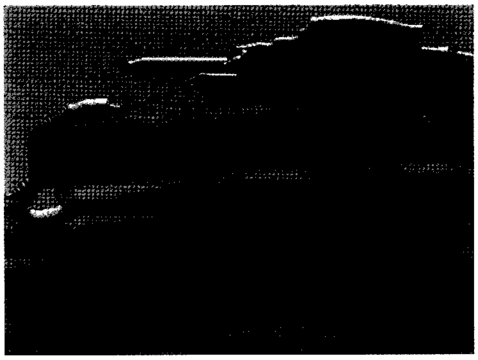

Fig. 18 Simulated wave sample of coastal and harbor zone.

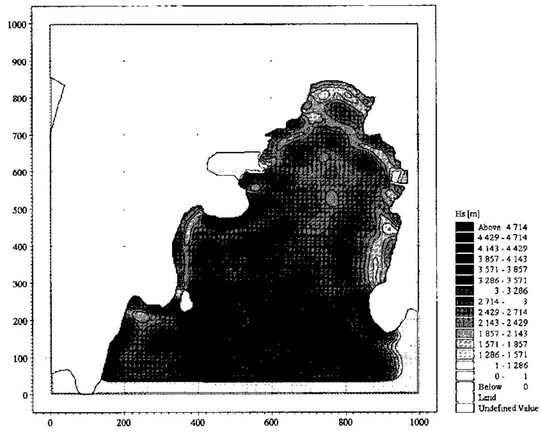

Fig. 19 Significant wave height

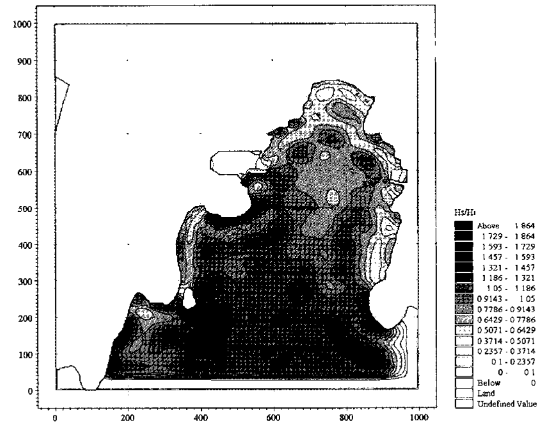

Fig. 20 Relative response (Hs/Hi)

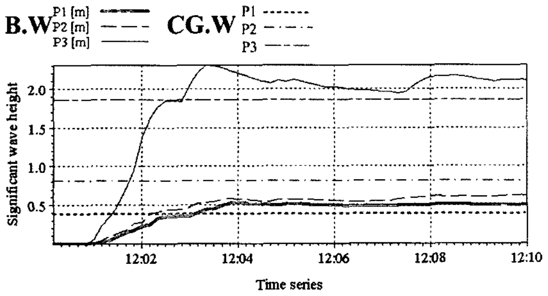

Fig. 21 Significant wave height plot

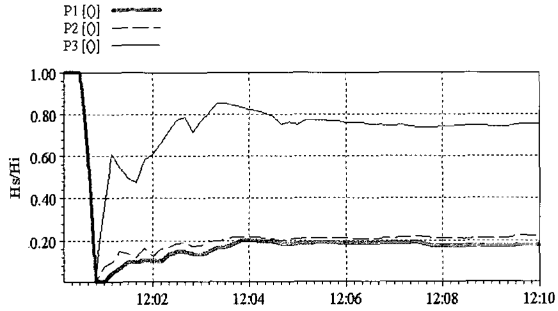

Fig. 22 Hs/Hi plot

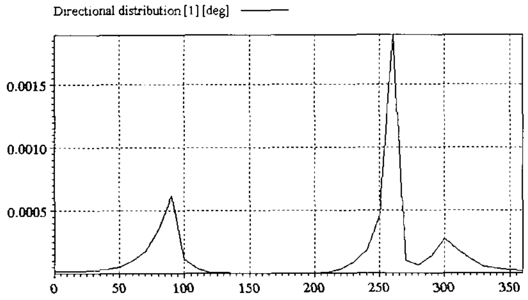

Fig. 23 Significant wave direction

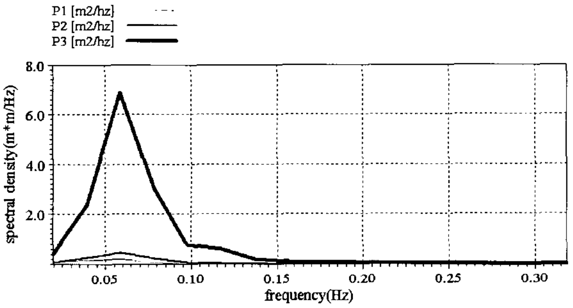

Fig. 24 Spectral density

4. Conclusion

Sin-Hyang harbor is a small fishery and sheltered port which has a very complicated shore line and coastal boundaries. This harbor is being modified with the expansion of docking facility and breakwaters. In this study, we tried to predict the design wave condition in Sin-Hyang harbor. We used three different numerical models for the different coastal environments that the variable wave transformations may be expected in such configurations. From the results obtained in this study it is believed that Boussinesq wave model held an excellent capability of simulating the wave breaking, shoaling, refraction, and diffraction phenomena. However, it is necessary to have huge grids and computation time to cover the whole simulation domain with a single Boussinesq model. The numerical model system was able to simulate wave transformations from generation-scale to shoreline or harbor-scale. The ultimate goal of the multiple modeling system is application towards the evaluation of a wide range of alternatives. The system saved computation time and preparation of simulation. We hope to contribute from this study that coastal engineers are able to assist in the placement, design, orientation, and evaluation of a wide range of potential solutions by this system. In this study, we had obtained only design wave parameters by numerical simulation. Hereafter, it is necessary to modify the model application for the coastal processes and analyze the results with the site observation data.

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