The Prediction of Wave Groups within a Harbor to Assist Ship Operation at the Entrance

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Abstract : Waves, which are the main source of ship motions in a seaway, considerably affect the performance of a ship. The study of waves and their impact on ship motions within harbors is an important aspect of the design and operation of harbors. The prediction of incoming groups of waves is particularly important for evaluating ship motion within a harbor. Such a prediction makes it possible to evaluate ship safety more accurately. The wave transformation model reported here is applied to actual ports based on Boussinesq wave equations both non-linear and dispersive wave processes be considered in order to capture physical effects such as wave shoaling, refractions, reflection and diffraction in variable depth environments. The prediction of incoming groups of waves is particularly important for evaluating ship motion within a harbor, Such a prediction makes it possible to evaluate ship safety more accurately and provide safe wave informations for navigation. Furthermore, a wave information support system is proposed for entering ships as one technique for improving the safety of ship operations. This system predicts the run of waves and reduces the danger by identifying the most dangerous point near the harbor entrance at the small wave groups.

Key words : *Support system for entering ship, Wave prediction, Wave groups, Boussinesq equation*

1. Introduction

It is very important to keep the ship operations safety within a harbor. Oceanographic conditions, especially waves, have a significant influence on safety in the ship operations. Estimates of wave action are necessary for the precise evaluation of its potential threat to ships.

The study of waves and their impact on shipping within harbors is an important aspect of the design and operation of harbors. The prediction of incoming groups of waves is particularly important for evaluating ship motion within a harbor. Such a prediction makes it possible to evaluate ship safety more accurately. The prediction of wave action near the harbor entrance, the most hazardous area for navigation, makes it possible to evaluate ship safety more precisely.

In this paper, the wave transformation model based on the Boussinesq equation is used to predict a wave groups near a harbor in shallow water. This wave information support system appears to be useful to entering ships because it predicts the wave groups.

2. Characteristics of Wave Groups

It is generally known that high waves tend to be observed successively, showing high wave groups and low

wave groups(Sawaragi, 1995). The grouping of high waves may influence the long-period oscillation of moored vessels and other floating structures, which are subjected to irregular waves(Goda, 1985). In addition, wave groups significantly influence ship safety as vessels enter and depart ports.

Fig. 1 Characteristics of wave groups by questionnaire surveys

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Consequently, it is necessary to understand the characteristics of incoming wave groups to provide safe conditions for navigation. Questionnaire surveys on wave characteristics in Japan have shown that navigators find it most difficult to navigate the run of waves, particularly, a succession of high waves. Furthermore, the findings have shown that most navigators rely on their practical experience to determine the best times to enter a harbor during a period of low waves.

As shown in Fig. 1, many harbors show the characteristics of "3H 4L"(3 high waves, 4 low waves), but there are also harbors that show the characteristic of "3H 8L"(3 high waves, 8 low waves) in the Pacific Ocean side(Kubo et al., 1996).

3. Assessment of the Boussinesq Model for Wave Group

3.1 Calculation Conditions

Accurate numerical simulations of wave disturbances within harbors require that both nonlinear and dispersive wave processes be considered in order to capture physical effects such as wave refractions, reflection, diffraction etc. Boussinesq equations are in the simplest class of mathematical models that contain all these effects in a variable depth of shallow water(Hirayama, 2002).

Fig. 2 Definition of the coordinate system

The coordinate system in this numerical model is illustrated in Fig. 2. The governing equations have the form of Eqs.(1), (2) and (3) (Madsen et al, 1992).

$$\frac{\partial \eta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0 \quad (1)$$

$$\begin{aligned} & \frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left(\frac{P^2}{D} \right) + \frac{\partial}{\partial y} \left(\frac{PQ}{D} \right) + gD \frac{\partial \eta}{\partial x} \\ & - \nu \left(\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} \right) + \epsilon P + \frac{f}{2D^2} P \sqrt{P^2 + Q^2} \\ & = \left(B + \frac{1}{3} \right) h^2 \left(\frac{\partial^3 P}{\partial x^2 \partial t} + \frac{\partial^3 Q}{\partial x \partial y \partial t} \right) + Bgh^3 \left(\frac{\partial^3 \eta}{\partial x^3} + \frac{\partial^3 \eta}{\partial x \partial y^2} \right) \\ & + h \frac{\partial h}{\partial x} \left(\frac{1}{3} \frac{\partial^2 P}{\partial x \partial t} + \frac{1}{6} \frac{\partial^2 Q}{\partial y \partial t} \right) + h \frac{\partial h}{\partial y} \left(\frac{1}{6} \frac{\partial^2 Q}{\partial x \partial t} + \frac{1}{3} \frac{\partial^2 P}{\partial y \partial t} \right) \\ & + Bgh^2 \left\{ \frac{\partial h}{\partial x} \left(2 \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2} \right) + \frac{\partial h}{\partial y} \frac{\partial^2 \eta}{\partial x \partial y} \right\} \end{aligned} \quad (2)$$

$$\begin{aligned} & \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{PQ}{D} \right) + \frac{\partial}{\partial y} \left(\frac{Q^2}{D} \right) + gD \frac{\partial \eta}{\partial y} \\ & - \nu \left(\frac{\partial^2 Q}{\partial x^2} + \frac{\partial^2 Q}{\partial y^2} \right) + \epsilon Q + \frac{f}{2D^2} Q \sqrt{P^2 + Q^2} \\ & = \left(B + \frac{1}{3} \right) h^2 \left(\frac{\partial^3 P}{\partial x \partial y \partial t} + \frac{\partial^3 Q}{\partial y^2 \partial t} \right) + Bgh^3 \left(\frac{\partial^3 \eta}{\partial x^2 \partial y} + \frac{\partial^3 \eta}{\partial y^3} \right) \\ & + h \frac{\partial h}{\partial x} \left(\frac{1}{6} \frac{\partial^2 P}{\partial y \partial t} \right) + h \frac{\partial h}{\partial y} \left(\frac{1}{6} \frac{\partial^2 P}{\partial x \partial t} + \frac{1}{3} \frac{\partial^2 Q}{\partial y \partial t} \right) \\ & + Bgh^2 \left\{ \frac{\partial h}{\partial x} \frac{\partial^2 \eta}{\partial x \partial y} + \frac{\partial h}{\partial y} \left(\frac{\partial^2 \eta}{\partial x^2} + 2 \frac{\partial^2 \eta}{\partial y^2} \right) \right\} \end{aligned} \quad (3)$$

where, P and Q are the depth-integrated velocity component in the x and y directions at each calculation mesh point, η is the surface elevation, h is the still-water depth, D is the total water depth, $B=1/15$ is the parameter for optimizing the dispersion characteristics, f is the coefficient of the friction at the sea bottom, ν is the coefficient of the vortex dynamic viscosity at breaking waves, and ϵ is the coefficient of the energy dissipating at the coastal line.

3.2 Application of the Boussinesq Model

Target port is located in Hyogo Prefecture, Japan. Fig. 3 is a setup of the calculation domain for K Port. Two kinds of wave recorders were installed near the harbor entrance. One is a submarine type at Points 1, 2 and 4, and the other is a buoy type at Point 3, as shown in the figure. Hence, the time series data arranged in the position shown from Points 1 to 14 are calculated in the simulation. Using the boundary condition, three breakwaters are arranged in 1200m×925m. The difference mesh interval is 5m. Simulations were carried out for 1200s considering time steps of 0.2s (Kubo et al., 2005).

Fig. 3 Hydraulic model at K port

Table 1 Calculation condition in this model

Height & Period	Main Direction	Component Wave	S_{max}
$H_{1/3}$: 1.46m $T_{1/3}$: 8.48s	22 deg	204	25

Fig. 4 shows an illustration of the observed wave history and spectrum results for 20 minutes, at the time when the numerical simulation was carried out. At that time, a significant wave height was 1.46m, and a significant wave period was 8.48s. As may be also seen in Fig. 4, the phenomenon of run of waves can be clearly observed.

3.3 How to Give Incident Waves

Irregular waves may be separated into some component waves by carrying out the Fourier transform of the irregular wave profile. Furthermore, the wave direction of these component waves is not uniform, such waves are referred to as multi-directional random waves. Generally, offshore waves are multi-directional random waves.

As usual, offshore waves are given by the directional spectrum using the typical energy balance equation, which is one of the methods used for calculating waves.

With this method, the spatial change of the wave energy in each frequency is calculated. By overlapping the waves linearly, the wave energy propagation in a target sea area is calculated. However, in order to analyze the time series in this paper, it is necessary to calculate the incidence of the wave profile, which changes constantly, and not that of something averaged by the spectrum.

Fig. 4 Observed wave history and spectrum

In order to calculate the incidence as a time series, the Fast Fourier Transform of the observed wave profile at Point 1 for 20 minutes was used. Since the number of data required for spectral analysis is based on 2^n pieces, in this case, 4096 pieces of measurement wave data are required for the numerical calculation. And it gives on incident boundary by making irregular wave formed by formula (4) obtained information of component waves into time series.

$$\eta = \sum_{n=1}^{\infty} \left\{ a_n \cos \left[k_n (x \cos \theta_n + y \sin \theta_n) - \sigma_n t + \varepsilon_n \right] \right\} \quad (4)$$

where a_n , f_n , θ_n and ε_n are the amplitude, frequency, wave direction, and initial phase of the n -th regular waves, respectively.

3.4 How to Determine Wave Direction

Generally, each wave direction of component waves is given with S_{max} (spreading parameter) and a random number by the directional spreading function, which shows the energy distribution of a wave.

However, it is possible to calculate wave direction, not only principle direction but also in each frequency due to the current velocity was also measured together when waves observed in this study. The Lissajous figure is determined for each component period, the wave direction is estimated relative to the component period in the diagram, as shown in Fig. 5.

Fig. 5 Estimated wave directions by the component wave velocities

4. Wave Prediction near the Harbor

To predict the wave near harbor entrance, the incoming wave given as an offshore wave at Point 1 and the propagated wave at Point 4 are calculated. The accuracy of this model is examined by comparing the wave profile calculated by this model and observation data obtained by a wave recorder at Point 4.

4.1 Analytical Method of Wave Groups

Funke and Mansard(1980) proposed the following new parameter GF(groupiness factor) to provide additional information of the wave grouping besides the run length and the repetition length of high waves.

The method for analyzing a wave groups is classified as follows.

- 1) Method A: analyzing by wave height
- 2) Method B: analyzing by wave envelope
- 3) Method C: analyzing by energy change of wave

From the viewpoint of the continuity of the phenomenon, methods B and C are excellent. Method C, used in this study, is called a smoothed instantaneous wave energy history (abbreviated SIWEH); it shows the time change by the smooth value of the wave energy and calculates the square root of SIWEH ($RE(t)$).

$$RE(t) = \sqrt{E(t)} \quad (5)$$

$$E(t) = \frac{1}{T} \int_{-\infty}^{\infty} \eta^2(t+\tau) Q(\tau) d\tau \quad (6)$$

where τ is the time lag, T_p is the peak period of the wave spectrum, $E(t)$ is SIWEH and $Q(\tau)$ is the data window for which they recommended using the following function.

$$Q(\tau) = 1 - \left(\frac{|\tau|}{T_p} \right) : |\tau| \leq T_p$$

$$Q(\tau) = 0 : |\tau| > T_p \quad (7)$$

If the square root of SIWEH is used, it is possible to predict a small wave group at the stage of a ship entering a harbor. That is, the square root of SIWEH is used by wave group prediction, because it is easy to treat wave characteristic more than time series, and it can be also expressed both small wave groups and large wave groups.

Fig. 6 expresses the procedure used to compare the results after the square root of SIWEH is calculated. It is the result that two upper figures comparing the time series wave profile of predicted value and observed value, with the value of square root of SIWEH at Point 4. Moreover, lower figure compare with two square root of SIWEH.

Fig. 6 Method used to calculate waves

4.2 Wave Prediction Result

The wave prediction method examined in this paper does not predict time series waves; rather, it tends to predict small wave groups (*i.e.*, a succession of low waves) using the square root of SIWEH.

Fig. 7 shows a comparison of the observed and calculated values of wave groups calculated at Point 4. As shown in figure, the predicted wave at beginning part is small because it takes time to reach to Point.

Fig. 7 Results of the wave comparison

4.3 Wave Prediction at a Specified Place without Wave Recorder

Wave recorders cannot be set up near breakwaters because they then become obstacles to enter/depart ship. Therefore, wave transformation cannot be observed as it occurs violently near breakwaters.

Using this numerical model with only one wave recorder installed on the offshore side, even if there is no wave recorder near the breakwater, wave groups at specified places can be predicted.

The results of the wave prediction of the calculated wave and the square root of the SIWEH by the numerical model near the harbor entrance are shown in Fig. 8.

Fig. 8 Wave groups prediction near a breakwater by the numerical model

5. Suggestion of Wave Information Support System for Entering Ship

The study of waves and their impacts on shipping within harbors is an important aspect of the design and operation of harbors. Especially, the prediction of incoming groups of waves is particularly important for utilization ship maneuvering within a harbor. A wave information support system is suggested for use with the wave prediction model in this paper. If we know wave data offshore at one

Fig. 9 General figure of the entering support system using wave information

point, transmit real time wave data to on shore, then wave transforming calculator calculates wave groups after 10~100sec as shown in Fig. 9.

Moreover, such a system can supply information on a wave groups to entering ships. Consequently, the entering ship can take measures to speed down or change its course to avoid the most dangerous maneuvering point (*i.e.*, the altering point) due to abeam sea. Using this system, it is expected to seize an opportunity for improving safety of ships entering harbors by analyzing the effects of long-period waves.

Furthermore, if a numerical model for the motions of ships as they enter and depart a harbor could be developed in the future, it would provide a better support system for entering ships by predicting waves and ship motions.

6. Conclusion

In this paper, wave predictions at harbor entrances were performed with the Boussinesq equation as one technique for improving the safety of maritime transportation. In conclusion, the following conclusions were reached:

- (1) A nonlinear wave transformation model was applied in an actual port, and the accuracy of calculations was examined by the SIWEH.
- (2) In time of calculation of wave information, wave transformation was calculated by giving incidence not directional spectrum by typical energy balance equations but time series of wave profile at offshore varies every moment.
- (3) Wave directions were given for all waves, not only the principal wave direction but also wave directions in each frequency, furthermore, the different number of component waves were estimated.
- (4) The prior prediction method of the wave groups which vessel receives observed wave profile was examined. Moreover, the prediction procedure of the wave group phenomenon was shown.

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