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Modeling of Velocities in Giant Waves

By:

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PO-58

MANAGEMENT PERSPECTIVE

Accidental release of polluting substances threatening health and safety. Prevent the frequency/severity and environmental consequences of emergencies - ship capsizing and resulting spills.

The occurrence of unusually large waves on the Great Lakes and on the oceans is a major factor in safety and pollution prevention (The sinking of Edmund Fitzgerald on Lake Superior and the sinking of the Ocean Ranger off Newfoundland are two examples where safety was compromised by unusually large waves). The internal water velocities (and hence the forces on ships and offshore structures) are not adequately described with present models. As a result of laboratory tests at NWRI during 1994, a more complete description of the kinematics has been made. A new model has also been developed which better predicts the internal velocities under the crests of these unusually large waves. The work was funded in part by a travel grant from NATO, contract no. 930137.

The authors will investigate the need for further research on the subject.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Rejet accidentel de substances polluantes menaçant la santé et la sécurité. Limiter la fréquence, la gravité et les conséquences environnementales des urgences liées au renversement de navires et aux déversements qui en résultent.

L'occurrence de vagues exceptionnellement fortes sur les Grands Lacs et les océans est un facteur important de la sécurité et de la prévention de la pollution (le naufrage du *Edmond Fitzgerald* dans le lac Supérieur et celui de l'*Ocean Ranger* au large de Terre-Neuve sont deux cas où la sécurité a été mise en péril par des vagues inhabituellement grosses). Les vitesses internes de l'eau (et donc les forces qui s'exercent sur les navires et les structures en mer) ne sont pas décrites adéquatement dans les modèles actuels. Après des tests en laboratoire menés à l'INRE en 1994, on a pu faire une description plus complète de la cinématique. Un nouveau modèle a aussi été développé, qui prédit mieux les vitesses internes sous la crête de ces vagues exceptionnement fortes. Les travaux ont été partiellement financés par une bourse de l'OTAN, contrat n° 930137.

Les auteurs examineront le besoin de recherches supplémentaires sur le sujet.

RÉSUMÉ : L'occurrence inattendue de vagues exceptionnellement fortes a été documentée souvent. On a déterminé que des interactions non linéaires entre des vagues se déplaçant en groupes sont un important mécanisme de formation de vagues géantes sur l'océan. Dans cette étude, on utilise, pour générer des vagues plongeantes profondes en canal de laboratoire, la technique non linéaire ciblée sur le lot, modifiée pour tenir compte d'un courant opposé. La cinématique des vagues est mesurée juste en amont du début du plongement. Les résultats sont comparés à ceux d'un modèle de superposition, d'un modèle d'étirement modifié, et d'un modèle basé sur la théorie de 3e ordre de Stokes développé pour la présente étude. Ce dernier représente significativement mieux que les deux autres la vitesse derrière le déferlement en volute.

Mots clés : vagues géantes, cinématique des vagues, modélisation

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Modeling of Velocities in Giant Waves

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ABSTRACT

The unexpected occurrence of unusually large waves has been documented on numerous occasions. In this study, the nonlinear packet-focusing technique, modified to account for an opposing current, is used to generate steep, plunging waves in a laboratory flume. The kinematics of these waves are measured just upwave of the onset of plunging. These results are compared to those of a superposition model, a modified stretching model and a model based on a Stokes 3rd-order theory developed for the present study. The present model represents the velocity beneath the plunging breakers significantly better than the other two models.

INTRODUCTION

Extremely large waves, though rare, have the potential to cause massive damage to ships — see, for example, Nickerson (1993). These waves, often termed freak and giant waves (twice and 2.5 times the significant wave height, respectively), are being documented more and more, but much remains to be learned about them.

Very little is known about the statistics of freak waves and giant waves and even less of the dynamic conditions under which they occur. Nonlinear interactions among individual waves travelling within a group have been identified as an important mechanism in the formation of giant waves in the ocean (Kjeldsen, 1984). Further, it is now well documented (Kjeldsen and Myrhaug, 1980; Irvine, 1987; Kjeldsen, 1991) that situations in which nonlinear wave groups interact with strong opposing ocean surface currents can lead to the formation of freak waves and giant waves. In this paper, we investigate the kinematics of these large waves on an opposing current in laboratory tests, and propose a new kinematic model which best describes them.

EXPERIMENTS

In order to investigate the kinematics of wave groups travelling on an opposing current, a set of experiments was conducted in the large wave tank at the Canada Centre for Inland Waters. A mean flow (U_M) of 0.040 m/s (±10%, away from the walls and bottom) was used for the experiments in addition to no flow.

The water surface elevation was measured to within ±2 mm using 4 capacitance wave staffs. The velocity was measured with an acoustic Doppler current meter (Sontek ADV-1) mounted horizontally on the carriage (Fig. 1).

The focus of the tests was to measure the kinematics in the wave crest just prior to breaking. Kjeldsen's technique (1982), with modifications to include current, was used to generate the waves. This nonlinear wave generation technique causes a wave group to coalesce at a predetermined location in the tank. Typically, the current meter was less than 1 m upwave of the point in the tank where the front face of the crest became vertical, marking the start of plunging.

LABORATORY RESULTS

Surface Profiles

Examples of water surface profiles just upwave of breaking, normalized by the peak wave number $k_{\hat{o}}$, are shown in Fig. 2a. The plunging waves were very repeatable even in opposing currents. The waves were clearly very steep, with crest-front steepnesses in the 0.25-0.41 range (I.A.H.R./P.I.A.N.C., 1986). In comparison with these laboratory steepnesses, crest-front steepnesses of freak waves measured with wave radar were in the same range on the Norwegian Continental Shelf (Kjeldsen, 1989) and in the North Sea (Sand et al., 1989).

In Fig. 2b, examples of time series of velocity normalized by

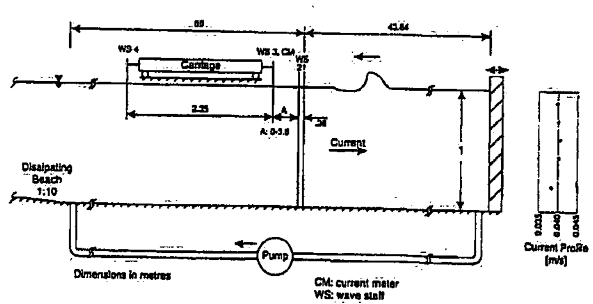

Fig. 1 Sketch of CCIW wind-wave flume showing location of wave staffs and current meter. Tank is 100 m long and 4.5 m wide. Vertical profile of current, 3.6 m downstream of WS2, shown in panel on right.

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KEY WORDS: Giant waves, wave kinematics, modeling.

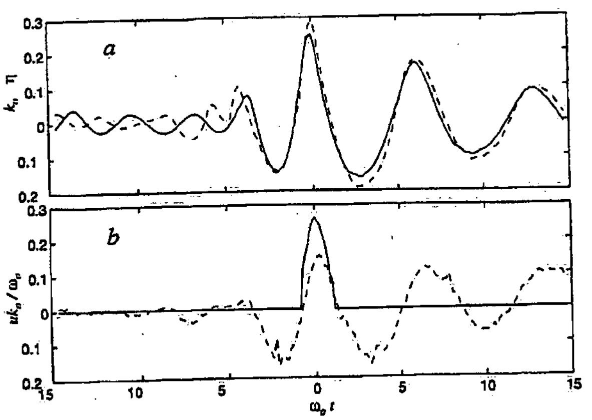

Fig. 2 Panel a: time series of water surface elevation from wave staff 3 (WS3), just upwave of breaking, normalized by peak wave number (k_o = 1.38) and frequency (ω_o): — U_M = 0, ε = 0.30; - - - U_M = 0.040 m/s, ε = 0.36. Panel b: corresponding normalized horizontal velocity for U_M = 0.040 m/s: — 0.04 m above still water level; - - - 0.20m below still water level. (Zero velocity indicated when probe above surface.)

the peak frequency ω_o and k_o are shown for 2 elevations beneath the wave crest.

Velocity Profiles

The maximum horizontal velocities beneath the crest just upwave of the breaking position are shown by the asterisks in Fig. 3. Replicate velocity measurements were taken at the nondimensional elevation of –0.05, and lines showing twice the standard deviation (approximately equal to the 95% confidence interval) are plotted. The variability increases from ±0.007 to about ±0.02 m/s from the no-flow to the 0.04 m/s flow case.

KINEMATIC MODELS

In the offshore industry, a stretching theory developed by Wheeler (1970) has traditionally been used for predicting kinematics in irregular sea states. In this study, we use a modified stretching model (Lo and Dean, 1986) as representative of this class of model. We also used the superposition method proposed by Donelan et al. (1992). Even when adapted to account for a mean flow, these linear models do not adequately represent the velocity beneath the coalescing group (Fig. 3).

Baldock et al. (1996) developed a second-order theory based on work by Longuet-Higgins and Stewart (1960), and used this to predict the measured kinematics in coalescing wave groups. However, comparison with their experimental data suggested that many of the wave-wave interactions occur at a higher order of wave steepness.

In the present study, we developed a third-order simulation of the kinematics in the steep wave crests. This third-order simulation technique is based on a combination of 2 earlier models. The first of these was developed by Kishida and Sobey (1988) and simulates a Stokes third-order wave train on a current with a linear profile. Assuming 2-dimensional, steady and inviscid flow, they write the governing Laplacian equation, and surface and bottom boundary conditions, in terms of the stream function. Here, a reference frame x, z located at the bottom and moving at the Stokes wave speed is used. The effects of vorticity, $\Omega = -\partial^2\psi/\partial x^2 - \partial^2\psi/\partial z^2 = \partial W/\partial x - \partial U/\partial z$, where U is the velocity in the direction of the waves and W is the vertical velocity, are accounted for in the dynamic free-surface boundary condition. In a current with a linear profile, $U(z) = U_M + \Omega_0\,(z - 1/2\,h)$, where h is the depth, U_M is a constant, and the vorticity is constant at $-\Omega_0$ throughout the fluid domain. To determine Ω_0, vertical profile measurements were made of the current in the tank. Estimates of $\Omega_0 \approx -\partial U/\partial z$ were made using vertical velocity profile measurements, giving 0.01 for the 0.04 m/s current condition. It is interesting to note that the values of Ω_0 in the laboratory tank were of the same order as those in the Gulf Stream, based on XBT data from the Surface Wave Dynamics Experiment data base (Oberholtzer and Donelan, 1996).

The problem as formulated above is complicated by the nonlinearity of the dynamic surface boundary condition, and the fact that the surface itself, $\eta(x)$, is unknown and must be found as part of the solution. As first proposed by Stokes (1847), who dealt with the irrotational problem, a solution can be obtained by the method of perturbation (Kishida and Sobey, 1988; Drennan et al., 1992).

However, this model does not give a complete description of the complete wave spectrum developed by the command signal in the wave flume: It yields results only for that frequency component corresponding to k_o above. Thus, the wave superposition model developed by Donelan et al. (1992) is also used. The procedure for the simulation then becomes:

1. A third-order wave train interacting with a current with a

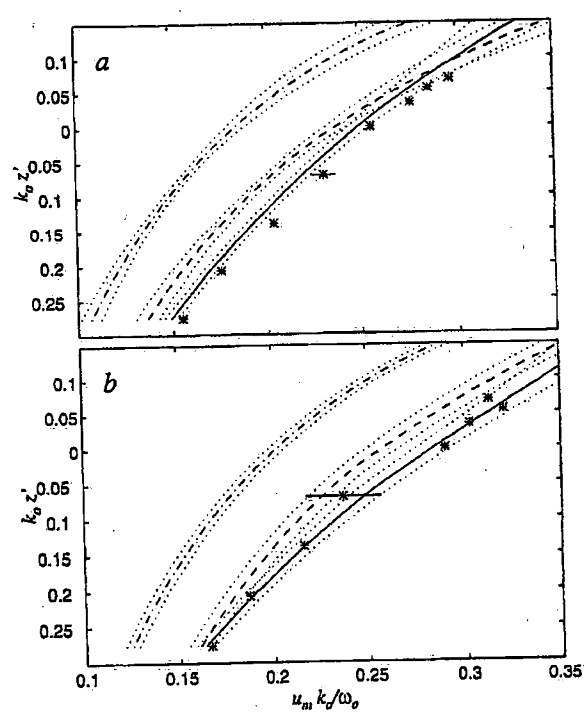

Fig. 3 Normalized maximum horizontal orbital velocities (u_m) beneath crest just upwave of breaking (corresponding to Fig. 2) versus elevation (z') normalized by k_o. *: measured values; - - -: mean of linear superposition model; -·-: mean of modified stretching model; —: present model. Horizontal bar on data point at 0.05 elevation represents 2 standard deviations about mean. Dotted lines around model lines enclose twice standard deviations. a): U_M = 0; b): U_M = 0.04 m/s.

constant vorticity is simulated.

2. The third-order wave train is subtracted from the experimentally obtained free-surface elevation.

3. The kinematics of the remaining wave signal are analysed using the linear model of Donelan et al. (1992).

4. Finally, the solutions obtained in steps 1 and 3 above are added, using the free surface of the nonlinear wave as mean water level for the additional wave components, in agreement with the concept behind the development by Donelan et al. (1992).

Model Comparison

The mean predicted velocity profiles beneath the crests using the modified stretching, superposition, and the present model for the 2 cases are shown in Fig. 3 along with the laboratory profiles. The models were run for the surface elevation time series of all of the laboratory runs (more than 20 runs for each condition), and the resulting mean profiles plotted. The dotted lines indicate plus and minus twice the standard deviation (approximately equal to the 95% confidence interval) for each.

The kinematic model developed here best reproduces the data. When no current is present, it slightly underestimates the velocity, lying just outside the 2 standard deviation range. The model results are remarkably close to the data for the 0.04 m/s current.

CONCLUSIONS

The present third-order kinematic model better represents the velocity beneath unusually large waves than the modified stretching model and the linear superposition model. It can be used for computation of ringing effects on platforms and represents a possible alternative to the U.K. Guidelines (Barltrop, 1989) for design in cases where waves and currents act simultaneously.

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