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Modelling of velocities in unusually large waves

By:

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MODELLING OF VELOCITIES IN UNUSUALLY LARGE WAVES

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Abstract. The unexpected occurrence of unusually large waves has been documented on numerous occasions. While little is known about the statistics of these waves, even less is known of the dynamical 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. In this study, the non-linear 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 up-wave of the onset of plunging, and these results are compared to those of a superposition model, a modified stretching model, and a model based on Stokes 3rd order developed for the present study. The present model represents the velocity beneath the plunging breakers significantly better than the other two models.

Résumé. La présence imprévisible de vagues anormalement grandes a fait l'objet de nombreux documents. Bien que l'on ne dispose que de statistiques peu nombreuses sur les vagues phénoménales ou géantes, on connaît encore moins bien les conditions dynamiques dans lesquelles elles surviennent. On a déterminé que les interactions non linéaires entre les vagues individuelles qui se déplacent en groupe sont un mécanisme important de la formation de vagues géantes dans l'océan. Dans le cadre de la présente étude, on génère des vagues cambrées déferlantes dans un glissoir expérimental en employant la méthode non linéaire par paquets, modifiée pour tenir compte des courants contraires. On procède à une analyse cinématique des vagues en mesurant le courant acoustique sous la crête à l'amorce du déferlement en volutes; les résultats sont comparés à ceux d'un modèle de superposition, à ceux d'un modèle d'élongation modifié et à ceux d'un modèle fondé sur les équations de Stokes de troisième ordre et mis au point pour la présente étude. Le modèle décrit la célérité de l'onde en deçà du déferlement en volutes beaucoup mieux que les deux autres modèles.

MANAGEMENT PERSPECTIVE

Title: **Modelling of Velocities in Unusually Large Waves**

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

Current Status: 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 large waves). These are waves larger than normally predicted using typical operational methods. There are two technical issues: when do they occur and how big are they; can the internal water velocities (and hence the forces on ships and offshore strucutres) be adequately described with present models so that ships and offshore structures can be safely designed? It turns out that existing models are not adequate. As a result of laboratory tests at NWRI during 1994-6, a new model has been developed which models better the internal velocities under the crests of these unusually large waves. This work was funded in part by a travel grant from NATO, contract no. 930137.

Next Steps: A paper will be presented at the Canadian Coastal Conference 1997. The work will be refined and submitted for journal publication to make the appropriate professional community aware of the improved modelling capability.

INTRODUCTION

The unexpected occurrence of unusually large waves, freak waves and giant waves, has been documented on numerous occasions. In this context "freak" and "giant" mean waves whose height is in excess of twice and 2.5 times the significant wave height respectively. Both Canada and Norway have suffered from severe accidents in which such waves occurred. The capsize of the semisubmersible platform "Ocean Ranger" off Newfoundland initiated with the impact of such a wave, crushing one of the windows of the control room and resulting in loss of watertight integrity and the loss of 84 lives due to capsizing. There are several areas around the world where unusually large waves occur from time to time such as the sea near Cap Farvel south of Greenland, and in the Agulhas current east of South Africa. Along the Norwegian coast, 26 ships were lost in capsizing accidents within a period of only 9 years. 72 people lost their lives due to unexpected large waves in normal gale conditions, and the traditional shipping route along the coast was then finally changed. In addition some severe near accidents have occurred to fast catamarans both in Norwegian waters and in the North Sea, resulting in severe heavy weather damages.

Very little is known about the statistics of freak waves and giant waves and even less of the dynamical 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). Other contributing factors are the focusing of waves on continental shelf edges and the interaction of surface gravity waves with internal wave fields. Furthermore 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 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 were conducted in the large wave tank at the Canada Centre for Inland Waters. The tank dimensions are 100 m by 4.5 m (Figure 1), and the water depth for all of the runs was 1.0 m. The experiments were conducted at about the mid point of the tank, so that wave energy reflected from the beach at the down wave end of the tank did not reach the experiment site during the course of the passage of the wave group. The beach, of uniform slope of 1:10, is composed of crushed stone with nominal size of 5 cm. The wave groups were spaced at least ten minutes apart to allow for the wave energy to be dissipated by the beach.

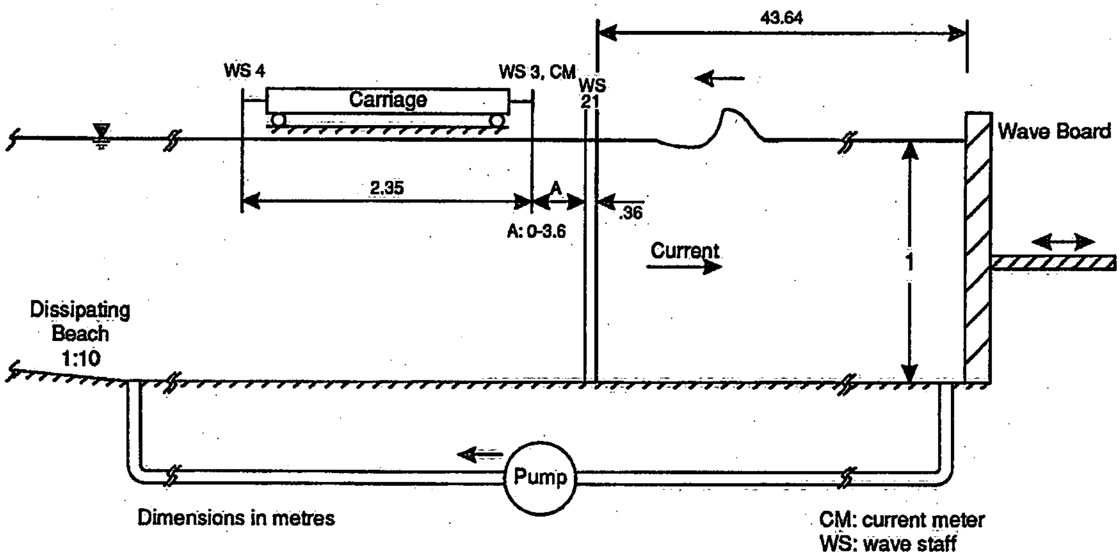

Figure 1. Sketch of the CCIW wind-wave flume showing the location of the wave staffs and the current meter.

The mean flow in the tank, in the opposite direction to the wave travel, was generated with a pump. The flow entered the tank through a diffuser in the floor about 36 m downwave from the measuring station, and left the tank immediately in front of the wave board, also through a floor diffuser. The flow at the measuring station was mapped and found to be two dimensional within ±10% of the mean, away from the side walls. Mean flows (U_M) of 0.040 and 0.095 m/s were used for the experiments.

The water surface elevation was measured using four capacitance type water surface piercing wave staffs of 0.5 mm diameter teflon insulated wires. Two were fixed in the tank and two were on a movable carriage, and all were located 0.3 m off the longitudinal centreline of the tank. The surface elevation measurements were accurate to within ±2 mm. The velocity was measured with an acoustic doppler current meter (Sontek ADV-1) mounted on the carriage, with its sensing volume located 0.6 m off the centreline of the tank. The current meter and one wave staff on the carriage (WS3) were positioned perpendicular to the wave direction. The current meter was mounted horizontally, so that the three probe arms formed a 77 mm diameter circle parallel to the wave direction. Furthermore all three probes have to be submerged for the meter to function properly. These placed a limit on how close the meter could be to the breaking point of the wave crest. The current meter was used at its maximum velocity range of ±2.5 m/s, resulting in maximum noise of ±2.5 cm/s. The current meter was positioned to the desired elevation before the beginning of each run. The current meter requires 'seed' material in the water to function. The water used in the tank did not contain enough natural seed for the meter, so hollow glass beads of nominal diameter of 10 microns were added to the water. Procedures were developed and followed to ensure that there was always enough seed material present during the runs to maintain the signal to noise ratio above that recommended by the supplier. The velocity and wave staff data for each run were logged on the current meter computer at 25 Hz. All of the wave staff data were filtered with 10 Hz filters, and amplified as required.

The focus of the tests was to measure the kinematics in the wave crest just prior to breaking. The technique of Kjeldsen (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. The command signals were designed to reproduce a given wave spectrum, and focus all individual wave components contained in the spectrum into one large wave, approximating the ultimate wave condition that can be met at sea. Because of small experimental variations, the exact location of breaking and the closest distance to it at which the current meter could be operated was found experimentally. Typically the locations were less than 1 metre upwave of the point in the tank where visual observations indicated the front face of the crest became vertical and surface irregularities began to form on the crest, marking the start of plunging. To position the current meter closer to the plunging location caused the downwave probe arm to be exposed at the desired measurement time. Furthermore, the measurement of the surface elevation had to be made slightly upwave of plunging to ensure a valid record for use in the velocity models. Later discussion of the steepness of the crest front measured in the tank indicates that the achieved measurement location was very close to the maximum surface elevation.

For horizontal velocity measurements under the crest where the meter was exposed above the preceding wave trough, the individual time traces were examined to ensure the meter was functioning properly at the crest. All of the wave groups had crest elevations at incipient breaking of about 20 cm above still water level (SWL). This technique allowed measurements to an elevation of 5 cm above SWL. Attempts were made to obtain velocity measurements from a surface elevation following platform, to get closer to the water surface, but these were unsuccessful due to instrument difficulties.

LABORATORY RESULTS

Surface Profiles

The water surface elevations (η) just upwave of breaking were measured, and the crest front steepness (ε) computed, the latter being the ratio of the crest height above SWL to the horizontal distance from the crest to the intersection with the SWL in front of the crest (see I.A.H.R./P.I.A.N.C. 1986). Fourier analysis of each surface profile was used to find the peak frequency, ω_o, and hence the peak wave number, k_o. These were then used for normalizing the results. Examples of non-dimensional surface elevation plots for each of the current conditions are shown in Figure 2. The plunging waves were very repeatable even in opposing currents. The waves were clearly very steep, with crest front steepnesses in the range 0.25 - 0.41. 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).

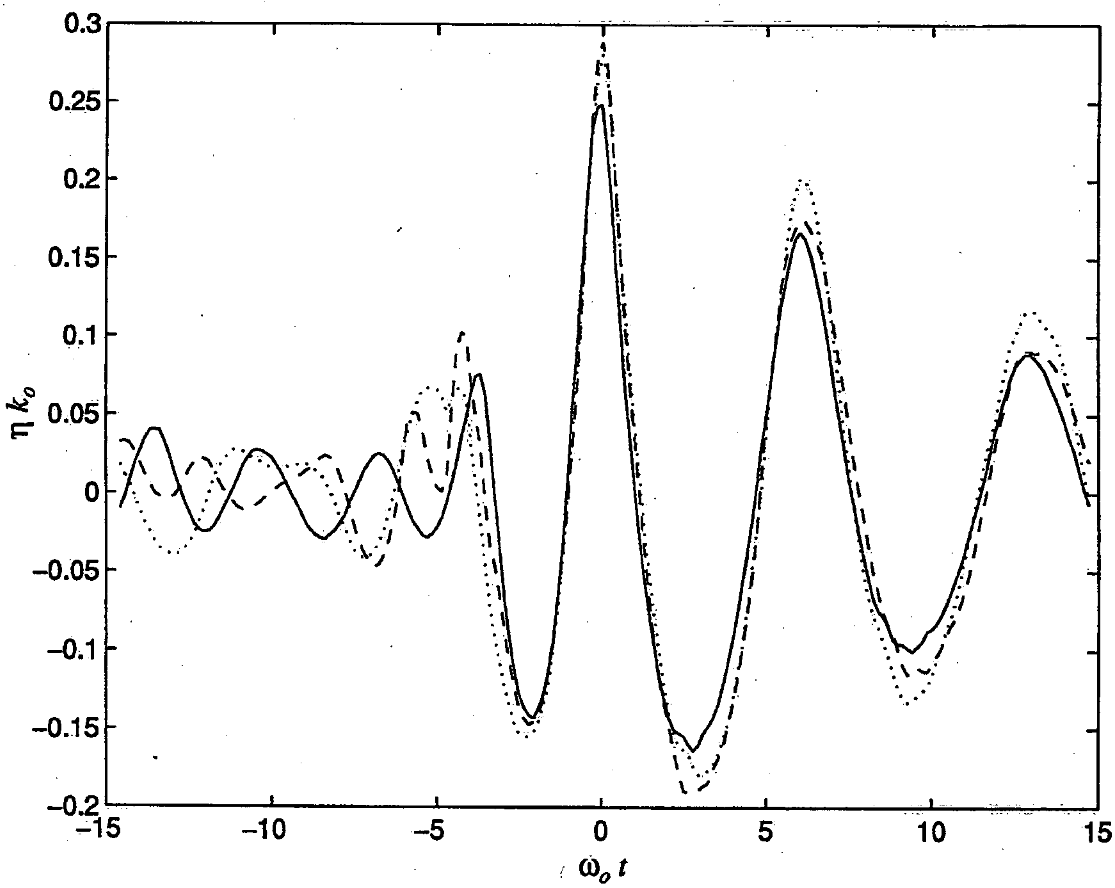

Figure 2. Time series of the water surface elevation from wave staff 3 (WS3), just upwave of breaking, normalized by the peak wave number (k_o=1.38) and frequency (ω_o): — U_M=0, ε=0.30; - - - U_M=0.040 m/s, ε=0.36; ··· U_M=0.095 m/s, ε=0.33.

Velocity Profiles

The maximum horizontal velocities beneath the crest just upwave of the breaking position are shown by the asterisks in Figure 3. Data were obtained over the range of dimensionless elevation of about -0.3 to 0.1, or in physical units, from -0.2 to 0.05 m elevation with respect to the still water level (z'). The profiles are qualitatively in agreement with simple wave theory. In the next section horizontal velocities under the wave crests are computed from two existing models and compared to these data. A new model is also proposed and compared.

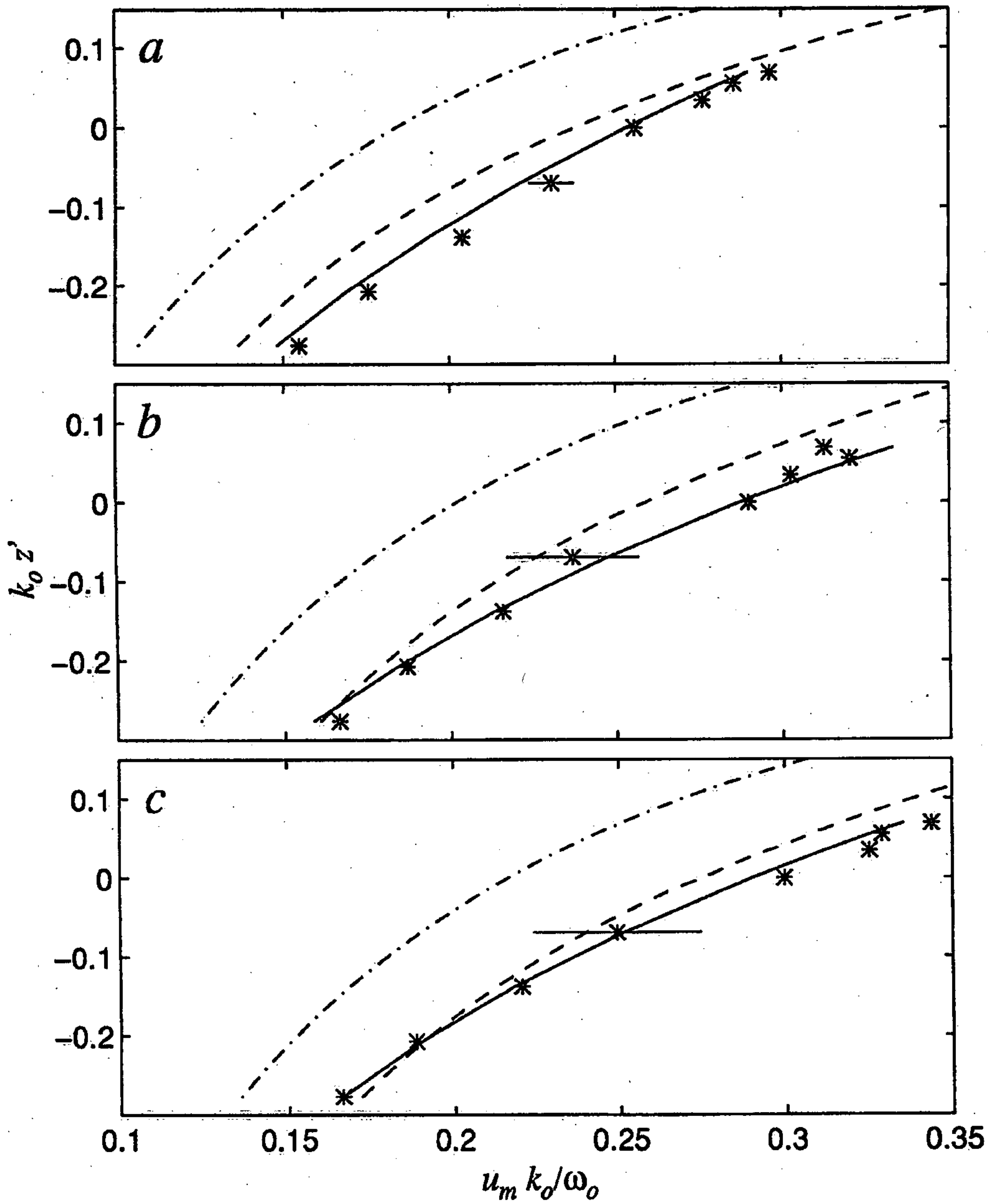

Figure 3. Maximum horizontal orbital velocities (u_m) beneath the crest just upwave of breaking (corresponding to Figure 2), normalized by k_o and ω_o, versus elevation (z') normalized by k_o. *: measured values; - - -: mean of linear superposition model; ---: mean of modified stretching model; —: present model. The horizontal bar on the data point at the elevation of 0.05 also represents two standard deviations about the mean. a): $U_M = 0$; b): $U_M = 0.04$ m/s; c): $U_M = 0.095$ m/s.

Replicate velocity measurements were taken at the nondimensional elevation of -0.05, and twice the standard deviation (approximately equal to the 95% confidence interval) are plotted. The variability is least for no current and increases to about ±0.03 m/s at the highest flow, the increased variablility being due in part to the turbulence of the mean current.

KINEMATIC MODELS

In the offshore industry a stretching theory developed by Wheeler (1970) has traditionally been used for prediction of 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 (Donelan et al. (1992) report that it produces velocities very similar to the Wheeler method). We also used the superposition method proposed by Donelan et al. (1992), based on the linear superposition of a sum of freely propagating wave trains. Even when adapted to account for a possible mean flow, these linear models do not adequately represent the velocity beneath the coalescing group, see Figure 3. We elaborate on this below.

Baldock et al. (1996) also found that stretching methods based on linear theory were not able to predict the kinematics in the highest crests. Baldock et al. therefore 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, although the second order solution provides an improved description of the water surface elevation in coalescing wave groups, many of the wave-wave interactions occur at a higher order of wave steepness.

In the present study we therefore developed a third order simulation of the kinematics in the steep wave crests. This third order simulation technique is based on a combination of two 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 two-dimensional, steady and inviscid flow, they write the governing Laplacian equation, and surface and bottom boundary conditions, in terms of the stream function $\psi(x,z)$. Here, a reference frame x,z located at the bottom and moving at the Stokes wave speed is used. The effects of vorticity, $\Omega = -\frac{\partial^2\psi}{\partial x^2} - \frac{\partial^2\psi}{\partial z^2} = \frac{\partial W}{\partial x} - \frac{\partial U}{\partial z}$, 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, $U(z) = U_M + \Omega_0 \, (z - \frac{1}{2} h)$, where h is the depth, U_M is a constant, and the vorticity is constant at $-\Omega_0$ throughout the fluid domain.

For our tests, the vorticity was estimated from the vertical profiles of the mean current to be 0.01 and 0.02 s^{-1} for the low and high currents respectively.

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) employ the dimensionless waveheight, $\alpha_o=k_oH/2$, originally introduced by Schwartz (1974) as the expansion parameter (see also Drennan et al., 1992). Here H is the wave height. The complete solution for $\psi(x)$ and $\eta(x)$ to third-order is given in Kishida and Sobey (1988); it is too lengthy to be repeated here.

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. Therefore 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 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 is 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 non-linear wave as mean water level for the additional wave components, in agreement with the concept behind the development of 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 three current cases are shown in Figure 3 along with the laboratory profiles. The modified stretching and superposition models were run for the surface elevation time series of all of the laboratory runs (more than 20 runs for each current condition), and the resulting mean profiles plotted. The modified stretching model underpredicts the velocity significantly throughout the profile. The superposition model more nearly represents the data. When there was no current, the velocity is under predicted at lower elevation, and more closely predicted towards the surface. For 0.040 and 0.095 m/s currents, the predicted velocity falls within two standard deviations of the measured velocity, but there is a systematic bias to lower values.

The model developed here best reproduces the data. At no flow, it slightly underestimates the velocity, lying just outside the two standard deviation range. For the two flows, the model results are remarkably close to the data.

CONCLUSIONS

The technique of Kjeldsen (1982), modified for opposing currents, was able to generate consistently unusually large waves, with crest front steepnesses in the range 0.25 - 0.41. The present third order kinematic model represents the velocity beneath unusually large waves better than the modified stretching model and the linear superposition model. It therefore represents an alternative to the U.K. Guidelines (Barltrop, 1989) for design in cases where waves and currents act simultaneously.

Rules for design of steel jackets have recently been changed in order to provide improved design when waves and currents are present at the same time, the normal situation (Mercier, 1982). After the ringing effect on platforms caused by resonance with high nonlinear waves was discovered, a considerable amount of work has been done to develop computational models for wave forces that take this phenomenon into account (Sterndorff and Thesbjerg, 1996). It is believed that the kinematic model developed within this study can contribute to investigations of the ringing effect.

ACKNOWLEDGMENT

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