LAGRANGIAN MEASUREMENTS OF ACCELERATIONS IN THE CRESTS OF BREAKING AND BROKEN WAVES.

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Abstract.

The present investigation reports synoptic measurements and analysis of particle accelerations and kinematics of plunging crests in deep water wave groups. The unexpected occurrence of unusully 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 on an opposing current have been identified as an important mechanism in the formation of giant waves in deep waters in the ocean. In this study, the non-linear packet-focusing technique is used to generate steep, deep water plunging waves in two laboratory flumes. In one of these flumes the plunging breakers were generated on opposing currents. 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 theory combined with a linear wave spectrum for an irregular sea on an opposing current, developed for the present study. The present model represents the velocity beneath the plunging breakers significantly better than the two other models.

1. Introduction.

Breaking waves play an essential role in air-sea interactions, and in assesment of impact loads on both fixed and floating coastal structures, platforms and ships see (Kjeldsen, 1997). Further breaking waves are very important for mixing and spreading of oil pollution in the upper surface layers of the sea. The dynamic action of the crest of a plunging breaker thus becomes particularly important. Even now when theoretical and numerical treatments of the breaking problem have progressed, controlled experimental measurements for development and calibration of numerical ocean basins are needed. The present investigation reports synoptic measurements and analysis of particle accelerations and kinematics of plunging crests. Furthermore a third order simulation technique is developed in order to predict wave kinematics in extreme waves occurring in irregular seas containing coalescing wave groups.

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2. Experiments.

One series of experiments were performed in the large (40 m long) Air-Sea Interaction Simulation Facility of the I.O.A. laboratory of the I.R.P.H.E. Institute, located in Marseille. The wave generation technique developed by (Kjeldsen 1982) was used for production of plunging breaking crests in deep water wave groups. A visualization technique (Bonmarin 1989) makes the wave profile visible and an associated image analysis process allows measurements of both the water surface geometry, crest front steepness and asymmetry (Kjeldsen & Myrhaug 1978), (IAHR/PIANC 1986), as well as detailed measurements of accelerations of tracer particles dragged away by breaking and broken waves. Ten experiments designated by the reference of A11 to A21 were performed.

Another series of experiments were performed in the large wave tank at the Canada Centr for Inland Waters. The tank dimensions are 100 m in length, 4.5 m in width and the water depth for all runs were 1 m.The water surface elevations were measured using four capacitanc type water surface piercing wave staffs; two were fixed in the tank and two were on a movabl carriage. The velocity was measured with an acoustic Doppler current meter (Sontek ADV-1) mounted on the carriage. The surface elevation data and the velocity data for each run were logged on the current meter computer at 25 Hz. A 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 immediatly in front of the wave board, also through a floor diffuser. Mean flows (U_M) of 0.04 and 0.095 m/sec were used for the experiments.

3. Results.

A Lagrangian measurement technique is needed in order to measure particle accelerations accurately in non-linear waves, see (Longuet-Higgins 1986.) In order to develop such a technique the wave-following properties of the tracer particles were mapped. A calibration experiment was performed with a symmetric regular wave with steepness ak = 0.31. Fig 1 shows the measured trajectory, and a theoretical trajectory predicted by second order wave theory. A significant Stokes drift in agreement with the theory was obtained. This relative goo agreement between experiment and theory validates the choice of the floating particles.
In the breaking waves the different steps of the measurements were i) the reconstruction of th trajectory of the floating particles, ii) measurements of their celerity, and iii) the measurement of their acceleration, these two last measurements being deduced from the trajectory. Fig. 2 shows an example of surface elevation and location of tracer particles in a plunging breaker developing in deep water. Fig. 3 shows the reconstruction of the trajectories of floating particles, one of them colliding with a breaking crest. Fig 4 shows an example of measured horizontal velocities of two particles P2 and P3, shown in the experiment A15,as it develops in Fig. 2. The horizontal velocities are normalized with the wave phase velocity c. Particle P3 reaches a horizontal velocity equal to the wave phase velocity, as can be seen.

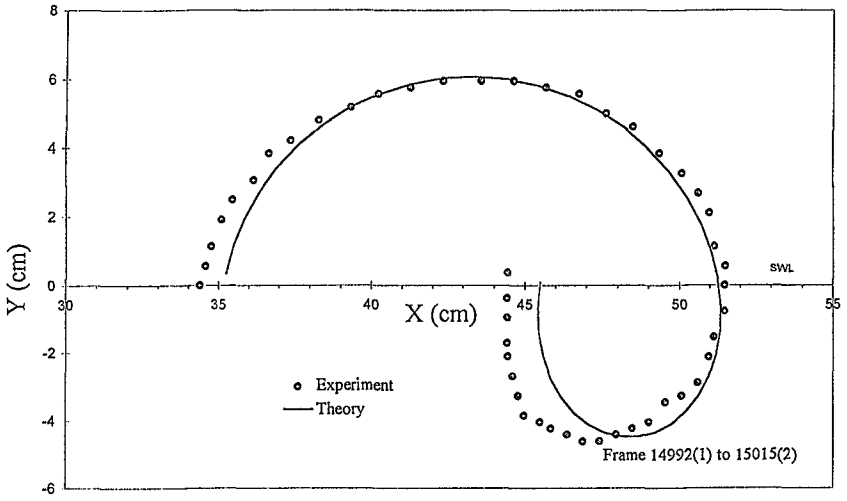

Fig. 1. Comparison of trajectories of a floating particle moving on a quasi symmetrical crest (ak=0.31), and second order Stokes wave theory.

Fig 5 then shows measured horizontal accelerations of the particles P2 and P3, normalized with the gravity acceleration. The horizontal acceleration of particle P3 reaches a value of 1.35 times the gravity acceleration

Particle P3 reaches a vertical acceleration 0.78 times the gravity acceleration. Fig 6 shows the total acceleration of this particle. The acceleration of the floating particles increases rapidly in the non-breaking region and reaches a maximum value at the time when the overturning part of the crest collides with them. Total acceleration vectors up to 1.55 g were measured at the free surface. Maximum acceleration and maximum velocity are nearly in phase in these breaking waves, leading to large wave forces, and a significant capsizing potential if encounter happens with small floating objects (small boats, rescue floats or wave buoys).

If wave forces are computed on structural elements of a steel jacket or a tension leg platform then both the particle velocity and the acceleration must be known, and data from the established data bank are used for calibration of the 3-order kinematic model developed in this study for extreme waves in irregular seas with or without currents.

Wave particle accelerations in non-linear waves can not easily be deduced from Eulerian measurements. The wave crests show an asymmetrical shape at the breaking onset (Kjeldsen 1997), and work is in progress to establish a correlation between surface particle accelerations and wave asymmetry, see (Kjeldsen, Bonmarin & Duchemin 1998).

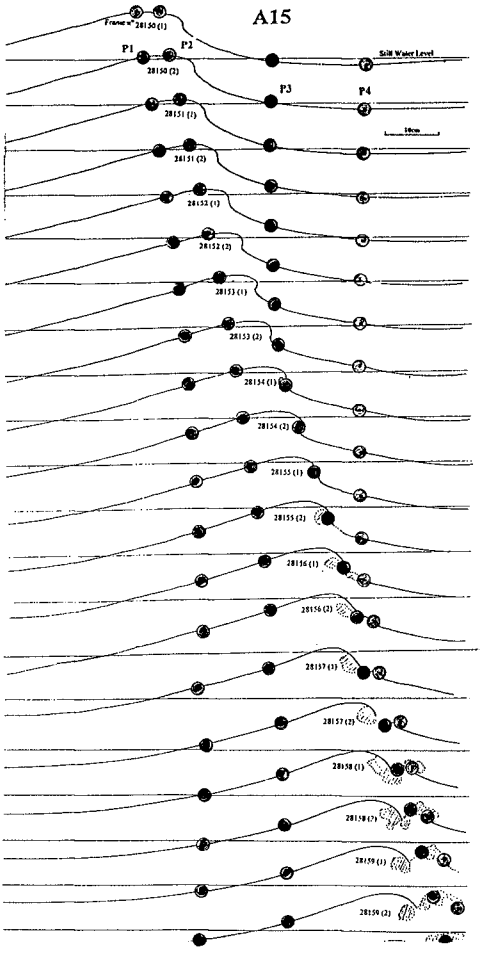

Fig. 2. Surface elevation and location of tracer particles in a plunging breaker developing in deep water. Experiment A15, frame period 0.02 sec.

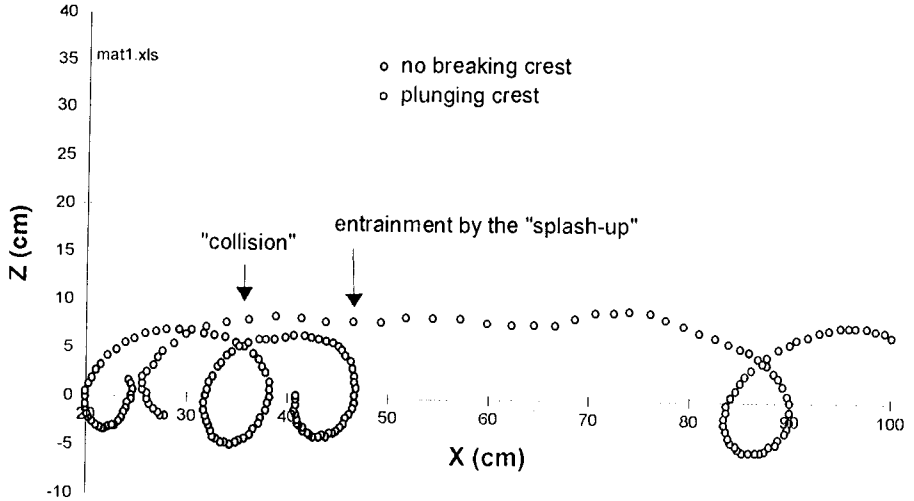

Fig. 3. Trajectory of a floating paticles.

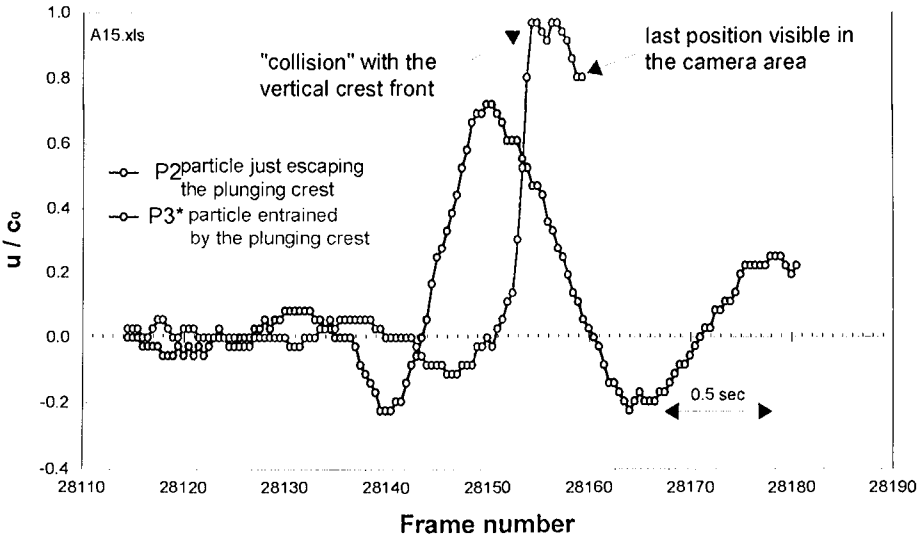

Fig. 4. Horizontal velocity of floating particles. Experiment A15.

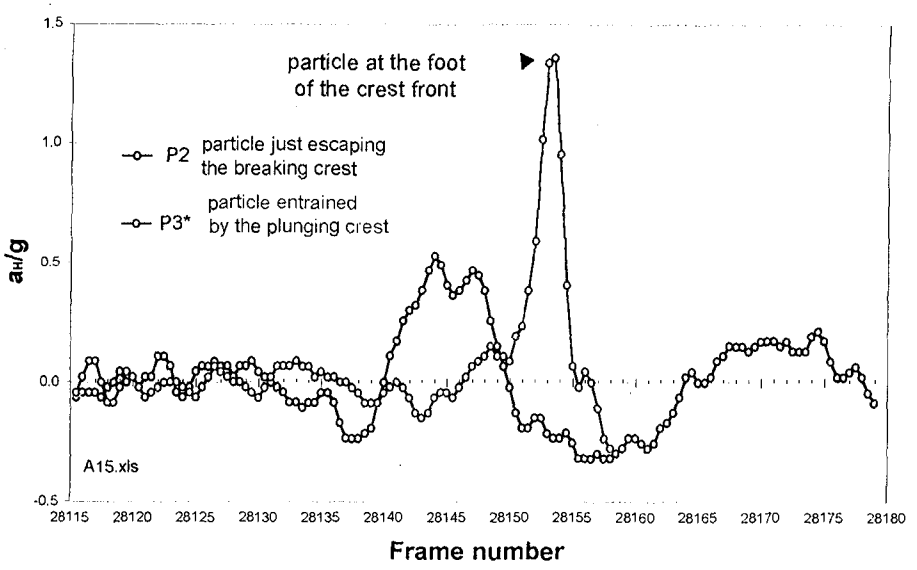

Fig. 5. Horizontal acceleration of floating particles. Experiment A15.

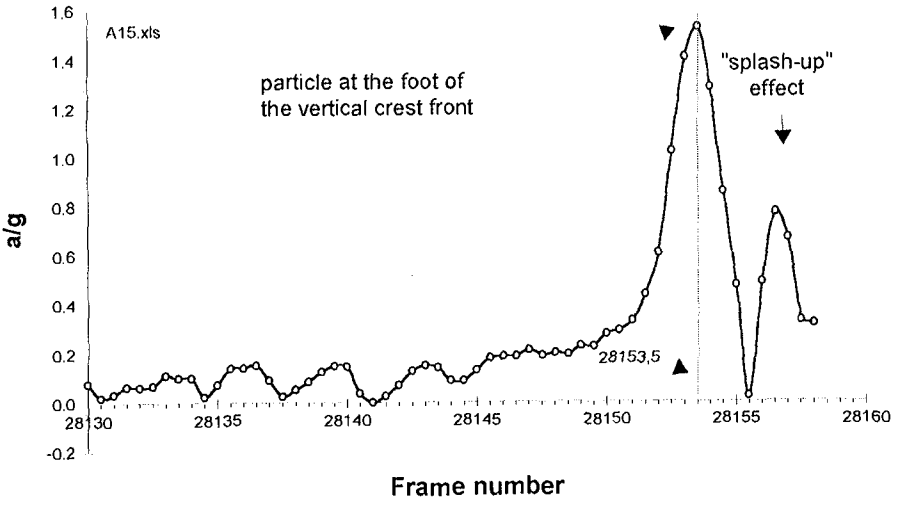

Fig. 6. Total acceleration of floating particle. Experiment A15.

4. Kinematic Models.

In the offshore industry a stretching theory developed by (Wheeler 1970) has traditionally been used for prediction of kinematics of 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 wave group.

In the present study we therefore developed a third order simulation of the kinematics in steep wave crests, see (Skafel, Drennan and Kjeldsen 1997). 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.

This model is then used both for cases where non-linear waves propagate on opposing currents, and for cases without currents. However this model does not give a complete description of the wave spectrum developed by the command signal in the wave flume. Therefore the superposition model developed by (Donelan et al. 1992) is also used. The procedure for computation then becomes:

- 1. A third order wave train interacting with a current with a constant vorticity is computed.
- 2. The third order wave train is subtracted from the experimentally obtained surface elevation.
- 3. The kinematics of the remaining wave signal is analysed using the superposition model of (Donelan et al. 1992).
- 4. Finally the solutions obtained in steps 1) and 3) above are added, using the 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).

5. Model Comparison.

Fig 7 shows an example from CCIW experimentsof internal maximum horizontal velocities measured below extreme wave crests. The mean predicted velocity profiles beneath the crests using the modified stretching model, the superposition model, and the present third order model are shown in Fig. 8 along with the experimental laboratory profiles. All the kinematic models were run for the surface elevation time series of all the laboratory runs (26 experiments with the same condition). The resulting mean profiles, along with twice the standard deviations about the means are plotted. The narrowness of the spread of the standard deviations presented in Fig. 8 serves as an indication of the excellent reproducability of the wave trains. Fourier analysis of each surface profile was used to find the peak frequency, and hence the peak wave number k_0. The mean peak wave number for all 26 runs, in this case k_0=1.38 m^{-1} was used for normalisation. It can be seen here that the modified stretching model underpredicts the velocity significantly throughout the profile. The superposition model more nearly represents the data. The new third order model developed here best reproduces the data. It slightly underestimates the velocity, lying just outside the two standard deviation range. A further development of the new model is in progress. (Kjeldsen, Skafel, Drennan 1998).

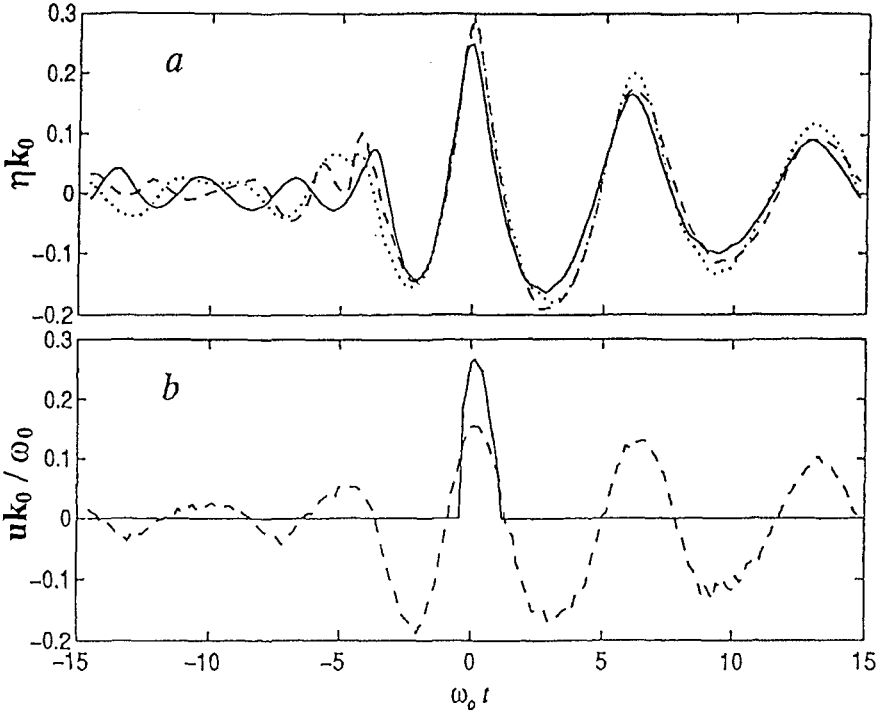

Fig. 7. Panel a shows the time series of the water surface elevation, just upwave of breaking, normalized by the peak wave number ($k_0 = 1.38$), and frequency ω_0. U_M is the mean current velocity of opposing current.

——— : $U_M = 0$ cm/sec. — — — : $U_M = 4$ cm/sec. - - - - - - : $U_M = 9.5$ cm/sec.

Panel b shows the corresponding normalized horizontal orbital velocity u for $U_M = 9.5$ cm/sec.

——— : 4 cm above the still water level. — —: 20 cm below the still water level.

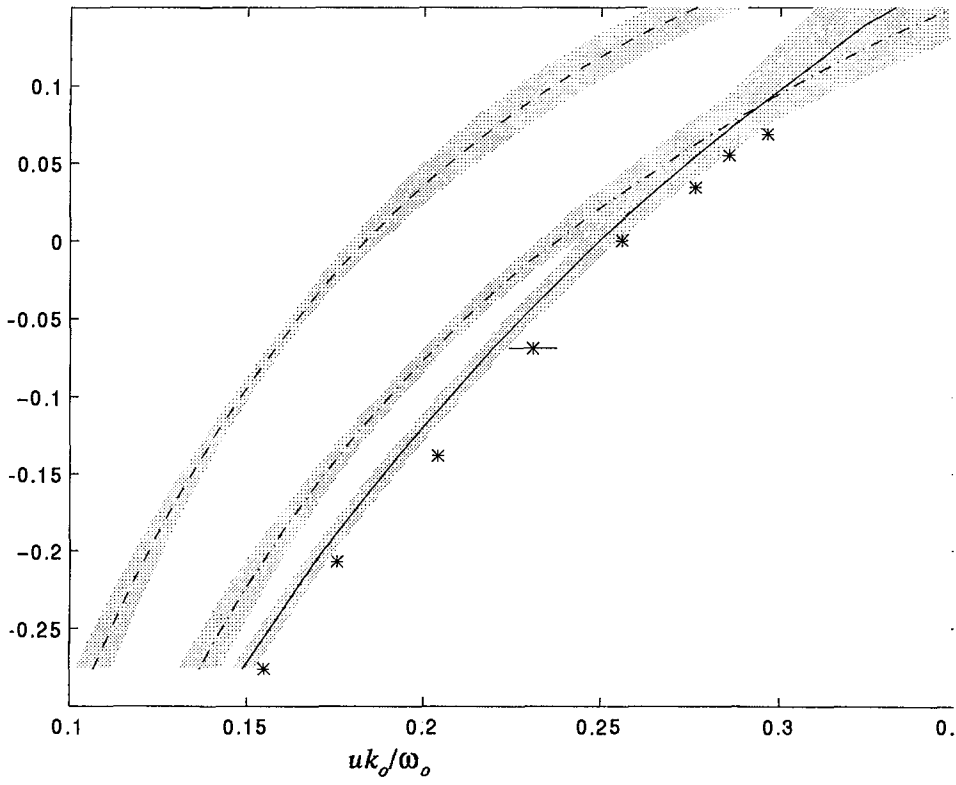

Fig. 8. Maximum horizontal orbital velocities (u) beneath the crest just upwave of breaking, normalized by k_0 and ω_0, versus elevation (z) normalized by k_0.
*** : measured values. — — — : mean of linear superposition model.**
—·—: mean of modified stretching model. _____ : present model.
The horizontal bar on the data point at the elevation of 0.05 represents two standard deviations about the mean. The shaded areas around the model lines enclose twice the standard deviations.

6. Conclusions.

1. A new third order kinematic model simulating the velocity beneath extreme waves has beer developed.; it represents the velocity beneath extreme waves occuring in irregular seas with o without current better than the modified Wheeler stretching model and the linear superpositior model.
2. The new third order kinematic model can easily be adopted to take into account the directional spreading in a non-linear directional sea state interacting with a current.
3. A Lagrangian measurement technique is needed in order to measure particle accelerations in non-linear waves. By means of a visualisation technique it was possible to measure both the Lagrangian particle accelerations in breaking wave crests, and Stokes drift in steep waves as well as particle drift caused by breaking wave crests.
4. Both horizontal and vertical accelerations were measured not so far from the ones predicted by the numerical model developed by (Vinje & Brevig 1980.) Total particle accelerations up to 1.55 g were measured in plunging breakers occurring in deep water.
5. The behaviour of the tracer particles is similar to the one of free floating oceanographic buoys (operated at sea without moorings as in parts of the LEWEX experiment, see (Beal 1989)). If buoys are moored it is well known that they follow a more linear mode. Moored buoys will therefore not measure particle accelerations in non-linear breaking waves correctly.
6. The behaviour of the tracer particles is also similar to the one of rescue floats deployed after a ship accident in a swell. Drift of rescue floats at sea is also depending on wind, and drag coefficients related to float design. Accurate modelling of surface drift of smaller objects is very important for management of search and rescue operations at sea.
7. The wave generation technique of (Kjeldsen 1982), modified for opposing currents, was able to generate unusually large plunging breakers with crest front steepnesses in the range 0.25 - 0.41, similar to observations on the Norwegian Continental Shelf.

7. Further Work.

1. Results are also obtained for spilling and plunging breakers on beaches. These will be dealt with in a seperate report.
2. A further development of experimental technique using smaller particles and a high speed camera is considered.
3. A further development of the new kinematic model incorporating an overturning jet on the steep irregular wave is considered, in order to simulate capsizing of smaller objects in a numerical ocean basin.

8. Acknowledgement.

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