Fishing Pier with accretion problems, Wildwood, N.J.

PART I

THEORETICAL AND OBSERVED CHARACTERISTICS

Estuaries of South Carolina

CHAPTER ONE

THE EXPERIMENTAL VERIFICATION OF NUMERICAL MODELS OF PLUNGING BREAKERS

by

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1. ABSTRACT

Results of a WAVE-FOLLOWER EXPERIMENT are presented, in which a moving current meter entrained in the crest of a steep Stokes wave and a moving high-speed film camera follows the wave with its non-linear phase velocity. Measurements of wave particle velocities are then obtained both in non-breaking steep wave crests, and in breaking waves. The breaking waves in deep water conditions are obtained by the application of a non-linear sweep frequency modulation technique, and the Stokes wave becomes unstable due to interaction of 43 wave components focused into one single point in space and time, KJELDSEN 1982.

The result of this interaction is a large freak wave, breaking as a plunging breaker in deep water. Measured crest particle velocities obtained with the current meter exceeded the phase velocity of this wave with 36 %. Digitalisation of the high-speed film showed that particle velocities at the very tip of the plunging jet obtained the value 2.65 times the linear phase velocity. These results are then compared with predictions obtained from numerical simulations by LONGUET-HIGGINS & COKELET 1976 and VINJE & BREVIG 1980.

2. INTRODUCTION

We still have a quite high frequency of damages to structures designed by engineers, and this implies both coastal structures and floating marine structures in deep waters such as semisubmersible platforms and smaller vessels. The Court of Inquiry has now released the report on the "Ocean Ranger" accident, where a semisubmersible platform capsized in severe sea conditions east of St. John's, Newfoundland, and more than 80 crew members lost their lives. The court of Inquiry's report says that a port hole was broken, and the rigg gradually lost water tight integrity, partly due to wrong actions from the crew. (Some general information about this particular accident is found in NATIONAL TRANSPORTATION SAFETY BOARD, report 1983). - In Norway on the average 3 vessels are lost each winter in severe seas and over

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the 9 last years not less than 26 vessels and 72 people has been lost. In 13 cases surviving members of the crews has confirmed to Courts of Inquiry that the vessels actually capsized in severe seas, and in some cases it was confirmed that these severe seas actually were breaking waves. This is a most unsatisfying situation, and even more because most of the lost vessels fullfill the requirements given by the Norwegian Maritime Directorate to their stability. And the lost vessels are not really smaller vessels, it is trawlers and freighters with total lenghts 50, 60 and even 70 meters. (See KJELDSEN, LYSTAD, MYRHAUG 1981 and KJELDSEN 1983). Also with regard to coastal structures and in particular with regard to new breakwaters, there is an extensive litterature available with cases that documents large unwanted damages to new structures and severe economic losses. Sines harbour on the west coast of Portugal is the best known example, but far from the only one. (See BAIRD et at 1980, YAMAMOTO et al 1981 and BRUUN 1979).

This most unsatisfying situation, has been the severe background for the author, to initiate the present research involving severe efforts into the performance of detailed measurements of the kinematics in the very crests of breaking waves occurring in deep waters. - AND THE RESULTS SHOWED, THAT WAVES IN DEEP WATERS WITH PERIODS AS LONG AS 19 SECONDS COULD BREAK AS PLUNGING BREAKERS WITH CREST PARTICLE VELOCITIES EXCEEDING THE PHASE VELOCITY OF SUCH WAVES WITH 36%.

3. EXPERIMENTAL ARRANGEMENTS

The english LORD RAYLEIGH followed the waves in a canal and studied them, riding on a horseback with "phase velocity".

For the present experimental programme a unique WAVE - FOLLOWER EXPERIMENT was designed. The experimental programme was performed in a 260 m long, 10 m deep and 10 m wide wave flume equipped with a large double-flap hydraulic wave generator hinged 1.05 m and 2.62 m below mean water level respectively. Steep regular wave trains generated with this wave generator are Stokes waves with phase locked superharmonics, as shown by KJELDSEN 1984a. Measurements of wave kinematics were performed in such wave trains. However in order to obtain control of violent plunging breakers at a fixed time and position in deep waters, a deterministic non-linear sweep-frequency modulation technique was applied, see KJELDSEN 1982. This particular technique takes into account the non-linear dispersion properties of Stokes wave packets. A wave train consisting of 43 transient wave phases with frequencies in the range 0.203 Hz $< \Delta f <$ 1.43 Hz and all with the same steepness 0.10 were generated followed by a train of Stokes waves with constant frequency. A special WAVE-FOLLOWER-SYSTEM was designed, consisting of a carriage that was perfectly synchronized with the dispersion of one particular wave phase and kept a selected current meter submerged in the wave crest while the wave dispersed over a distance of 15 - 20 meters and developed asymmetry and finally broke as a violent plunging breaker in deep waters. The maintenance of the exact position of the current meter in the wave crest during the dispersion was monitored and controlled by a moving high-speed film camera also installed on the carriage. In advance of these experiments an in-depth dynamic calibration of 4 different types of current meters operating on 4 physically different principles were performed. 2 commercial available current meters were tested and 2 current meters under development at Norwegian Hydrodynamic Laboratories were also tested. Only one of these four types of current meters fullfilled the strict requirements to a satisfying dynamic response, and only these one was used in the WAVE-FOLLOWER EXPERI-

MENTS. Fig. 1. shows the princip for the WAVE-FOLLOWER-SYSTEM. The plunging breaker in deep water was obtained experimentally taking advantage of the fact that group velocity of wave components is a function of wave steepness. 43 non-linear wave components were then phase locked i a deterministic way at one preselected point in space and time, leading to a steep elevated deep water freak wave, that broke as a plunging breaker. In Fig. 1. the full lines are energy lines. In addition phase lines and the path line for the WAVE-FOLLOWER carriage are shown.

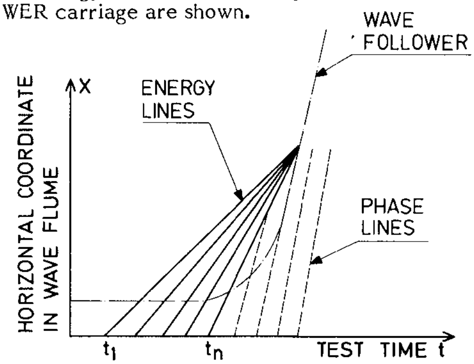

Fig. 1 Non-linear wave dispersion leading to freak waves breaking as plunging breakers in deep waters. Solid lines are energy lines. Further phase lines and the track of the WAVE-FOLLOWER carriage are shown.

Four different types of current meters based on 4 different physical principles, were selected for this particular investigation.
The 4 types of instruments were the following:

1) Acoustic transit time current meter.
2) Acoustic doppler type current meter operated in backscatter mode. (Developed at NHL.)
3) Electromagnetic current meter based on Farady's principle.
4) Modified pitot tube developed at NHL.

All four types of current meters were then examined in depth during an extensive calibration programme. The evaluation of each current meter were then based on the following properties:

a) Dynamic calibration.
Attenuation of amplitude and phase delay in oscillatory flow mapped as a function of frequency.
b) Surface penetration properties.
c) Performance in a fluid containing air bubbles.

Only one of the four different types of current meters under evaluation, fullfilled the strict requirements to a satisfying dynamic response, a satisfying response in a fluid containing air bubbles, and a satisfying response when a liquid surface was penetracted by a current meter moving relatively to that surface. Thus the only current meter that passed the calibration tests and was selected for these WAVE-FOLLOWER-EXPERIMENT was an ultrasonic transit time current meter with a working frequency of 4 Megahertz. This particular instrument measures the velocity of sound in the fluid and compensates automatically for any possible change of this velocity. It is well known, that it is impossible to use a low-frequency instrument because the velocity of sound drops significantly when air is entrained into the fluid. However, what is much less well known, is that at very high frequencies this effect disappear. Fig. 2 shows experimental results by FOX, CURLEY & LARSON 1968 and shows that in water containing air bubbles the velocity of sound stabilizes at very high frequencies close to the value for an air-free-fluid. In the present investigation a carrier frequency of 4 Megahertz was used, and this is well beyond and outside the critical limit shown in Fig. 2.

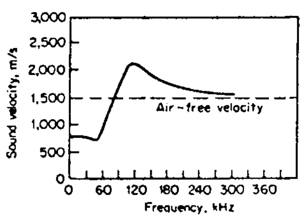

Fig.2 Velocity of sound as function of carrier frequency in a fluid containing air bubbles. (From FOX, CURLEY & LARSON 1968).

A special designed rig was used for dynamic calibration of the current meters, see Fig. 3. In this rig the current meters were oscillated at different frequencies, and amplitude attenuation as well as phase distortion were mapped. This calibration was first made with the current meter submerged at all times, and later it was performed with the current meter penetrating the free surface as shown in Fig. 3. A position galvanometer attached to the roof measured the exact position of the current meter at all times.

Fig. 4 shows an example of the obtained results from such a dynamic calibration. Above is the position of the moving current meter and below is the measured particle velocity.

Fig. 5 shows a comparison between the surface penetration properties of two different kinds of current meters. Above is shown the ideal curve for a surface penetrating instrument. The output shall be zero, and a moment later, it shall be 100 % of the true fluid velocity at that particular position. Further the intergrated velocity should be equal to the cross-hatched area. Below are shown the curves for the ultrasonic transit time current meter, and for the electromagnetic current meter. We observe that a time t elapses, that is 5 times the instrument time constant τ , before the amplitude of the received signal has reached 95 % of the true value. As the time constant is as small as τ = 0.01 sec for the ultrasonic current meter it is nearly perfect for this kind of surface penetration experiments, while the electromagnetic current meter (Design Marsh McBirney) is much too slow and cannot be used for this kind of measurements in wave crests.

In order to further map the performance of the selected instrument in an air/fluid mixture, the current meters were installed in an oscillating water tunnel as shown in Fig. 6. From the bottom air bubbles were then released in a controlled manner, the bubbles passed the current meter, and the response of the current meter to the passing of these free bubbles was then monitored.

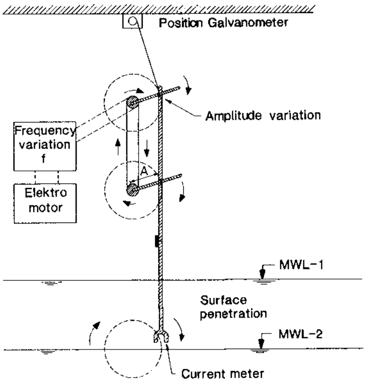

Fig. 3 Rig applied for dynamic calibration of current meters.

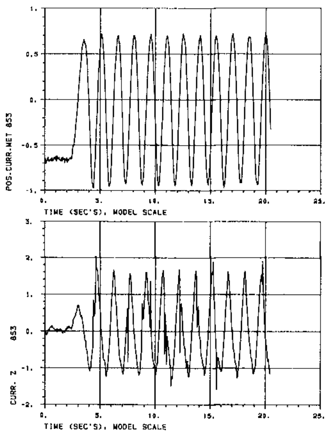

Fig. 4 Example of results from a dynamic calibration test. Above the position of the moving current meter, below the measured particle velocity.

A more comprehensive and complete description of the experimental arrangement and the development of the instruments are given by KJELDSEN 1984.

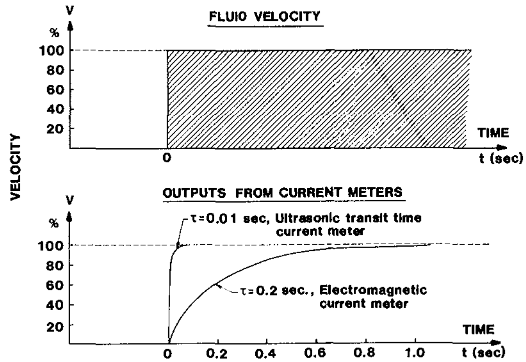

Fig. 5 Surface penetration properties of ultrasonic transit time current meter and electromagnetic current meter.

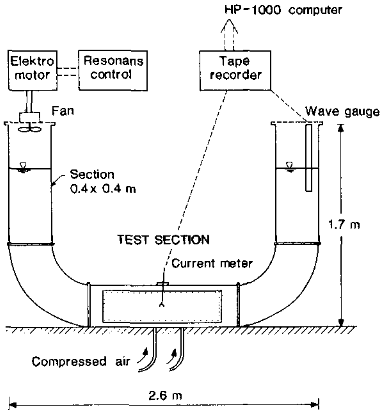

Fig. 6 Experimental arrangement used to map performance of current meters in an air-fluid mixture.

4. RESULTS - NON-BREAKING WAVES

Phase locked superharmonics contained in the generated Stokes waves are analysed by KJELDSEN 1984a. In order to further control the quality of the generated waves a non-dimensional plot of synoptic wave shape is prepared in which experimentally obtained values of wave shape are compared with calculations for high order Stokes waves made by COKELET 1977 using Padé approximations to an order of 110 with ε as the expansion parameter. This plot is shown in Fig. 7. A strong coherence is observed between experimental values and calculations made with $\varepsilon^2 = 0.70$. Steep wave crests and flat troughs are pronounced. Use of Stokes wave theory to represent the single experimentally obtained waves, then seems to be a very good approximation, until the Stokes wave finally becomes unstable and breaks due to the deterministic non-linear focusing and wave-wave interaction.

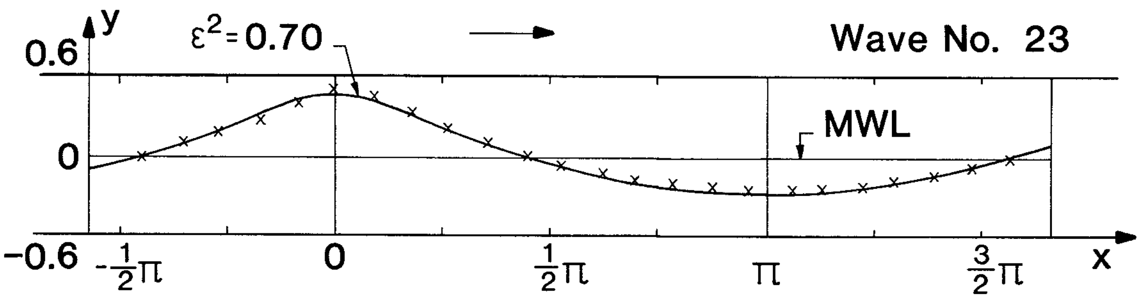

Fig. 7. Non-dimensional synoptic comparison between experimentally obtained Stokes wave and calculations made by COKELET 1977 using $\varepsilon^2 = 0.70$ as the expansion parameter. (Conversion from time domain to synoptic domain is made by application of equations given by COKELET 1977, page 210).

a)

b)

c)

d)

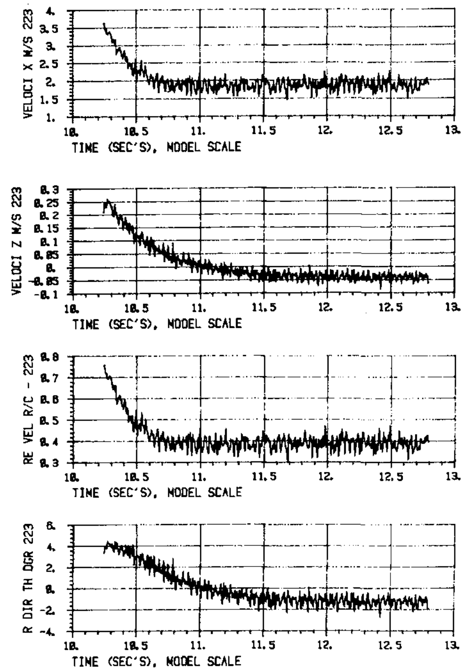

Fig. 8. Measurements of particle velocities with a moving current meter in steep Stokes waves 120 mm above mean water level.

Fig. 8 shows an example of the obtained results for steep Stokes waves. Fig. 8a is the horizontal particle velocity positive in the direction of wave dispersion. After entrainement of the current meter into the wave crest the horizontal particle velocity stabilizes at a value near 1.8 m/sec which shows, that a steady state condition is present in the interior of the wave crest, as it was expected. Fig. 8b shows the vertical particle velocity positive upwards. (In this case a slight negative vertical velocity -0.03 m/sec is measured, which indicates that the position of the current meter has been slightly in the rear part of the wave. The expected value for the vertical particle velocity is 0, when the current meter is maintained directly below the wave crest. However this inaccuracy in alignment is very small as the ratio Z/X is less than 2 %). More important is it to observe that also the vertical particle velocity stabilizes at a fixed value, which proves that the current meter moves exactly with the phase velocity of the gravity wave. During these measurements the gravity wave dispersed over a distance of 16 m in the laboratory. A strong coherence is seen between the horizontal and the vertical particle velocities when the current meter is entrained. Fig. 8c then shows the resulting velocity vector normalized with respect to the phase velocity of the wave, and Fig. 8d finally shows the tilt of the velocity vector which in this case becomes -1.5 degrees directed downwards from the horizontal.

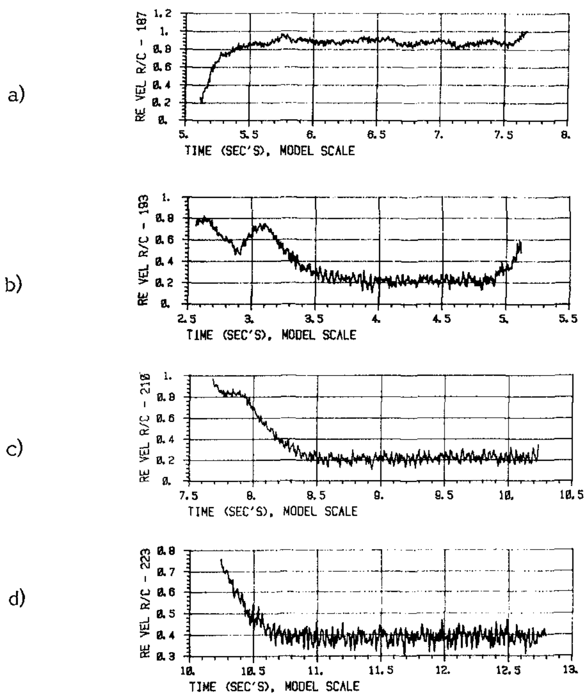

Fig. 9 Resulting velocity vector normalized with respect to phase velocity measured at 4 different vertical levels. a) 420 mm, b) 320 mm, c) 220 mm and d) 120 mm above mean water level. The crest height of the wave is 440 mm.

Fig. 9 then shows the resulting velocity vector obtained in 4 different vertical levels, namely 420 mm, 320 mm, 220 mm and 120 mm above mean water level. In the case where the current meter is moving in the level at 420 mm, it is entrained only 10 - 20 mm below the crest. It is then most remarkable to observe that the resulting velocity vector drops significantly when the current meter is lowered only 100 mm from the top position.

These experiments indicate that a velocity distribution above mean water level, as shown in Fig. 10 could be applied for design purposes. The very large particle velocities are confined to a very local region close to the upper part of the wave crest. In this local region the obtained recording of horizontal particle velocity in a coordinate grid moving with phase velocity is very close to zero in the entire recording period. It is therefore concluded that the Stokes 120 degrees corner flow is a good approximation to the interior flow field for such a local upper region in very steep Stokes waves.

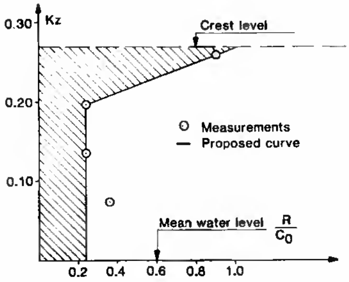

Fig. 10 Non-dimensional distribution of particle velocities above mean water level for non-breaking waves.

5. RESULTS - PLUNGING BREAKERS

Let us next consider the results obtained in breaking waves. The current meter then moved with phase velocity inside a steep Stokes wave over a distance as long as 16 meters until this particular wave phase due to the non-linear focusing suddenly becomes unstable and breaks as a plunging breaker, see Fig. 11.

Fig. 11 Moving current meter entrained in the very crest of a deep water plunging breaker at a level of 420 mm above mean water level.

This travel inside the wave takes less than 4 seconds, which means that the syncronisation has to be perfect. The position inside the wave crest was monitored with a moving high-speed film camera. This camera was operated with a speed of 200 frames/sec, and the camera was syncronized with a clock signal, that was recorded together with the measured particle velocities. Not less than 225 single experiments of this kind, with the current meter moving at different elevations above mean water level were performed. Fig. 12 shows the obtained horizontal and vertical particle velocities in one of these experiments. The current meter operated at a level of 420 mm above mean water level is entrained in the very crest of the wave at a time 5.1 seconds. The horizontal particle velocity then obtains the phase velocity of this particular wave which is 4 m/sec in the laboratory scale. It keeps this velocity for quite a long time because the wave now appears as a steady wave. However suddenly the wave becomes unstable and the measured velocity increases in a burst with a value that reaches 5.42 m/sec in the laboratory scale! (Scaling of results to representative prototype values is treated in section 7). The corresponding vertical particle velocity is also displayed in Fig. 12. It has a more modest pattern and increases from 0 to 0.42 m/sec. It is directed vertically upwards.

a)

b)

c)

d)

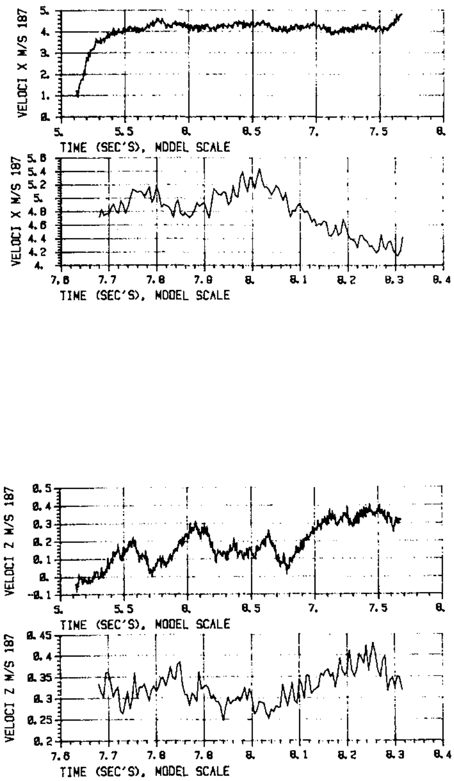

Fig. 12 Horizontal and vertical particle velocities measured 420 mm above mean water level in the plunging breaker shown in Fig. 11. The horizontal particle velocity is steady with a value near 4.00 m/sec until the wave breaks in a violent burst at a time t = 8 seconds.
a) and b) horizontal particle velocity,
c) and d) vertical particle velocity.

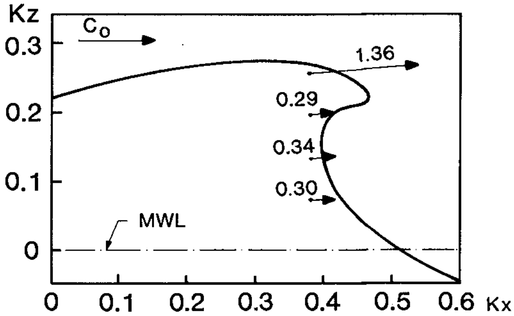

Fig. 13 Magnitude and tilt of resulting particle velocity vectors in the crest of a plunging breaker normalized with respect to the phase velocity.

The tilt and the total magnitude of the resulting particle velocity vector inside the breaking wave are shown in Fig.13 for 4 measured levels. The results are here normalized with respect to a linear phase velocity which is here taken as the velocity of the moving carriage. The measured tilt of the velocity vector at the very top of the wave crest is near 0. When the burst comes it obtains a snall deflection 5.5 degrees upwards.

6. COMPARISON WITH MEASUREMENTS ON FILM

The experiments with non-linear focusing of wave components leading to violent plunging freak waves in deep waters were repeated in a smaller wave flume with glass windows that permitted high-speed filming from the side. In order to obtain quantitative measurements from this film related to the tip of the plunging jet in the front of the wave, the velocity with which the film camera was operated was increased to 300 frames /sec. Fig. 14 shows above a typical stage in the development of the plunging jet and below the position of the tip of the jet measured on the frames of the film and plotted in a KX - KZ coordinate grid. It is then possible to obtain one of the two components of the particle velocity on the boundary, namely the one that is normal to the boundary. The time lapse between each frame is 3.33 milliseconds. At position 2, 3 locations of the tip of the jet is identified. The normal velocity is then measured and becomes 2.67 m/sec. 20 frames later at position 3, 3 new locations of the tip of the jet is identified. The normal velocity derived from these is 4.07 m/sec. Again 20 frames later at position 4, 3 locations are identified and the normal velocity becomes 4.07 m/sec. These values have then to be compared with a representative phase velocity for this particular plunging wave. This phase velocity is here defined as the linear phase velocity (C_o = 1.54 m/sec), that can be derived from the zero-downcross wave period T^B_{zd} = 0.984 sec measured with a stationary instrument at the position of breaking. The rod visible in Fig. 14 is a stationary current meter, but also a wave gauge giving surface elevation might have been used for that purpose. The width of the wave flume is 1.00 m and the current meter is installed 0.5 m behind the tip of the jet viewed at the window. We then obtain the following non-dimensional results:

POSITION	V_n (m/sec)	$\frac{V_n}{C_o}$
2	2.67	1.73
3	4.07	2.65
4	4.07	2.65

These results have then to be compared with available numerical simulations of plunging breakers in deep waters. LONGUET-HIGGINS & COKELET 1976 developed a model that in some cases achieved values as high as 2.8 times the linear phase velocity. This very high value occurred also in the numerical simulation at the very tip of the jet. The present experimental results thus confirms the physical existence of such very high values. VINJE & BREVIG 1980 developed a model that achieved values 1.8 times the linear phase velocity. This figure seems to be too low, and there is a discrepancy between the two numerical simulations, when the objective is evaluation of kinematics.

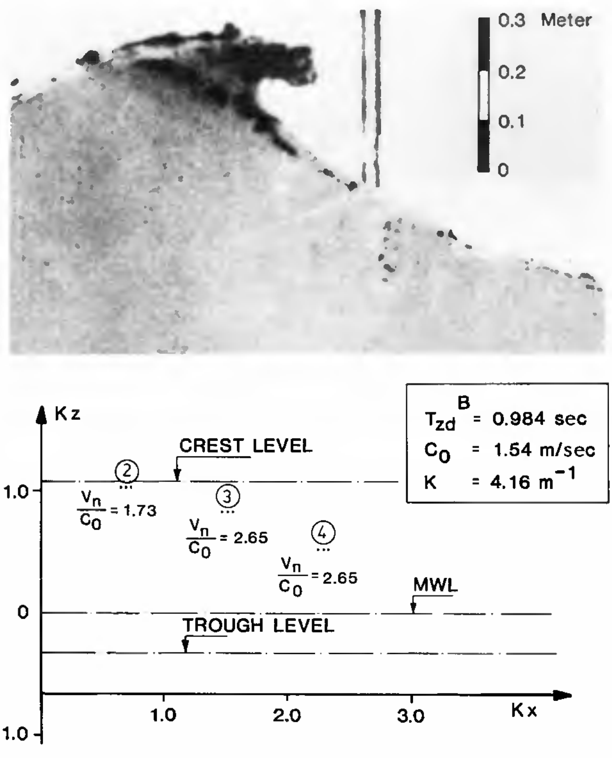

Fig. 14 Above tip of plunging jet obtained from the frames of a high-speed film. Below positions of the tip of the plunging jet viewed in a KX - KZ coordinate grid.

7. A NEW CRITERIA FOR INCEPTION OF BREAKING

The very high velocities in the crests of the waves of the kind reported here, have to be squared when drag forces on structures exposed to such waves are calculated. A study containing an attempt to evaluate the probabilities for encounter of such waves is available. This study is based on statistics of steepnesses of 25.000 waves observed during 22 gales on the Norwegian Continental shelf, see KJELDSEN 1981. Another most important aspect for design of structures is the crest length of breaking waves in a 3-dimensional sea, and such results are also available KJELDSEN 1984b.

The last and most important topic to consider is then the position of the violent plunging breaker relative to the envelope of the non-linear wave group in which it occurs. Fig. 15 shows the measured surface fluctuation of a focused freak wave converted to prototype values. It appears as a plunging breaker as shown on Fig. 11. However, it appears with a wave period T_{zd}^{B} = 19 sec and a zero-upcross wave height H_{zu} = 30 m. It thus breaks violently with a much lower steepness than the limiting steepness for monochromatic waves, and it contains very high particle velocities as measured with the current meter and plotted at the appropriate elevation. The present experiments confirm that violent breaking waves always appear in the front of the wave groups. Both the inception of wave breaking and the strength of the breaking of a particular wave phase is thus governed by a transition and a sudden jump in wave number, combined with a high wave energy flux. The breaking criteria valid for a sea containing wave groups can therefore be expressed as the joint probability of a certain wave number jump and the associated wave energy flux both exceeds certain critical thresholds (see KJELDSEN 1984 c.)

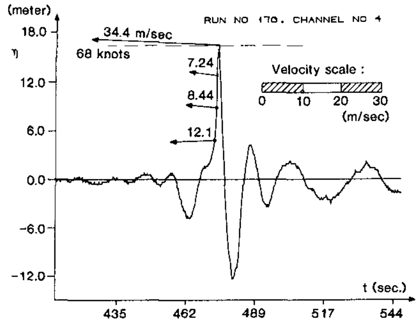

Fig. 15 The plunging breaker scaled to prototype values. The resulting particle velocity vectors obtained with the current meter are plotted at appropriate vertical elevations.

8. CONCLUSIONS

1) A moving current meter entrained in the very crests of focused plunging breakers showed that the ratio between the measured particle velocity vector and the phase velocity increased to a value 1.36 in a position a few millimeters below the crests in the centre of the waves.

2) Frame-to-frame analysis of a high-speed film showed that the particle velocity component normal to the boundary of the wave increased to a value that was 2.65 times the phase velocity valid for a position at the very tip of the plunging jet. This confirms the high values obtained at this particular position by LONGUET-HIGGINS & COKELET 1976 in their numerical simulation.

3) The violent breaking waves in deep waters always appeared in the front of the non-linear wave groups. Both the inception of wave breaking and the strength of the breaking of a particular wave phase within a wave group is thus governed by a transition and a sudden jump in wave number, combined with a high wave energy flux.

9. ACKNOWLEDGEMENTS

Acknowledgements are given to a skilled highly professional staff at Norwegian Hydrodynamic Laboratories, that assisted during the performance of these demanding experiments. Further Norwegian Hydrodynamic Laboratories gratefully acknowledge a grant from the Continental Shelf Committee of the Royal Norwegian Council for Scientific and Industrial Research (NTNF), on the project "EXTREME RESPONSES FROM BREAKING WAVES IN DEEP WATERS".

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