CHAPTER SIXTY TWO

SHORT-CRESTED BREAKING WAVES

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Abstract

The likely effects of short-crested (sc) breaking waves on ships and structures are summarised in the case of the simplest non-trivial sc sea at medium/high crossing angle.   Typical experimental data of sc breaking wave-height and sc water particle speeds are given at model-scale.

1.   INTRODUCTION

In recent years, more attention has been devoted to extreme waves (e.g. 15).   It is suggested that there are at least two classes of extreme waves, which frequently may break:

a)   "Tail of the distribution" - type waves where two or more waves are temporarily superposed (16).

b)   Current-wave interaction, producing high steepness waves (14, 17, 26).   To these should probably be added a third category:

c)   Short crested waves, in particular where high waves come together from two or more directions at middle or high crossing angle.   An inshore example is given in Figure 1.1

Figure 1.1:   Near-shore short-crested breaking wave
formed from two obliquely-crossing waves.

Little attention has been paid to the last of these. Salter (23) formed a three-dimensional deep-water plunging wave by arranging that the phases of waves from an array of generators came into coincidence at a point.   Halliwell and Machen (10) pointed out that short-crested (sc)

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breaking waves could be higher than long-crested and gave some results
for shallow water. Hsu and Silvester (12) and Hsu (13) compared these
results with predictions based on a third-order perturbation analysis.

The term 'short-crested' sea is often used to describe any sea having
components from more than one direction, but in this paper the simplest
non-trivial case will only be considered, that is a sc sea composed of
two equi-amplitude equi-period waves crossing obliquely. It is to be
expected that before breaking the finite-amplitude standing wave res-
earch reported in the 1950s and 1960s may be relevant. A step towards
three-dimensional behaviour was made by Verma and Keller (28), and a
third-order perturbation analysis of two obliquely-crossing waves was
made by Hsu et al (11). Roberts (21) generalised and extended the
analysis of the resonance behaviour of steady sc waves, using the pre-
ferred term "harmonic resonance".

In this paper, we begin in Section 2 by examining the loss of HMS COBRA
in 1901 to which sc waves may have contributed. After some general dis-
cussion of sc breaking waves, some results are given in Section 3 from an
experimental facility of two intersecting channels and sc steepness is
compared with limiting long-crested steepness. The measurement of sc
water-particle speed is considered in Section 4 where some success with
a hot-film anemometer is reported.

2. THE IMPORTANCE OF SHORT-CRESTED BREAKING WAVES FOR SHIPS AND STRUCTURES
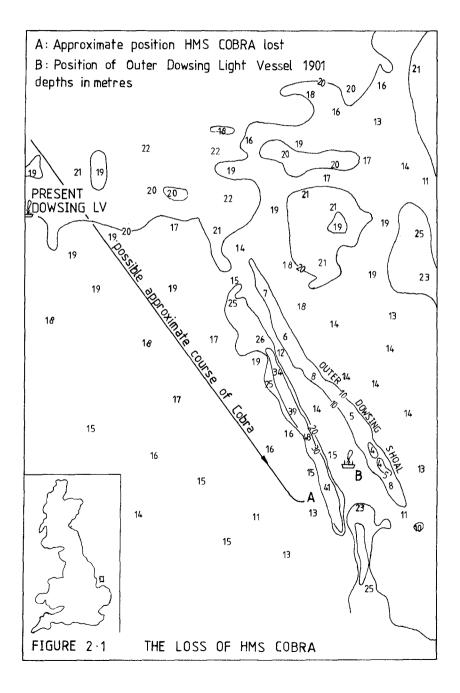
In a wind-sea, the angles between directional components are small and
whitecapping will accord to normal criteria. The short-crestedness of
the sea might be described as of low entropy. On the other hand, if we
imagine two separate long-crested waves (associated perhaps with a swell
or highly peaked spectrum) crossing obliquely at medium or high angle,
then a high energy event with modified breaking criteria is possible.

In the case of such a crossing event the secondary wave flux can be
produced by refraction around a shoal, by reflection from a deep-channel
or structure, or by similar action through the action of a current
regime. Clearly in these cases the secondary source is an image source.
High crossing waves due to an image source are in practice likely to be
rather localised.

Equally a secondary source could be real in the sense of wave flux from
a second storm or from a wind-shift, but there is some experience that
the short steep seas caused by very strong winds attenuate quite quickly
when the wind drops or changes direction (see for instance Fig. 2 of
(22), (6) and (8)); a secondary real wave flux is therefore only likely
to be of the same order as a high primary source in a localised region
of time and space.

2.1 Loss of HMS COBRA

Pierson (19) discussed the loss of two trawlers in the North Sea, sugg-
esting that crossing waves could be to blame. Recently Faulkner et al
(7) re-examined the loss of the torpedo-destroyer HMS COBRA in the North
Sea in 1901 (their principal interest being in the structural aspects of
the vessel). In the case of COBRA, more information is available

A: Approximate position HMS COBRA lost
B: Position of Outer Dowsing Light Vessel 1901
depths in metres

PRESENT
DOWSING LV

possible approximate course of Cobra

OUTER DOWSING SHOAL

A

B

FIGURE 2·1   THE LOSS OF HMS COBRA

regarding the position of the ship than in Pierson's and there is eye-
witness evidence that it was lost in a crossing sea. The mate of the
light vessel 2nm (3½Km) to the north-east reported winds NNW Force 6,
the helmsman wind NW, and heavy rolling was experienced when heading
slightly north of east. In spite of the sea being described by the
light vessel mate as only "middling rough" the ship was seen to execute
three terrific plunges with waves breaking over her forecastle and the ship
broke in two. Survivors described the sea as "a heavy sea, a cross sea,
not a regular sea, the wind one way and the tide another, as though
there had been a change in the wind" (7).

There was some ambiguity about the exact position but the COBRA was near
the Outer Dowsing Channel, the general alignment of which is NNW/SSE (Fig.
2.1). At this point the west bank of the channel is steep with chart depths
of 15m and 40m top and bottom respectively, and its lie is N16° W over
a 3Km length. Waves from the NW/NNW would have been obliquely incident
on the discontinuity, and those of middle and higher period would have
been reflected. A simple analysis by Snell's law indicates that, at the
state of the tide at the time, waves from the NW would have been reflec-
ted for periods of 8 sec and more; from the NNW, of 5 sec and more.
Faulkner et al (7) estimated the characteristic wave period as 7 sec.

A crossing-wave regime would have been set up near the discontinuity.
7-sec waves would have implied a depth-to-wavelength ratio of about 0.24,
and the primary wave flux, the reflected secondary component(s) and any
swell would have been approximately superimposed until a breaking limit
were reached. There remains some doubts, however, whether the short-
crested seas were breaking, what contribution additional swell made,
what effect tidal currents had, and to what extent the present-day chart
indicates the bathymetry of 1901.

2.2 Summary of Short-crested Breaking Effects

There are other examples of the importance of short-crested wave effects
both offshore and inshore, but restrictions of space preclude inclusion
here. The effects of sc (breaking) waves on ships and structures are
as follows:

a) The sc pyramidal or breaking waves may present a vessel or structure
    with a steeper than expected wave environment, which may exceed
    normal steepness criteria before reaching instability.

b) Along the centre-line of the sc wave the wavelength is L sec$\propto$($\propto$
    being defined in Figure 3.1) and a ship steaming in that direction
    is more likely to be entirely in a trough immediately before the
    bow is struck by the three-dimensional crest. (In two dimensions,
    an abnormal length of trough has been advanced as an important
    factor in the casualties off the South African coast (17)).

c) The sc wave profile speed may be high (higher by a factor of the order
    of sec$\propto$).

d) At breaking a sc jet or inverted saucer of water may issue from the
    crest. Little information is available about maximum water-particle
    speeds, but behaviour is likely to depend partly upon d/L_1. Some results

are given in Section 4.

e) Silvester (25) discussed the effects of crossing waves on sediment
movement. Increased sediment transport can accompany crossing waves.

f) There are likely to be consequences for fatigue calculations.

3. SC BREAKING WAVES - THEIR MODELLING AND HEIGHT

3.1 Modelling

Although it might be expected by symmetry and neglecting energy losses
at the wall, that two obliquely-crossing waves would be analytically the
same as one wave obliquely reflected from a straight vertical wall, if
the wall is of finite length the diffracted wave must be included. High
energy crossing events are likely to be localised and the diffracted
wave may have to be included in some general sc breaking waves. There
are, therefore, two alternative crossing-wave circumstances which can be
modelled, one including the diffracted wave (Set-up A) and the other not
(Set-up B).

The decision which to model will be significant as the diffracted wave
may be important for a considerable distance (2). Clearly A can be
modelled by reflecting waves from a straight vertical wall, or alternat-
ively by bringing together waves from two intersecting channels. B could
be modelled in a large basin with an array of wave generator elements
with their phases set such that two obliquely-crossing waves were gener-
ated, but depending upon the scale a diffracted wave may still make a
significant contribution. There are further possible modelling problems.

The basin at the University of Western Australia has some attractive
features (25) and perhaps lies somewhere between A & B. For reasons of
finance and the need for a local facility, an A-type basin was built at
Newcastle (Figure 3.1), in which the angle α is variable. It is however
not an ideal facility and suffers from the following deficiencies: diff-
raction of wave energy takes place into the adjacent channel which is
then subject to reflection at the paddle; the test aperture is rather
limited; and the channels, being of finite width, can support standing
waves, in spite of cross-wave filters.

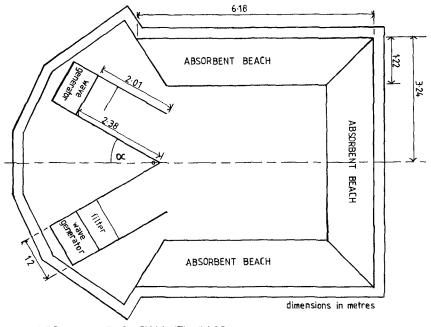### 3.2 Short-crested Instability Criteria

As α is varied (theoretically) between 0° and 90°, the sc behaviour
changes from being purely progressive to purely standing. .In the general
case, the two principal instability criteria, as summarised in (10) &
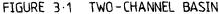(13) are:

a)   Kinematic: $u_{max} > f(C_s)$ .... (3.1A)

b)   Dynamic: $v_{max} > h(g)$ .... (3.1B)

Where u_{max} and v_{max} are maximum water particle speeds parallel to the
basin centre-line and vertically upwards respectively, $f(C_s)$ is some
function of short-crested celerity and $h(g)$ is a function of gravitat-
ional acceleration. Here the terms kinematic and dynamic are preferred
as used by Hsu (13) after Dean (5).

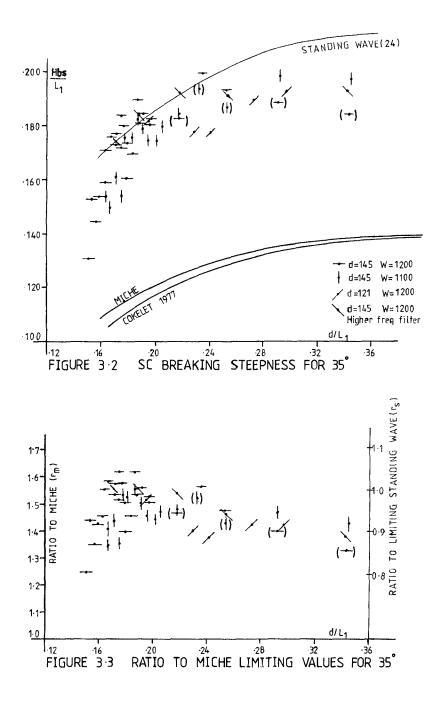Clearly when α is high, the dynamic condition is likely to dominate.

FIGURE 3·1   TWO-CHANNEL BASIN

Hsu (13) found a third-order solution to the dynamic stability criterion at all d/L from 0.05 to 0.5 for $70° \leqslant \alpha \leqslant 90°$. In the range $55° < \alpha < 70°$ he found the stability equation unsatisfied in a number of d/L values. On the other hand at lower values of α it may be expected that the kinematic condition will be dominant. In Equation (3.1A) $f(C_s)$ may be approximately equal to C_s, or alternatively a long-crested kinematic condition may be more appropriate. In this respect Hsu (13) found that for part-range of d/L a maximum value of u occurred which was less than C_s, finding it questionable that u_{max} was a valid criterion for the highest wave where it was less than C_s.

The author has watched a large number of in-shore sc breaking waves and there appears to be a maximum value of α for a forward-breaking sc wave which is of the order of $45°$. For wave-loading and slam considerations the kinematic condition is probably the more important criterion, but for ships experiencing pyramidal seas both conditions are likely to be of interest.

3.3   Short-crested wave height

In the model basin the sc breaking wave-height (H_{bs}) varied with the parent wave steepness ($K\overline{H}$), and there appeared to be a particular value of $K\overline{H}$ which gave the highest acceptable value of H_{bs}. At values of $K\overline{H}$

FIGURE 3·2   SC BREAKING STEEPNESS FOR 35°

FIGURE 3·3   RATIO TO MICHE LIMITING VALUES FOR 35°

higher than the optimum, one of two circumstances applied, either H_{bs}
decreased with the sc breaking wave being "pushed through" because of
high energy concentration, or unacceptable spilling occurred in the
channels. An envelope curve of H_{bs}/L_1 versus d/L_1 was plotted for
$\alpha = 35°$ (Figure 3.2); two values of channel width (W = 1200 & 1100mm)
and two values of d (145 and 121mm) were used. The bracketted points
are those where, at one d/L_1, W was changed but the KH setting was not
re-optimised. A series was also carried with a higher frequency cross-
wave filter. The data is compared with limiting progressive steepness
(according to Miche, and Cokelet (3)) and limiting standing wave steep-
ness (24)). Fig. 3.3 shows the ratios of the experimental data points
to the Miche value (r_m) and limiting standing wave (r_s):-

$$\binom{r_m}{r_s} = \binom{1/0.142}{1/0.22} \frac{H_{bs}}{L_1 \tanh Kd} \qquad \cdots\cdots\cdots\cdots (3.2)$$

Compare Figure 3.3 with Roberts' conclusion that deep water sc waves
could be up to 60% steeper than progressive waves (21).

Daemrich et al (4) found that for $\alpha = 20°$ the height of a Mach Stem
breaking wave did not exceed the predicted Miche limiting value for pro-
gressive waves. Further work needs to be done, but this may indicate
the sensitivity of behaviour to variation of α in the range $20°$-$30°$ (21
Fig. 4).

4. WATER PARTICLE SPEED MEASUREMENTS

4.1 Experimental Method

Available was a Thermo-Systems Inc. 1054 Constant Temperature Anemometer,
with which conical hot-film probes (1231W) were used.

Breaking waves represent a hostile environment for hot-film anemometry.
The problem of air entrainment was however likely to be less severe if
measurements were made only up to the location where the front face of
the sc waves became vertical.

Regarding the air-water interface, there have been conflicting views.
Baldy et al (1) felt that the exploration, by fixed probes, of the air
and water flows near the interface was "not generally feasible" and went
on to use a wave-follower mounting. Wills (29) used a fixed hot-wire
probe at the interface, but he was interested in the air flow above the
surface.   His discussion of the problems facing the experimenter at
the air/water interface is illuminating. Van Dorn and Pazan (27) recog-
nised that the frequency response of the equipment was sufficiently high
for an equilibrium value to be measured within a small distance of the
probe traversing from air to water (in their case 0.1mm).

To measure velocity on the water-side of the interface is easier than on
the air-side. The reason for this is that if measurements are made on
the airside a high overheat may be necessary to rapidly evaporate the
water film and this degree of overheat may increase the rate of accretion
of any contamination from the water-surface onto the sensing element.

In the two-channel basin a water-surface suction and filtering system was
used to reduce contamination, but it was still likely to be a major

problem.   It was decided to use a low value of overheat to reduce accret-
ion, and the lowest value which would give adequate sensitivity to flow
was used.   4% overheat was chosen.   The usual heat balance equation is:

$$\frac{e_b^2 \, R}{(R + R_3)^2} = \left[A + B \, (\rho V)^{\frac{1}{n}} \right] (T_s - T_e) \quad \dots\dots\dots (4.1)$$

where e_b is the bridge voltage, R the probe resistance, R_3 the resistance
in the other bridge arm, ρ density, V speed, T_s the sensor operating tem-
perature, T_e the water temperature and A, B constants.   For good sensit-
ivity to flow variation, a high T_s is required, that is high overheat.
The choice of a low overheat of 4% necessitated close control of T_e to
be maintained.

A simple test of the probe traversing the interface was conducted (at an
overheat of 4%) at a constant speed in a towing tank.   By means of a
suitable mounting and a string and pulley, the probe was caused to tra-
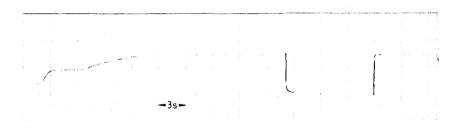verse a number of times the water surface which had previously been

−3s−

Fig. 4.1   Towing Tank Trial

swept clean, Figure 4.1 showing the bridge output voltage.   The acceler-
ation of the carriage to 1 m/s is clear, followed by traverses of the
interface.   The evaporation of the water film can just be seen.   Upon
successive immersion a consistent value of e_b was evident.   The record
was made on a heat recorder of bandwidth to about 50Hz which will there-
fore filter high frequency transients.

A calibration rig was constructed alongside the basin and water was drawn
from the central area of the basin and discharged onto one of the absorb-
ent beaches (Figure 4.2).   The calibration rig had similarities to that
used by Goodman and Sogin (9) who demonstrated that heat transfer was not
affected by whether the flow was turbulent or laminar.   In the calibrat-
ion rig for the present work, Reynold's Numbers were in the range 1.5×10^4
to 4×10^4.   Temperature increase through the calibration rig was about
$0.05°C$ which was equivalent to a change in speed of the order of 1%.

One would expect two principal reasons for changing calibration, dirt
accumulation on the probe and temperature variation.
a)   Dirt accumulation: Richardson and McQuivey (20) proposed that a
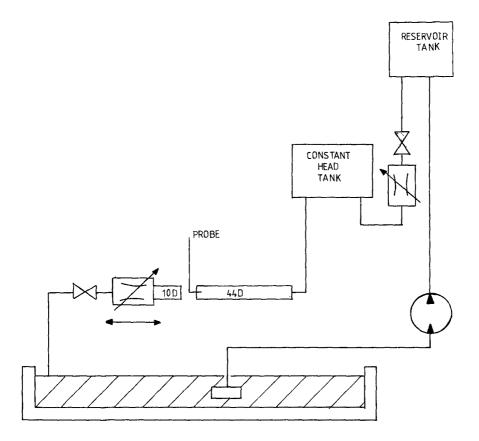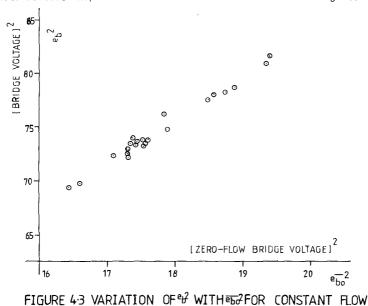dirty probe behaved as a clean probe at lower overheat, but Morrow and

FIGURE 4·2   CALIBRATION RIG

Cline (18) concluded this was untrue. Because of the anticipated high
drift from water surface contamination a second simple test was conducted
with a highly contaminated water surface, at an overheat of 4%. The probe
was mounted such that it was wetted by the crests of a series of waves.
The output was monitored and it was noted that for the condition of the
water at the time, rapid degradation occurred when the drying time bet-
ween wave crests exceeded 0.7sec., but no degradation occurred for less
than 0.6sec. This drift was probably due to the progressive accretion of
water surface contamination onto the probe. Therefore for subsequent
measurements small wave periods were chosen and the probe calibration
was re-checked and the probe cleaned after every measurement.

b) Temperature variation: One standard method of allowing for a change of
T_e by varying overheat slightly for the same e_{bo} was unsatisfactory in
this case for the degree of control required. It can be easily shown from
Equation (4.1) that for the same probe setting and the same flow one would

expect an approximately linear relationship between $e_b{}^2$ and $e_{bo}{}^2$. Experimental confirmation is given in Figure 4.3 where the middle group of points relates to small changes in T_e and the low and high values are a result of dropping and raising overheat slightly, that is varying T_s. This linear relationship was used to correct measured values of $e_b{}^2$ to a base

FIGURE 4·3 VARIATION OF $e_b{}^2$ WITH $\overline{e_{bo}}{}^2$ FOR CONSTANT FLOW

value of $\overline{e_{bo}}{}^2$ the square mean zero-flow measurement before and after calibration. The procedure also corrected for variations in other resistances. In Table 4.1 Runs 1 and 2 were calibration runs for a cleaned probe at differing water temperatures with similar values of $e_b{}^2$ after correction. For comparison Run 3 shows the calibration run for a lightly contaminated probe. The base value of $\overline{e_{bo}}{}^2$ was 17.56.

Calib-ration run	T_e	e_{bo} BEFORE	$\dfrac{CAL}{e_b}$	e_{bo} AFTER	$\overline{e_{bo}}{}^2$	Correction Factor	Uncorrected $e_b{}^2$	Corrected $e_b{}^2$	Remarks
1	18.3	4.16	8.455	4.16	17.26	1.017	71.45	72.56	Uncontam.
2	17.45	4.24	8.64	4.25	18.02	0.974	74.65	72.71	Uncontam.
3	17.5	4.25	8.49	4.25	18.06	0.972	72.08	70.06	Light Con-tamination

TABLE 4.1: Effect of Temperature Variation and Contamination

4.2   Results

Profiles of maximum total water particle speed U/c_1 were measured along the basin centre-line (average of 5 consecutive waves), with the right-angled probe pointing towards the channel apex. Figures 4.4a and b show the development of the U/c_1 profile (shown by the circled points) for $\frac{d}{L_1} = 0.34$ at four distances from the apex (x/L_1). The corresponding sc wave profiles are also shown. For comparison the horizontal speed profiles $(\frac{u}{c_1})$ in a hypothetical long-crested wave of this height according to Van Dorn's hyperbolic equation is shown (27):

$$\frac{u}{C} = \frac{a z^1}{b - z^1} + \frac{u_o}{C}$$

Where z^1 is the fractional ordinate from trough to crest at which u is given, a & b are arbitrary constants 0.10 and 1.125 respectively. $u_o/C = 0.20$ and C is the wave celerity.

In Figures 4.5 to 4.7, U/c_1 profiles are shown at breaking for $d/L_1 = 0.29$, 0.24 and 0.19. Differing values of d and W were used. It is seen that there is good consistency of the U/c_1 profiles at breaking of the four values of d/L_1. Measurement accuracy is estimated as $\pm 15\%$.
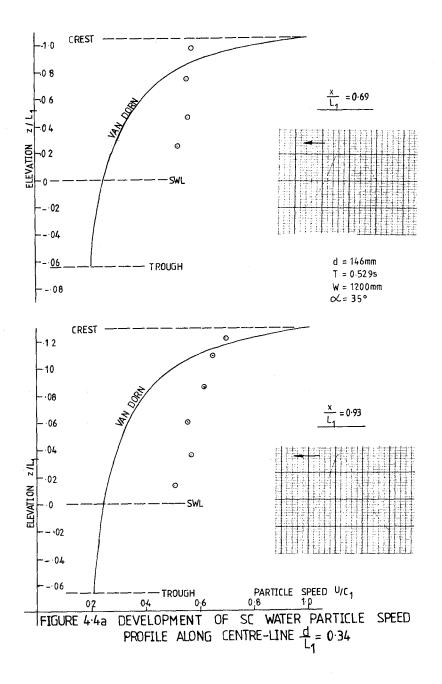
Table 4.2 summarises the maximum values of U(Umax) found for each d/L_1, and compares it with linear pattern speed (secα) and with a measured estimate of sc celerity C_s. It will be seen that maximum water particle speeds were less than pattern speeds except for $d/L_1 = 0.24$ for which there was variation in the sc jet speed; at these values of d/L this is qualitatively not in disagreement with Figure 4 of (13). However higher speeds later in the breaking process cannot be ruled out.
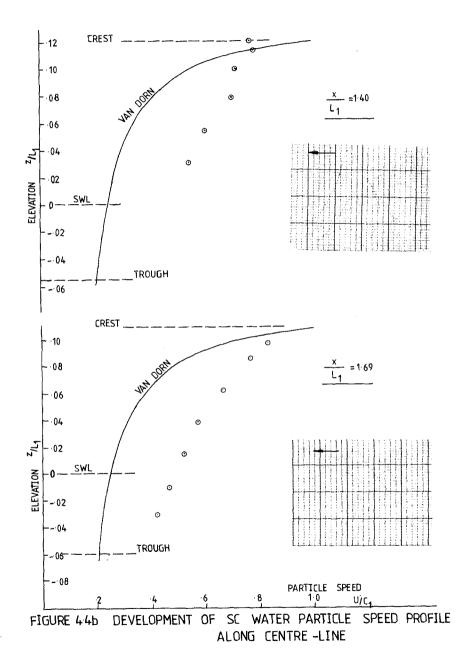
Further work is desirable on the crest values of U as breaking develops: measurements are required at lower d/L_1 values; and an increase of scale is desirable.

d/L_1	secα	Measured C_s/C_1	Measured $Umax/C_1$
0.34	1.22	1.33	0.83
0.29	1.22	1.31	0.89
0.24	1.22	1.31	0.82-1.28
0.19	1.22	1.39	0.78

Table 4.2   Summary of U_{max}

FIGURE 4·4a DEVELOPMENT OF SC WATER PARTICLE SPEED PROFILE ALONG CENTRE-LINE $\frac{d}{L_1} = 0·34$

FIGURE 4.4b DEVELOPMENT OF SC WATER PARTICLE SPEED PROFILE
ALONG CENTRE –LINE

CREST OF SC WAVE

VAN DORN

d = 145 mm
T = 0·597 s
W = 1100 mm
$\alpha = 35°$
$\dfrac{x}{L_1} = 1·66$

SWL

SC TROUGH

PARTICLE SPEED

U/C_1

ELEVATION z/L_1

FIGURE 4·5   SC WATER PARTICLE SPEED PROFILE $d/L_1 = 0·29$

CREST

VAN DORN

d = 121 mm
T = 0·597 s
W = 1200 mm
$\alpha = 35°$
$\dfrac{x}{L_1} = 1·89$

SWL

TROUGH

Particle Speed U/C_1

ELEVATION z/L_1

FIGURE 4·6   SC WATER PARTICLE SPEED PROFILE $\dfrac{d}{L_1} = 0·24$

CREST

VAN DORN

$d=121$
$T=0.687s$
$W=1200$
$\propto=35°$

$\dfrac{x}{L_1}=1.49$

ELEVATION z/L_1

SWL

u/c_1

TROUGH

FIGURE 4.7 SC WATER-PARTICLE SPEED PROFILE $d/L_1=0.19$

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