WAVE SET-UP, 2 : EXPERIMENTAL INVESTIGATION ON NORMALLY INCIDENT WAVES

Progress report wave set-up investigation (SK 31)

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CONTENTS

I INTRODUCTION

When surface waves approach a coast and enter shallow water, the mean water level decreases slightly until the breaker line. This is called wave set-down (negative wave set-up). On the shoreward side of the breaker line, in the surf zone, where the wave height decreases, the mean water level rises and comes above the still water level (apart from possible wind effects). This is called wave set-up. The magnitude of the wave set-up is defined as the vertical distance between mean and still water level.
The phenomenon is important in relation to

- currents, both parallel and perpendicular to the coast (long-shore currents, set-up currents, rip currents) and thus also for transport of sediment in and near the breaker zone,
- design and control of shore protection works as dikes, sea walls, beaches and dunes.

The first model and field observations of wave set-up are dated to about 1960 (see references in [1, 2, 3]). The first theoretical expressions for wave set-up were derived by several researchers in the period 1961-1964, after the introduction of the concept of radiation stress.
In 1976 an investigation into wave set-up due to obliquely incident regular waves has been started in the Laboratory of Fluid Mechanics of the Delft University of Technology. This report describes the first series of experiments, namely the experiments with normally incident waves. The purpose of these experiments is to make a link with other wave set-up experiments, especially the measurements by Bowen, Inman and Simmons [1] in a flume and one of the wave set-up experiments by the Delft Hydraulics Laboratory in a flume, which were performed in 1975 and 1976.
Chapter 2 contains a short resume of the theory of wave set-up in normally incident waves. In chapter 3 the experimental procedure is described. Chapter 4 summarizes the phenomena which may be generated

in the wave basin simultaneously with the desired wave (and may hinder the steady and regular wave pattern). Chapter 5 presents the experimental results and the comparison with results by other investigators. Chapter 6 contains the summary, discussion and suggestions for further work.

2 THEORY

This chapter contains a short theoretical description on wave set-up in waves of perpendicular incidence. Reference is made to [4] for the restrictions and the assumptions which have been made and for the derivation of several equations.
The equation describing the position of the mean water level reads

$$\rho g(h + \bar{\eta}) \frac{d\bar{\eta}}{dx} + \frac{dS_{xx}}{dx} = 0 \tag{2.1}$$

where h = still water depth,
$\bar{\eta}$ = wave set-up (difference between mean and still water level),
x = horizontal coordinate, normal to the shore, positive shorewards,
S_{xx} = component of radiation stress tensor.

Equation (2.1) follows from conservation of x-momentum. The radiation stress is defined as the contribution of the waves to the momentum transport tensor. The concept of radiation stress has been developed by Longuet-Higgins and Stewart [2, 5, 6, 7, 8] and independently by Dorrestein [3] and Lundgren (see [1, 9, 10]).
If λ = wave length, $k = 2\pi/\lambda$ = wave number and H = wave height, then the x-component of the radiation stress through second order of wave amplitude is given by

$$S_{xx} = \frac{1}{8} \rho g H^2 \left(\frac{2kh}{\sinh 2kh} + \frac{1}{2}\right) \tag{2.2}$$

which in shallow water reduces to

$$S_{xx} = \frac{3}{16} \rho g H^2 \tag{2.3}$$

Expression (2.2) follows from linear Airy wave theory, in which a small wave amplitude is supposed.
Two different regions, one seaward* and one shoreward* of the breaker line (surf zone) can be distinguished.

Zone seawards of the breaker line

Outside the surf zone the waves have an ordered character: the motion is nearly irrotational and contains little turbulence. The dissipation of energy is relatively small, so it can be assumed that energy is approximately conserved:

$$\frac{1}{8} \rho g H^2 nc = \text{constant}, \tag{2.4}$$

where c = phase velocity of the waves,
nc = group velocity of the wave train.

In this region the mean free surface can be computed [1, 4, 7, 9] to give

$$\bar{\eta} = -\frac{1}{8} \frac{kH^2}{\sinh 2kh} . \tag{2.5}$$

In shallow water this expression becomes

$$\bar{\eta} = -\frac{1}{16} \frac{H^2}{h} . \tag{2.6}$$

Combination of (2.4) and (2.5) yields

$$\bar{\eta} = -\frac{1}{8} H_o^2 k_o \frac{\coth^2 kh}{2kh + \sinh 2kh} , \tag{2.7}$$

where H_o = deep water wave height,
k_o = deep water wave number.

From wave theory follows that kh(tgh kh) = $k_o h$, so

$$\bar{\eta} = -H_o^2 k_o f (k_o h) , \tag{2.8}$$

where $f(k_o h)$ = function of k_o and the local still water depth h.

The wave set-down at the breaker line follows from (2.6) and, because $\bar{\eta}_b << h_b$, can be written as

$$\bar{\eta}_b = - \frac{1}{16} \gamma H_b , \tag{2.9}$$

where $\gamma = \dfrac{H_b}{h_b + \bar{\eta}_b}$, (2.10)

H_b = breaker height ,

$h_b + \bar{\eta}_b$ = mean water depth at the breaker line.

In fact two regions seaward of the breaker line can be distinquished, namely (1) well outside the surf zone where the linear theory is most applicable and (2) near the breaker line where the waves are too steep to use the linear theory.

Surf zone

In the breaker zone, where the waves are unstable and the fluid motion tends to lose its ordered character, wave energy is dissipated mainly due to the generation of turbulence. For this reason potential flow theory is no longer valid. Other analytical descriptions for the waves in the surf zone, however, are not available. Therefore empirical or semi-empirical approaches are necessary.
Using similarity arguments, it is assumed that the wave height is proportional to the local mean water depth (Longuet-Higgins and Stewart [8] , Bowen, Inman and Simmons [1]):

$$H(x) = \gamma \left[h(x) + \bar{\eta}(x) \right] . \tag{2.11}$$

The laboratory measurements by Bowen et al [1] show that an assumption of similarity in the surf zone is reasonable. Further the radiation stress expression (2.3), which followed from linear wave theory, is maintained.

Substitution of (2.11) into (2.3) gives

$$S_{xx} = \frac{3}{16}\rho g\gamma^2(h + \bar{\eta})^2 . \qquad (2.12)$$

Substituting (2.12) into (2.1) gives the gradient of the wave set-up

$$\frac{d\bar{\eta}}{dx} = -\frac{\frac{3}{8}\gamma^2}{1+\frac{3}{8}\gamma^2}\frac{dh}{dx} . \qquad (2.13)$$

This equation indicates that the gradient of the wave set-up in the surf zone is proportional to the local bottom slope. Equation (2.13) can be integrated between $x = x_b$ (breaker line) and $x = x_m$ (line of maximum set-up), see [9] , yielding

$$\bar{\eta}_{max} - \bar{\eta}_b = \frac{\frac{3}{8}\gamma^2}{1+\frac{3}{8}\gamma^2}(\bar{\eta}_{max} + h_b) . \qquad (2.14)$$

Substitution of (2.9) into (2.14) gives

$$\bar{\eta}_{max} = \frac{5}{16}\gamma H_b . \qquad (2.15)$$

3 EXPERIMENTAL PROCEDURE

The experiments were made in the 16.60 x 34.00 m^2 wave basin of the Laboratory of Fluid Mechanics of the Delft University of Technology. The wave basin arrangement is shown schematically in figure 1. The snake-type wave generator has a 32.80 m long flexible wave board, which consists of rubber panels, each 0.40 m wide. The wave generator can produce regular long-crested waves with a constant angle of incidence which can be varied. The stroke of the wave board at the bottom can be adjusted between zero (pure rotation) and the stroke at the still water level (pure translation). In all experiments the combination of translation and rotation was chosen such that the amplitude of secondary waves was expected to be minimal. Opposite to the wave board a 1:10 smooth concrete slope was built. The distance between the toe of the slope and the wave board was 8.35 m. The water in the constant depth part of the wave basin was 0.40 m deep.

The wave set-up and set-down were measured with tappings, mounted in the concrete beach, flush with the slope, in two rays of each 30 tappings (fig. 1). The horizontal distance between 2 tappings was 0.20 m. The inside diameter of the tappings was 1.5 mm. The tappings were connected with manometer tubes, in which the static head was measured. The assumptions involved in translating such measurement into mean water level were considered by Longuet-Higgins and Stewart [7] ; see also lit. [4] , [9] or [21] . The most important assumptions are a gently sloping bottom and a slow variation of the waves in horizontal direction. The manometer tubes were readed by photograph, allowing an accuracy of about ± 0.1 mm. Wave set-up and set-down measurements were made in ray 1, and also in and near the surf zone of ray 2.

Surface elevations were measured with a resistance-type wave gauge and analysed by a crest-trough apparatus to determine the mean wave height. The actual wave and the mean wave height were recorded on paper. Wave heights were measured in points of ray 1, starting 2 m from the wave board and as far as possible on the slope. Inside the surf zone the response of the wave gauge was not linear due to the small water depths here; this was corrected. The horizontal distance between 2 points where wave heights were measured was 0.20 m. In each point wave heights were measured during about 90 seconds to give a mean value.

Measurements of wave run-up and the position of the plunge point were made visually. Especially an accurate determination of the position of the plunge point was very difficult; observations could be made with an accuracy of about $\pm$ 0.05 m.

4 THE WAVES

In addition to the primary wave, the progressive sinusoidal wave with the period T of the motion of the wave board and with a crest which is parallel to the wave board, other undesired waves could be generated simultaneously in the wave basin, viz.:

a reflected component of the primary wave (reflection on the beach),
b reflected component of a (reflection against the wave board),
c secondary waves (importance depends on Ursell parameter, see [11]),
d subharmonic standing waves between wave board and beach (have an unknown origin).

All these waves have crests which are parallel to the wave board. Other disturbing waves are:

e standing waves between the side-walls (period T),
g higher order components of e (in general not important),
h standing edge waves between the side-walls with period T or 2T (see for instance [12, 13, 14]),
i standing cross-waves between the side-walls (period 2T, see [15]).

These waves have crests perpendicular to the wave board.
The occurrence of these disturbing waves and their magnitude depend on variables and quantities as the wave period, the wave height, the slope of the beach, the water depth, the distance between the wave board and the toe of the slope and the motion of the wave board. The waves c, d, e and h can disturb the wave pattern in an undesirable way. Moreover several kinds of currents may occur. Especially rip currents [16] can hinder a steady wave pattern, because their positions are not steady in general.
Preceding to the experiments described in this report, an investigation was carried out to minimize the disturbing influences. The most regular waves were selected to go on. Nevertheless these waves were not exactly reproducible; the wave height, for instance, measured at a certain place outside the surf zone and averaged over 90 seconds, varied about ± 4%.
The figures 2, 3 and 4 show profiles of the selected waves.

5 EXPERIMENTAL RESULTS

The experimental data of the observations in ray 1 are given in table 1. The wave height H_1 in the constant depth part of the wave basin is obtained by averaging the mean wave heights which were measured in 33 points. The surf similarity parameter ξ_o, defined as

$$\xi_o = \frac{tg\alpha}{\sqrt{H_o/\lambda_o}} \tag{5.1}$$

where λ_o = deep water wave length,
is a very important parameter: several surf zone properties and quantities can be expressed as functions of ξ_o [9]. The breaker type classification resulting from the experiments by Galvin [17] can be written as

$$\left.\begin{array}{llr} \text{surging or collapsing} & \text{if} & \xi_o > 3.33, \\ \text{plunging} & \text{if } 0.46 < & \xi_o < 3.33, \\ \text{spilling} & \text{if} & \xi_o < 0.46 \end{array}\right\} \tag{5.2}$$

The Ursell parameter, defined as

$$Ur = \frac{\lambda^2 H}{h^3} \tag{5.3}$$

can be considered as a measure for the effect of secondary waves (see [11]). In the experiments Ur < 13 (in the constant depth part of the wave basin), so the influence of secondary waves can be expected to be negligible.
The measured breaker height-to-depth ratios H_b/h_b are in agreement with measurements by Battjes [9], Iversen [18] and Goda [19].
The maximum set-up $\bar{\eta}_{max}$ is obtained by extrapolating the curve drawn through the measured and plotted set-up values, with the exception of the measurement near the plunge point. Near this point the mean pressure at the bottom was influenced strongly by the vertical wave impact. Translating the mean pressure measurement into mean water level is not possible by neglecting this influence.

The experimental results are shown in the figures 2, 3 and 4, except the results of the wave set-up measurements in ray 2, which are shown in subsequent figures. The break point is defined as the point of the maximum wave height. The horizontal distance between 2 points in the surf zone where wave height measurements were made was 0.20 m except for experiment 31-4, for which this distance was 0.10 m. As can be seen from figures 5, 6 and 7, a mutual distance of 0.20 m is likely too large to reveal always the plunge point in the wave height graph. To verify the similarity arguments on which equation (2.11) is based, the measured values of γ in the surf zone are given in table 2 and the nondimensional wave height H/H_b is plotted versus the nondimensional water depth $(h+\bar{\eta})/(h_b + \bar{\eta}_b)$ in figure 8. In agreement with the experimental results by Bowen, Inman and Simmons [1] the assumption of constant γ is reasonable. Compared to the experiments 31-2 and 31-4, the spatial variation of measured wave height is rather large for 31-3. This is caused by more reflection and more influence of secondary waves (higher Ursell number).

The figures 9, 10 and 11 present a comparison between measured and theoretical wave set-up and wave set-down in ray 1, and also the wave set-up measured in and near the surf zone of ray 2. The difference between the wave set-up measured in ray 1 and ray 2 is rather small for 31-2 (fig. 9) and especially 31-4 (fig. 11). The differences for 31-3 are greater: in ray 2 the position of the plunge point was more seaward and the gradient of the wave set-up in the surf zone was smaller than in ray 1. The maximum wave set-up, however, was almost the same. The theoretical wave set-down is obtained from (2.5), using (2.4) and the measured value of H_1. Well outside the surf zone the difference between theoretical and measured wave set-down is small. The difference between theoretical and observed wave set-down is significant near the breaker line, where the waves were too steep for the linear theory to remain valid. Although the waves were higher than predicted by the linear theory, the wave set-down was less than predicted by the same theory. This is in agreement with the observations by Bowen et al [1]. The position of the break point in the theoretical wave set-down curve is calculated from the measured value of H_b/h_b using the linear theory. In the surf zone the theoretical set-up is obtained from (2.13), substituting the measured value of $\bar{\gamma}$, the over the surf zone averaged value of γ , and starting at the computed break point. The figures 9, 10 and 11 show a rather small difference between measured and theoretical maximum wave set-up, but a larger difference between measured and theoretical gradient of wave set-up.

A comparison of wave set-up, wave height and wave run-up observations in ray 1 with the theory and some empirical formulae is given in table 3. Le Méhauté and Koh [20] derived the following wave breaking criterion

$$\frac{H_b}{H_o} = 0.76\ (tg\alpha)^{1/7}\ \left(\frac{H_o}{\lambda_o}\right)^{-1/4} \qquad (5.4)$$

from several experimental investigations in two-dimensional wave tanks by other investigators. Substitution of (5.4) into (2.15) gives an expression for the maximum value of the wave set-up

$$\bar{\eta}_{max} = 0.24\ \bar{\gamma}\ H_o (tg\alpha)^{1/7}\ \left(\frac{H_o}{\lambda_o}\right)^{-1/4} \qquad (5.5)$$

A reliable empirical formula for the wave run-up height on a slope was given by Hunt (see reference in [1] or [9]):

$$R = C_p H_o\ tg\alpha\ \left(\frac{H_o}{\lambda_o}\right)^{-1/2} \qquad (5.6)$$

where R = wave run-up height (above S.W.L.),

C_p = porosity factor.

For a smooth slope eq. (5.6) can be written as

$$R = \xi_o H_o . \qquad (5.7)$$

The agreement between measured H_b/H_o and the value predicted by Le Méhauté and Koh's formula (5.4) is rather well (table 3). As already appeared from the figures 9 through 11 the difference between measured and theoretical wave set-down near the break point is large. This applies also but to a less extent to the gradient of wave set-up in the surf zone. The agreement between measured $\bar{\eta}_{max}$ and the value computed from $\bar{\eta}_{max} = \frac{5}{16} \bar{\gamma} H_b$ is reasonable, while the agreement between measured and theoretical run-up is excellent. The difference between $\bar{\eta}_{max}$ and the value predicted by (5.5), however, is not small (in experiment 31-3).
The experimental data of the experiments by Bowen et al [1] and one of the experiments by the Delft Hydraulics Laboratory are given in table 4. Bowen et al [1] do not report on the breaker type: in table 4 the breaker type is obtained from Galvin's breaker type classification (5.2). The experimental results by Bowen et al [1] are remarkable in that the measured values of H_b/h_b are large compared to measurements by Battjes [9], Iversen [18] and Goda [19]. The comparison of above measurements with theory and some empirical formulae is given in table 5. The difference between measured H_b/H_o and the value predicted by (5.4) is about 10% at most. The agreement between measured $\bar{\eta}_{max}$ and the value computed from $\bar{\eta}_{max} = \frac{5}{16} \bar{\gamma} H_b$ is rather well, while the agreement between measured and theoretical run-up is excellent. The difference between measured $\bar{\eta}_{max}$ and the value computed from (5.5), however, is not small in some experiments.
Bowen et al [1] compared the theoretical ratio of set-up slope to beach slope, which is given by

$$\frac{1}{tg\alpha}\frac{d\bar{\eta}}{dx} = \frac{+\frac{3}{8}\gamma^2}{1+\frac{3}{8}\gamma^2} \tag{5.8}$$

to the measured ratio of set-up slope to beach slope, which was taken as

$$K = \frac{1}{tg\alpha}\,\frac{\bar{\eta}_{max} - \bar{\eta}_b}{x_{max} - x_b}\,. \tag{5.9}$$

Thus, the measured ratio of set-up slope to beach slope was averaged over the surf zone, giving a reasonably good agreement with the theoretical set-up slope-to-beach slope ratio as expressed by (5.8), but also neglecting the real steeper set-up slope.
A comparison between the experimental results of T2 - 4B from the Delft Hydraulics Laboratory and experiment 31-4 is shown in fig. 12. The similarity in beach slope and wave period permits a comparison. The agreement is good, especially for the gradient of the set-up in the surf zone, but also for the magnitudes of set-up and set-down as appears from

31-4	$\frac{\bar{\eta}_{max}}{H_b} = 0.31$	$\frac{\bar{\eta}_b}{H_b} = -0.024$
T2-4B	$\frac{\bar{\eta}_{max}}{H_b} = 0.33$	$\frac{\bar{\eta}_b}{H_b} = -0.025$

The breaker depths are almost equal, in spite of higher waves for 31-4. Hence, the ratio of breaker height to mean water depth differs slightly: $\gamma_b = 0.81$ for T2 - 4B, $\gamma_b = 0.95$ for 31-4. The difference in $\bar{\gamma}$ is small, however, which may be seen from fig. 12.

6 SUMMARY, DISCUSSION AND SUGGESTIONS FOR FURTHER WORK

The experiments described in this report and also the experiments by Bowen et al [1] and the Delft Hydraulics Laboratory indicate that the maximum value of the wave set-up on flat solid beaches due to normally incoming waves may be approximated rather accurately by

$$\bar{\eta}_{max} = \frac{5}{16} \gamma H_b \tag{6.1}$$

where H_b = measured breaker height.
Equation (6.1) expresses the maximum wave set-up in terms of an inshore parameter (γ) and an inshore quantity (H_b). Equation (5.5)

$$\bar{\eta}_{max} = 0.24 \gamma H_0 (tg\alpha)^{1/7} \left(\frac{H_o}{\lambda_o}\right)^{-1/4} \tag{6.2}$$

gives the maximum wave set-up as a function of offshore parameters and quantities, the beach slope $tg\alpha$ and still γ. From the experimental results given by Battjes [9] , Iversen [18] and Goda [19] it is possible, however, to estimate γ from ξ_o (see [9] , p. 21). The agreement of all measurements (including the observations by Bowen et al [1] and the one by the Delft Hydraulics Laboratory) with the value predicted by (6.2) is reasonable, but less than with (6.1). All experiments present an excellent agreement of measured run-up with Hunt's formula.
As expected for plunging breakers the set-up does not start at the break point but near the plunge point. Nevertheless the steeper set-up slope (steeper than predicted by theory with eq. (2.13)) yields a maximum set-up close to the theoretical value (6.1). Near the plunge point translation of mean pressure measurement into mean water level fails (does apply to the experiments described in this report, Bowen et al [1] do not report on this). This is caused by the plunge phenomenon (wave impact). Neglecting the measurements near the plunge points, the curves drawn through the other set-up measurement-points are practically straight.

In the surf zone the theory is based on the assumption of proportionality of wave height to mean water depth (2.11). Also the experiments described in this report show that this assumption is reasonable.
Well outside the surf zone the difference between measured and theoretical wave set-down is small. Some scatter occurs due to reflection, secondary waves, measuring errors, etc.
In all experiments the difference between observed and theoretical set-down is significant in front of the breaker line (this difference will increase when the theoretical set-down is computed from the measured wave heights). A possible explanation for this phenomenon may be that not only near the plunge point but also in front of the break point the translation of mean pressure measurement into mean water level fails. This idea is elaborated below.
The mean pressure at the bottom ($\bar{p}$) can be written as (see [4] , [21]):

$$\bar{p} = \rho g(h + \bar{\eta}) + P \tag{6.3}$$

where $\rho g(h + \bar{\eta})$ = mean hydrostatic pressure at the bottom,
P = mean hydrodynamic pressure at the bottom.

Equation (6.3) follows from conservation of vertical momentum.
P can be written as ([4] , [21]):

$$P = \frac{dS_{xz}}{dx} + \text{small terms} \tag{6.4}$$

$$\text{where } S_{xz} = \overline{\int_{-h}^{\eta} \rho uw dz} , \tag{6.5}$$

η = elevation of free surface above S.W.L.,
u = horizontal velocity,
w = vertical velocity,
z = vertical coordinate, measured positive upwards from S.W.L.,
the overbar indicates a time average.

S_{xz} can be considered as the (x,z)-component of the three-dimensional radiation stress tensor. Substitution of the linear wave theory expressions for η, u and w into (6.5) gives $S_{xz} = 0$. Near break and plunge point the velocities due to the waves do not behave sinusoidally, however, but are strongly asymmetric. Hence, generally S_{xz} is not zero here. Besides, the growth and change of asymmetry occurs along a short distance (in plunging breakers), possibly yielding a considerable gradient of vertical radiation stress. The term (6.5) will have more influence in plunging breakers: in spilling breakers the waves become asymmetrically too, but much less than in plunging breakers.
Above mentioned explanation seems to be confirmed by the experiments by Bowen et al [1] : the difference between theoretical and measured $\bar{\eta}_b$ was less in experiments with breakers which were calculated as spilling. Some additional measurements were made to check this explanation. In these experiments the mean water level was also measured with a wave gauge. The signal of the wave gauge was fed into an electronic filter to damp the wave motion. The differences between these set-down observations and the set-down observations with manometers, however, were very small. Consequently, P have not influenced the set-down measurements with manometers in front of the breaker line.
The number of experiments, described in this report, is limited to three. The agreement between these experiments and the 11 experiments by Bowen et al [1] and the experiment by the Delft Hydraulics Laboratory is satisfactory and therefore continuation of the experiments with obliquely incident waves is justified. Results of these experiments will be reported in the next progress report.

APPENDIX A: REFERENCES

1. Bowen, A.J., Inman, D.L. and Simmons, V.P., Wave "set-down" and set-up, J. Geoph. Res., vol. 73, 1968, p. 2569-2577.

2. Longuet-Higgins, M.S. and Stewart, R.W., A note on wave set-up, J. Mar. Res., vol. 21, 1963, p. 4-10.

3. Dorrestein, R., Wave set-up on a beach, Proc. Second Techn. Conf. on Hurricanes, June 1961, Miami Beach; Washington, D.C., 1962, p. 230-241.

4. Visser, P.J., Wave set-up, 1: literature and theoretical investigation, in press, 1977.

5. Longuet-Higgins, M.S. and Stewart, R.W., Changes in the form of short gravity waves on long waves and tidal currents, J. Fluid Mech., vol. 8, 1960, p. 565-583.

6. Longuet-Higgins, M.S. and Stewart, R.W., The changes in amplitude of short gravity waves on steady non-uniform currents, J. Fluid Mech., vol. 10, 1961, p. 529-549.

7. Longuet-Higgins, M.S. and Stewart, R.W., Radiation stress and mass transport in gravity waves, with application to "surf-beats", J. Fluid Mech., vol. 13, 1962, p. 481-504.

8. Longuet-Higgins, M.S. and Stewart, R.W., Radiation stresses in water waves; a physical discussion, with applications, Deep-Sea Res., vol. 11, 1964, p. 529-562.

9. Battjes, J.A., Computation of set-up, longshore currents, run-up and overtopping due to wind-generated waves, Communications on Hydraulics, Department of Civil Engineering, Delft University of Technology, Report no. 74-2, 1974.

10. Battjes, J.A., Set-up due to irregular waves, Proc. 13th. Conf. Coastal Eng., Vancouver, B.C., 1972, p. 1993-2004.

11. Hulsbergen, C.H., Origin, effect and suppression of secondary waves, Proc. 14th. Conf. Coastal Eng., Copenhagen, 1974, p.392-411.

12. Bowen, A.J. and Inman, D.L., Edge waves and crescentic bars, J. Geoph. Res., vol. 76, 1971, p. 8662-8671.

13. Guza, R.T. and Davis, R.E., Excitation of edge waves by waves incident on a beach, J. Geoph. Res., vol. 79, 1974, p. 1285-1291.

14. Guza, R.T. and Inman, D.L., Edge waves and beach cusps, J. Geoph. Res., vol. 80, 1975, p. 2997-3012

15. Garrett, C.J.R., On cross-waves, J. Fluid Mech. vol. 41, 1970, p. 837-849.

16. Bowen, A.J., Rip currents, 1. Theoretical Investigations, J. Geophys. Res., vol. 74, 1969, p. 5467-5478.

17. Galvin, C.J. Jr., Breaker type classification on three laboratory beaches, J. Geoph. Res., vol. 73, 1968, p. 3651-3659.

18. Iversen, H.W. Laboratory study of breakers, Nat. Bur. of Standards, Circular 521, Washington, D.C., 1952, p. 9-32.

19. Goda, Y., A synthesis of breaker indices, Trans. Jap. Soc. Civ. Eng., vol. 2, 1970, p. 227-230.

20. Le Méhauté, B. and Koh, R.C.Y., On the breaking of waves arriving at an angle to the shore, J.Hydr. Res., vol. 5, p. 67-88.

21. Liu, P. L-F. and Mei, C.C., Effects of a breakwater on nearshore currents due to breaking waves, Tech. Mem. no. 57, C.E.R.C., 1975.

APPENDIX B: SYMBOLS

The symbols used in the text are listed below. The remaining symbols used in appendix C are listed in table 3.

c = phase velocity
g = gravitational acceleration
H = wave height
H_o = deep water wave height
H_1 = mean wave height in constant depth part of wave basin
H_b = breaker height
h = still water depth
h_1 = still water depth in constant depth part of wave basin
h_b = still water depth at breaker location
K = over surf zone averaged (measured) ratio of set-up slope to beach slope
k = wave number
k_o = deep water wave number
nc = group velocity
P = mean hydrodynamic pressure at the bottom
$\bar{p}$ = mean pressure at the bottom
R = wave run-up height
S_{xx} = (x, x)-component of radiation stress tensor
S_{xz} = (x, z)-component of 3-dimensional radiation stress tensor
T = wave period
u = horizontal velocity,
Ur = $\lambda^2 H/h^3$ = Ursell parameter
w = vertical velocity
x = horizontal coordinate, positive shorewards
z = vertical coordinate, positive upwards from S.W.L.

α = slope angle with respect to the horizontal

γ = wave height-mean water depth ratio in surf zone

$\bar{\gamma}$ = over surf zone averaged value of γ

γ_b = wave height-mean water depth ratio at breaker location

η = elevation of free surface above S.W.L.

$\bar{\eta}$ = mean value of η: wave set-up or wave set-down

$\bar{\eta}_b$ = wave set-down at breaker location

$\bar{\eta}_{min}$ = minimum wave set-up (maximum wave set-down)

$\bar{\eta}_{max}$ = maximum wave set-up

λ = wave length

λ_o = deep water wave length

ξ_o = $tg\alpha/\sqrt{H_o/\lambda_o}$

ρ = mass density of water

APPENDIX C: 5 TABLES

The symbols used in table 5 correspond with the symbols used in table 3.

experiment	T sec	$tg\alpha$	λ_o cm	h_1 cm	$\frac{h_1}{\lambda_o}$	λ_1 cm	H_1 cm	H_0 cm	$\frac{H_0}{\lambda_o}$	ξ_o	Ur_1	H_b cm	h_b cm	$\frac{H_b}{h_b}$	$\bar{\eta}_b$ cm	breaker type	$\bar{\eta}_{min}$ cm	$\bar{\gamma}$	$\bar{\eta}_{max}$ cm	R cm
31-2	1.17	0.101	215	40.0	0.186	188	8.65	9.44	0.044	0.48	4.8	10.8	9.02	1.20	-0.31	pl.	-0.35	1.11	3.50	4.6
31-3	1.69	0.101	447	40.0	0.089	304	8.56	9.08	0.020	0.71	12.3	12.6	10.97	1.15	-0.33	pl.	-0.51	1.14	3.90	6.6
31-4	1.30	0.101	264	40.1	0.152	217	7.70	8.42	0.032	0.56	5.6	10.3	11.10	0.93	-0.25	pl.	-0.34	0.97	3.22	4.7
	meas		calc	meas		calc	meas	calc				meas	meas		meas	meas	meas		meas	meas

the index 1 refers to a value in constant depth part of wave basin,

pl. = plunging breaker,

$\bar{\gamma}$ = over surf zone averaged value of γ,

R = wave run-up.

table 1 : experimental data of observations in ray 1

distance from breakpoint in cm / experiment	0	10	20	30	40	50	60	70	80	90	100	110	$\bar{\gamma}$
31-2	1.24		1.17		1.03		1.10		1.03				1.11
31-3	1.18		1.22	1.19	0.98		1.22		1.15		1.04		1.14
31-4	0.95	1.01	1.03	1.09	1.06	0.77	1.02	1.01	0.81	0.99	0.93	0.91	0.97

table 2: measured values of γ in surf zone

experiment	$\frac{H_b}{H_0}$	$\frac{H'_b}{H_0}$	$\frac{H''_b}{H_0}$	$\bar{\eta}_b$ cm	$\bar{\eta}'_b$ cm	$\bar{\eta}_{min}$ cm	$\bar{\eta}_{max}$ cm	$\bar{\eta}'_{max}$ cm	$\bar{\eta}''_{max}$ cm	K	K'	K''	R cm	R' cm
31-2	1.14	1.07	1.20	-0.31	-0.75	-0.35	3.50	3.74	3.91	0.37	0.32	0.30	4.6	4.53
31-3	1.39	1.21	1.46	-0.33	-0.90	-0.51	3.90	4.48	4.71	0.41	0.33	0.28	6.6	6.45
31-4	1.22	1.08	1.29	-0.25	-0.62	-0.34	3.22	3.11	3.31	0.36	0.26	0.24	4.7	4.72
	meas			meas		meas	meas			meas			meas	

$\frac{H'_b}{H_o}$: calculated with linear theory, $\bar{\eta}'_{max} = \frac{5}{16} \bar{\gamma} H_b$,

$\frac{H''_b}{H_o} = 0.76 \, (tg\alpha)^{1/7} \, (\frac{H_o}{\lambda_o})^{-1/4}$, $\bar{\eta}''_{max} = 0.24 \, \bar{\gamma} \, H_o (tg\alpha)^{1/7} \, (\frac{H_o}{\lambda_o})^{-1/4}$,

$\bar{\eta}'_b = -\frac{1}{16} \, \bar{\gamma} \, H_b$, $R' = \xi_o H_o$,

$K = \frac{1}{tg\alpha} \frac{d\bar{\eta}}{dx}$ = measured set-up slope-to-beach slope ratio,

$K' = \frac{\frac{3}{8}\gamma^{-2}}{1 + \frac{3}{8}\gamma^{-2}}$ = theoretical set-up slope-to-beach slope ratio,

$K'' = \frac{\bar{\eta}_{max} - \bar{\eta}_b}{tg\alpha.(x_{max} - x_b)}$ = over surf zone averaged set-up slope-to-beach slope ratio.

table 3: comparison of observations in ray 1 with theory and some empirical formulae.

experiment	T sec	$tg\alpha$	λ_o cm	h_1 cm	$\frac{h_1}{\lambda_o}$	λ_1 cm	H_1 cm	H_o cm	$\frac{H_o}{\lambda_o}$	ξ_o	Ur_1	H_b cm	h_b cm	$\frac{H_b}{h_b}$	$\bar{\eta}_b$ cm	breaker type	$\bar{\eta}_{min}$	$\bar{\gamma}$	$\bar{\eta}_{max}$ cm	R cm
71/3	0.82	0.082	105					3.60	0.034	0.45		4.40	4.15	1.06	-0.17	sp.		0.90	1.48	1.70
71/4	0.82	0.082	105					5.15	0.049	0.38		5.90	5.5	1.07	-0.19	sp.		0.88	1.60	1.84
51/4	1.14	0.082	202					4.20	0.021	0.58		6.60	5.0	1.32	-0.19	pl.		1.11	2.07	2.32
51/6	1.14	0.082	202					6.45	0.032	0.47		8.55	6.8	1.26	-0.32	pl.		1.15	2.95	3.25
51/8	1.14	0.082	202					9.00	0.045	0.40		10.60	9.7	1.09	-0.47	sp		1.00	3.30	3.70
35/7	1.65	0.082	424					4.25	0.010	0.83		7.75	5.9	1.31	-0.18	pl.		1.22	3.37	3.66
35/10	1.65	0.082	424					5.85	0.014	0.71		9.65	6.8	1.42	-0.25	pl.		1.19	3.70	4.23
35/12	1.65	0.082	424					7.10	0.017	0.65		11.45	9.5	1.21	-0.26	pl.		1.17	4.15	4.75
35/15	1.65	0.082	424					8.90	0.021	0.58		13.00	9.7	1.34	-0.43	pl.		1.17	4.65	5.20
24/17	2.37	0.082	876					6.20	0.0071	0.99		11.80	8.8	1.34	-0.30	pl.		1.24	4.50	6.17
24/20	2.37	0.082	876					7.50	0.0086	0.90		12.70	9.2	1.38	-0.38	pl.		1.28	5.28	6.60
T2-4B	1.28	0.10	255	29.8	0.117	1.92	6.21	6.71	0.026	0.62	8.6	8.62	10.8	0.80	-0.22	pl.	-0.33	0.94	2.86	

71/3 through 24/20 : experiments by Bowen, Inman and Simmons

T2-4B : one of the experiments by the Delft Hydraulics Laboratory

table 4 : experimental data

experiment	$\frac{H_b}{H_0}$	$\frac{H'_b}{H_0}$	$\frac{H''_b}{H_0}$	$\bar{\eta}_b$ cm	$\bar{\eta}'_b$ cm	$\bar{\eta}_{min}$ cm	$\bar{\eta}_{max}$ cm	$\bar{\eta}'_{max}$ cm	$\bar{\eta}''_{max}$ cm	K	K'	K"	R cm	R' cm
71/3	1.22	1.08	1.24	-0.17	-0.25		1.48	1.24	1.26		0.23	0.26	1.70	1.61
71/4	1.15	1.02	1.13	-0.19	-0.32		1.60	1.62	1.59		0.22	0.26	1.84	1.93
51/4	1.57	1.18	1.40	-0.19	-0.46		2.07	2.29	2.04		0.32	0.32	2.32	2.42
51/6	1.33	1.11	1.26	-0.32	-0.61		2.95	3.07	2.91		0.33	0.34	3.25	3.00
51/8	1.18	1.04	1.16	-0.47	-0.66		3.30	3.31	3.25		0.27	0.30	3.70	3.54
35/7	1.82	1.34	1.69	-0.18	-0.59		3.37	2.95	2.74		0.34	0.39	3.66	3.53
35/10	1.65	1.20	1.55	-0.25	-0.72		3.70	3.59	3.37		0.34	0.38	4.23	4.11
35/12	1.61	1.20	1.48	-0.26	-0.84		4.15	4.19	3.85		0.34	0.31	4.75	4.56
35/15	1.46	1.20	1.40	-0.43	-0.95		4.65	4.75	4.55		0.34	0.37	5.20	5.10
24/17	1.90	1.45	1.84	-0.30	-0.91		4.50	4.57	4.42		0.37	0.36	6.17	6.10
24/20	1.69	1.42	1.75	-0.38	-1.02		5.28	5.08	5.26		0.38	0.40	6.60	6.73
T2-4B	1.28	1.06	1.36	-0.22	-0.51	-0.33	2.86	2.53	2.68	0.36	0.25	0.22		4.17

71/3 through 24/20: experiments by Bowen, Inman and Simmons

T2-4B : one of the experiments by the Delft Hydraulics Laboratory

table 5: comparison of observations with theory and some empirical formulae

APPENDIX D: 12 FIGURES

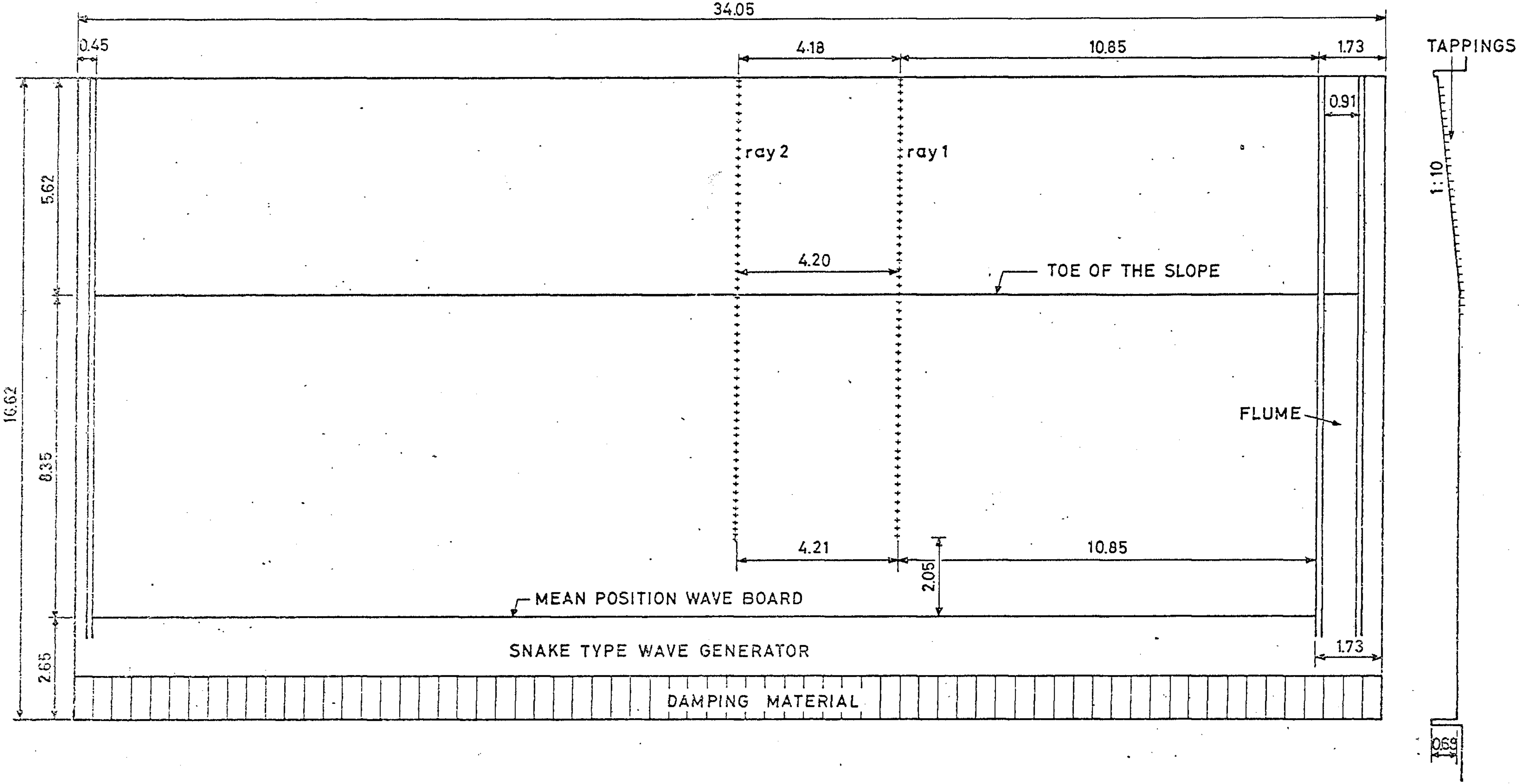
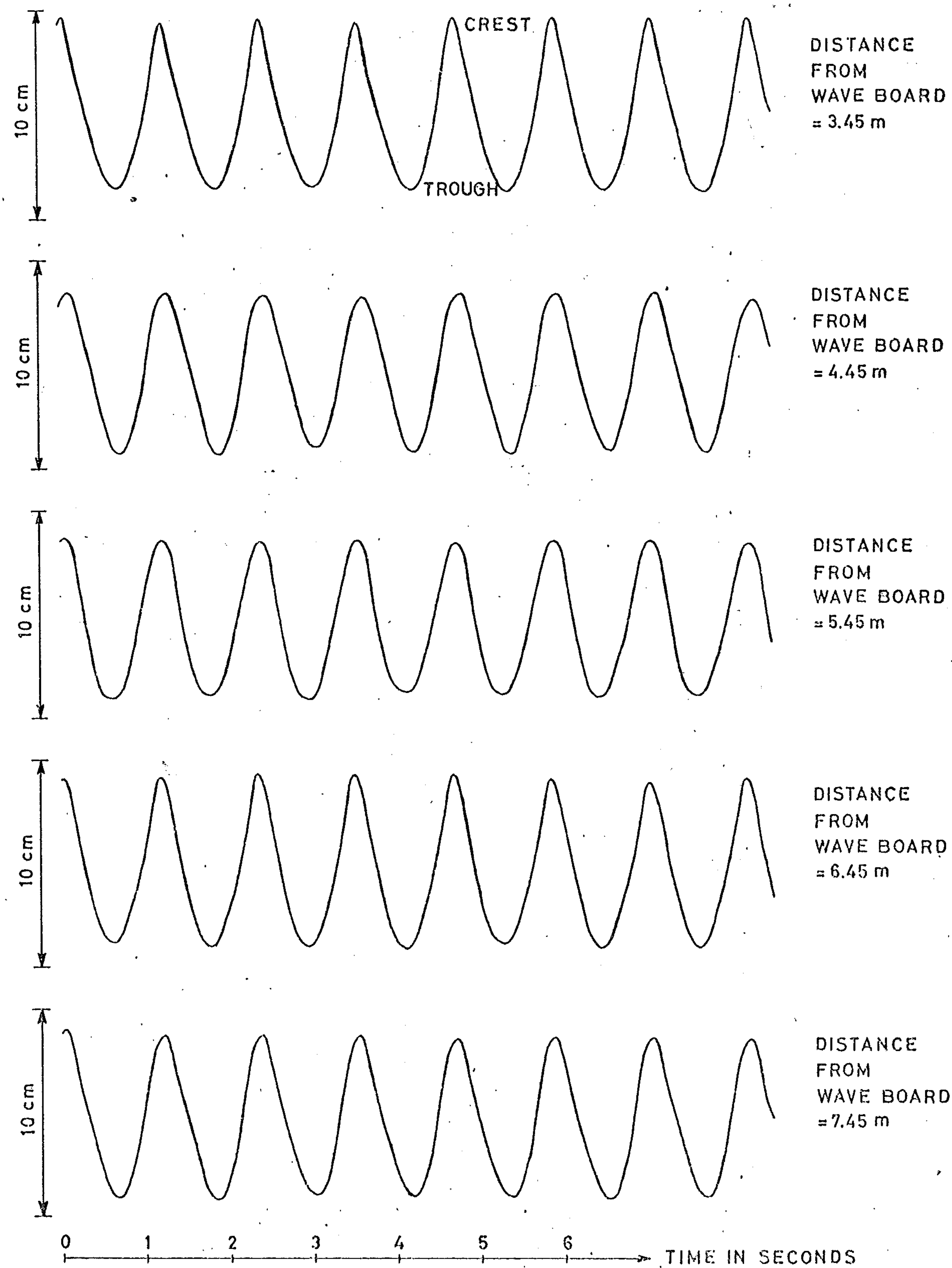
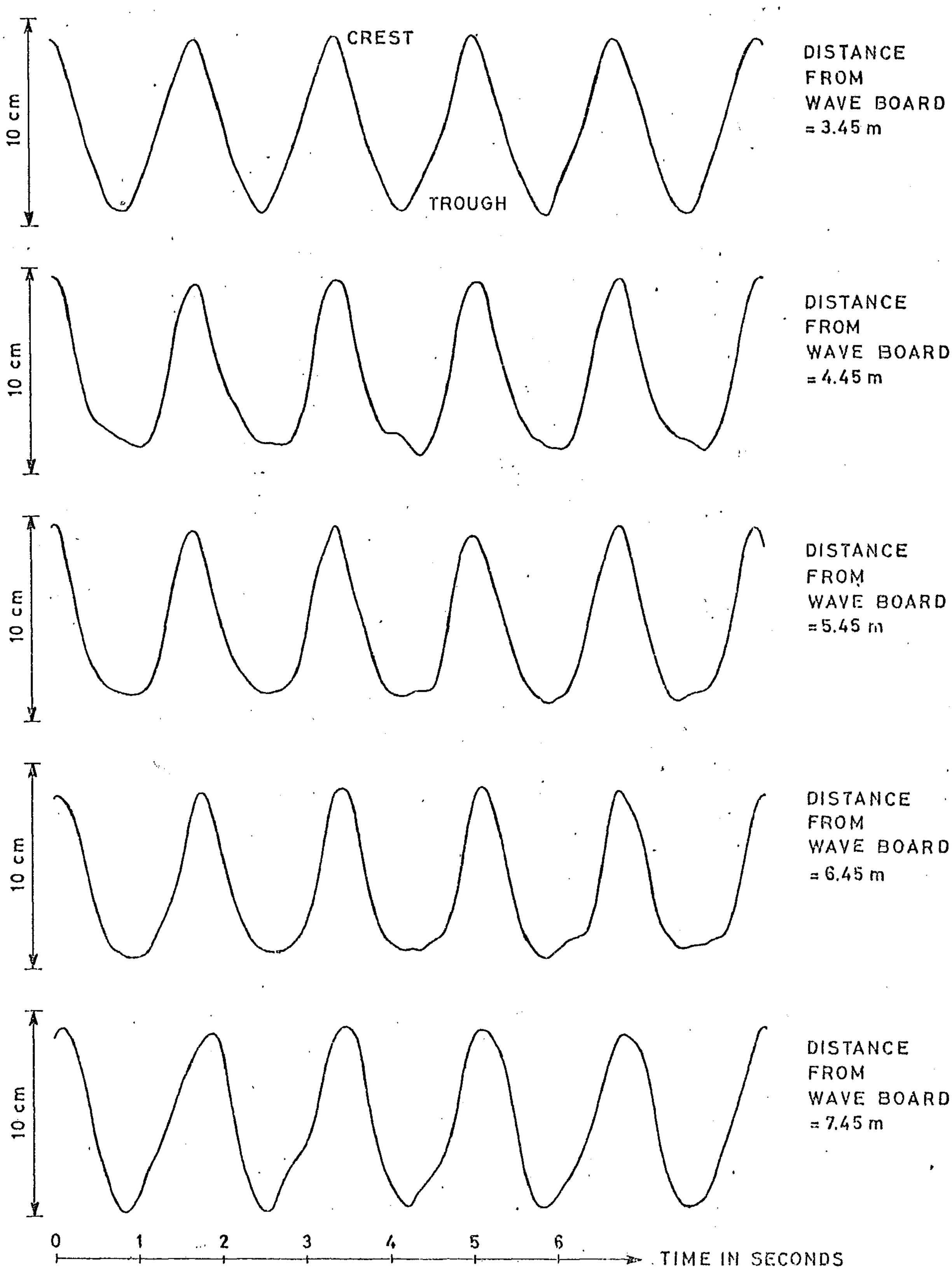


FIG.1 SCHEMATIC PLAN WAVE BASIN (MEASURES IN METERS)



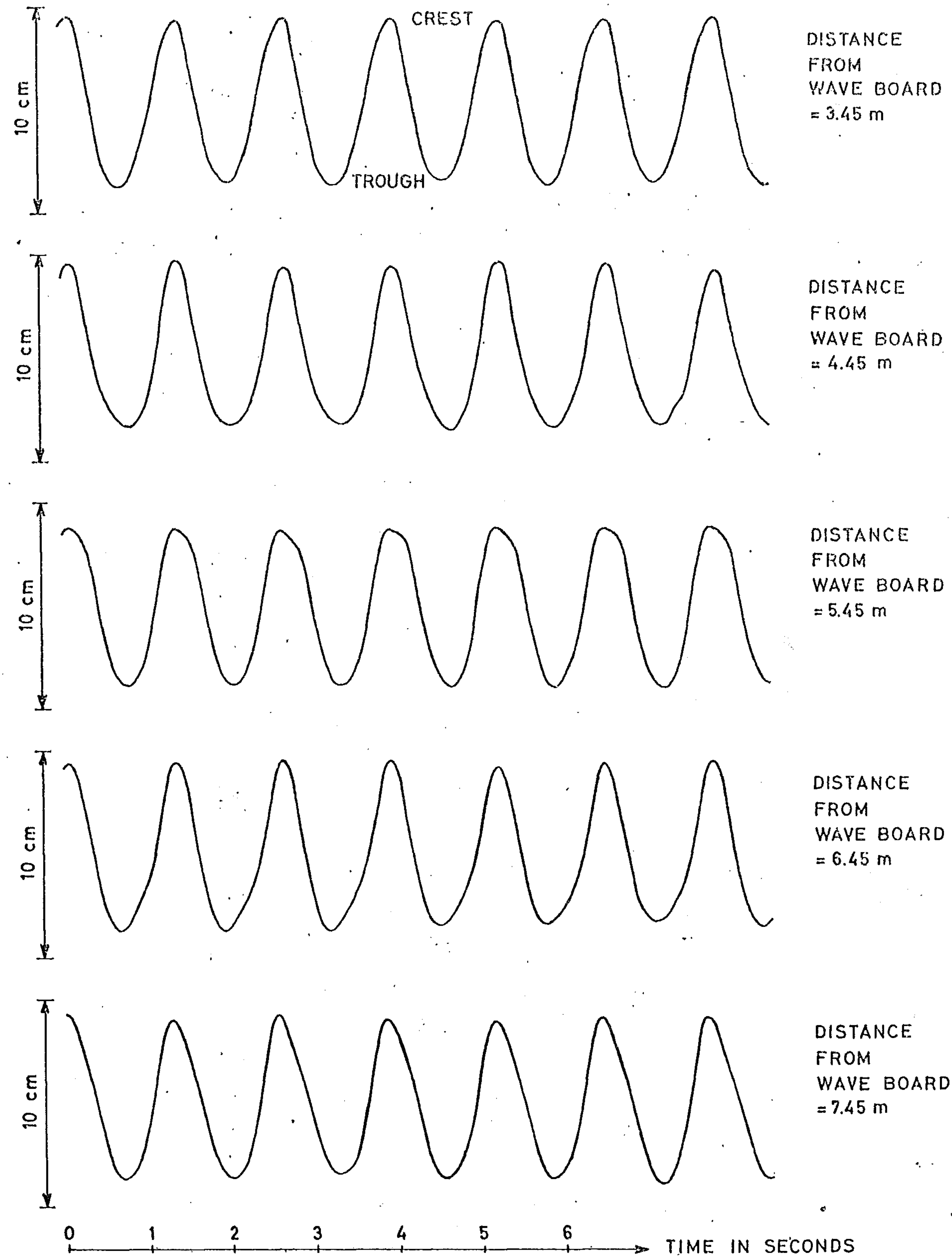
EXP. 31 – 2 $T = 1.17$ sec $h_1 = 40.0$ cm $H_1 = 8.65$ cm ray 1

FIG. 2 : WAVE PROFILES



EXP. 31 − 3 $T = 1.69$ sec $h_1 = 40.0$ cm $H_1 = 8.56$ cm ray 1

FIG. 3 : WAVE PROFILES



EXP. 31 – 4 $T = 1.30$ sec $h_1 = 40.1$ cm $H_1 = 7.70$ cm ray 1

FIG. 4 : WAVE PROFILES

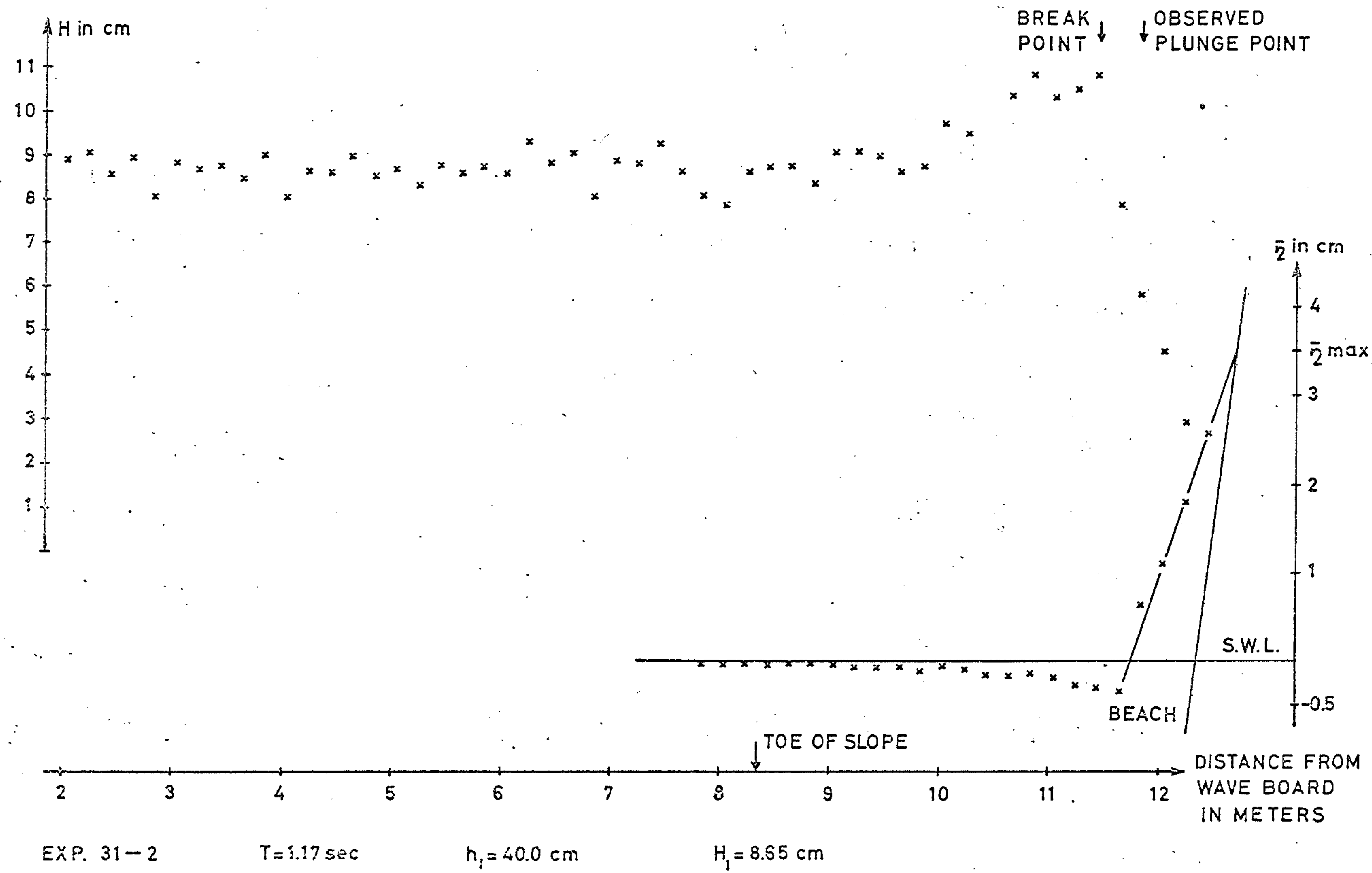
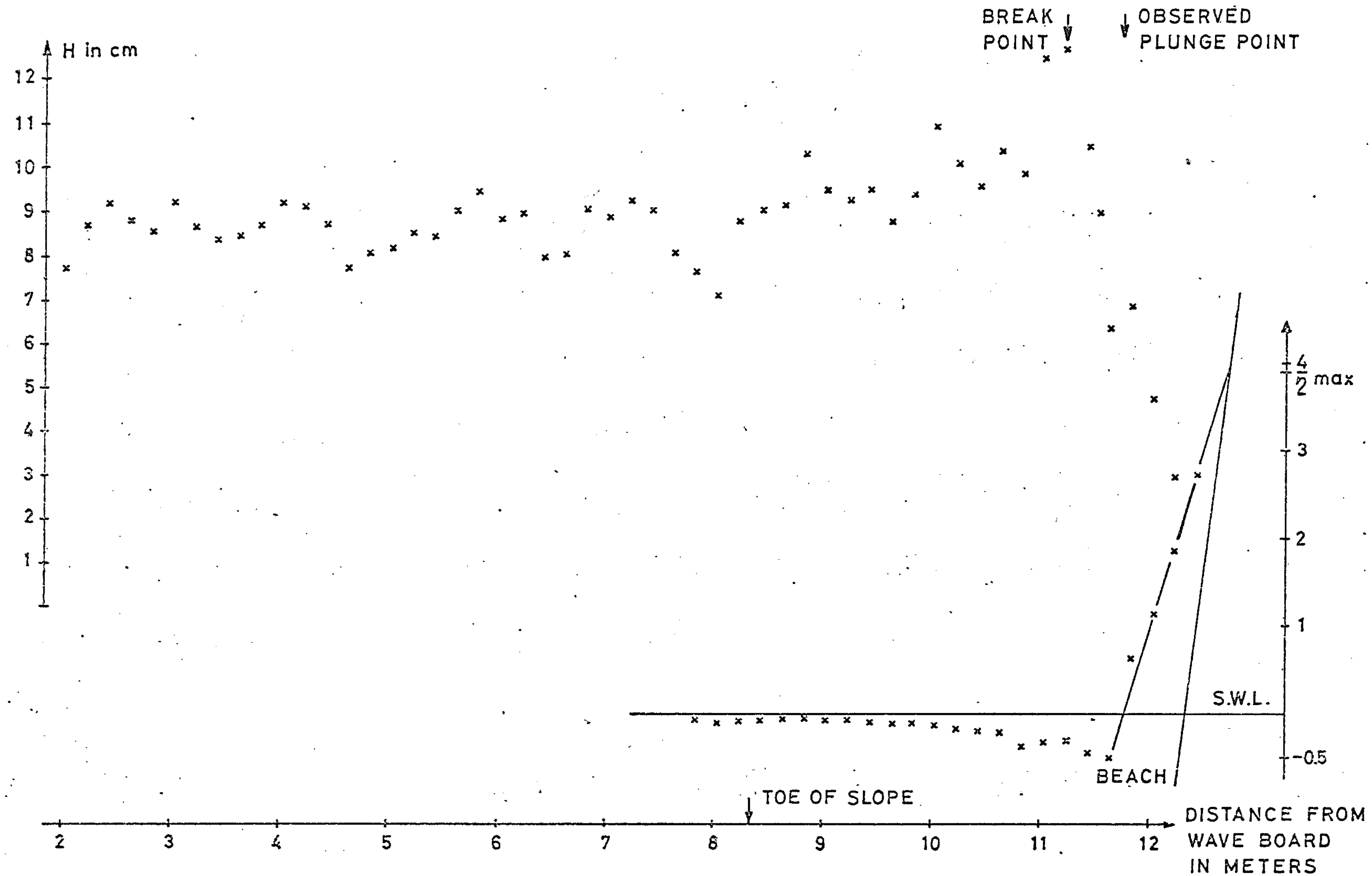
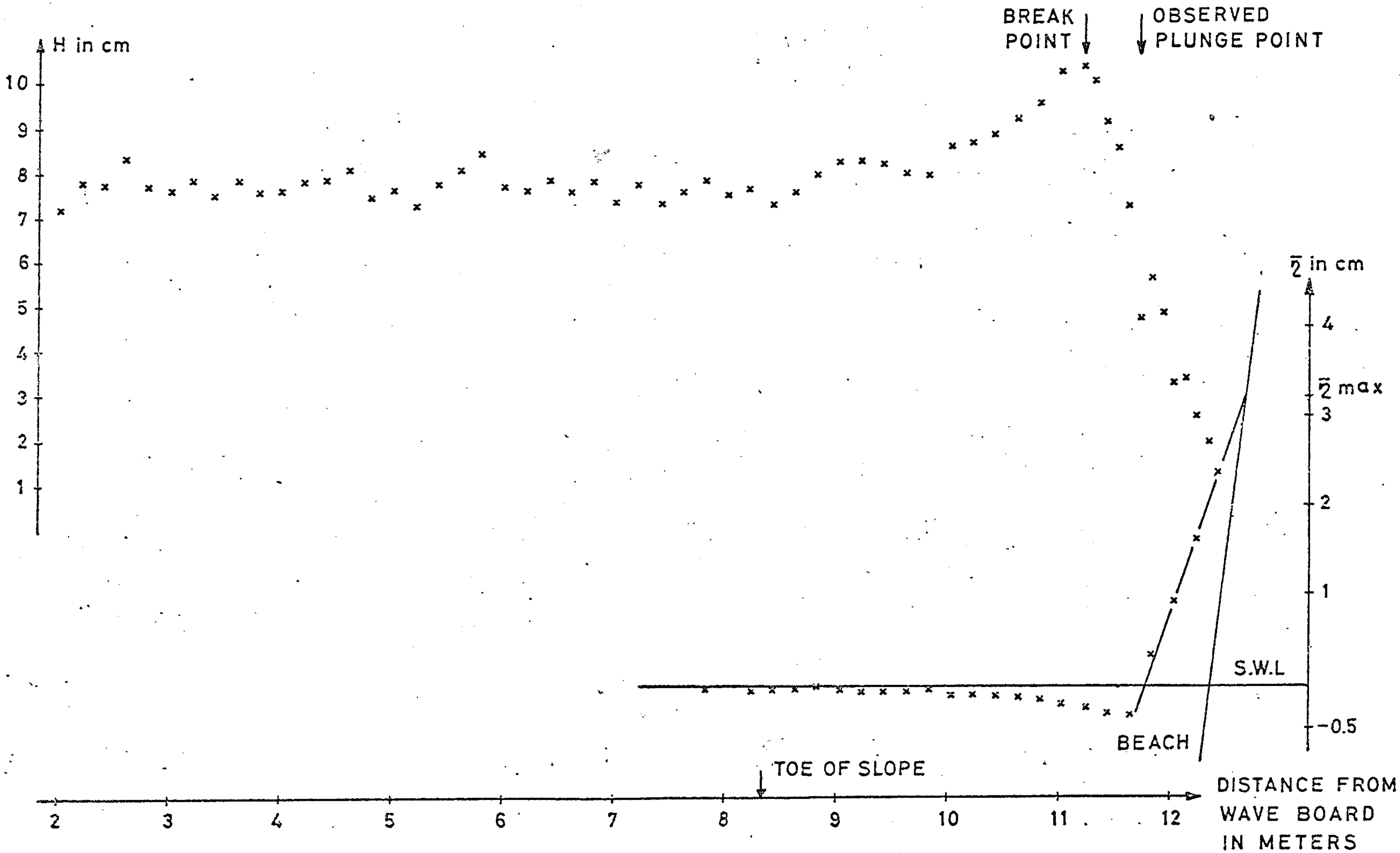


FIG. 5 : WAVE HEIGHTS AND SET-UP MEASURED IN RAY 1.



EXP. 31 − 3 T = 1.69 sec h_i = 40.0 cm H_i = 8.56 cm

FIG. 6 : WAVE HEIGHTS AND SET-UP MEASURED IN RAY 1.



EXP. 31 – 4 T = 1.30 sec h_1 = 40.1 cm H_1 = 7.70 cm

FIG. 7 : WAVE HEIGHTS AND SET-UP MEASURED IN RAY 1.

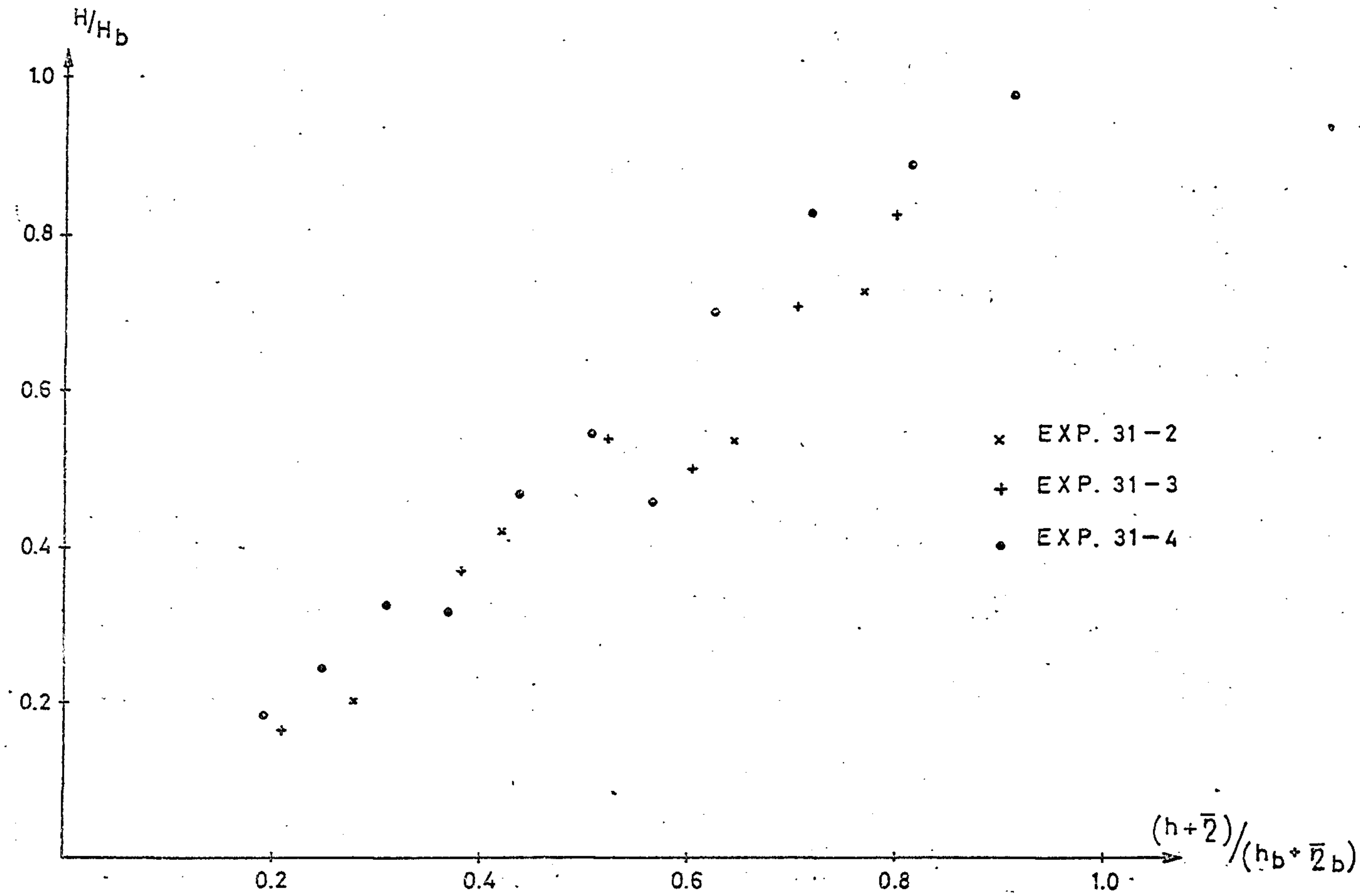


FIG. 8 : NONDIMENSIONAL WAVE HEIGHT AS FUNCTION OF NONDIMENSIONAL MEAN WATER DEPTH .

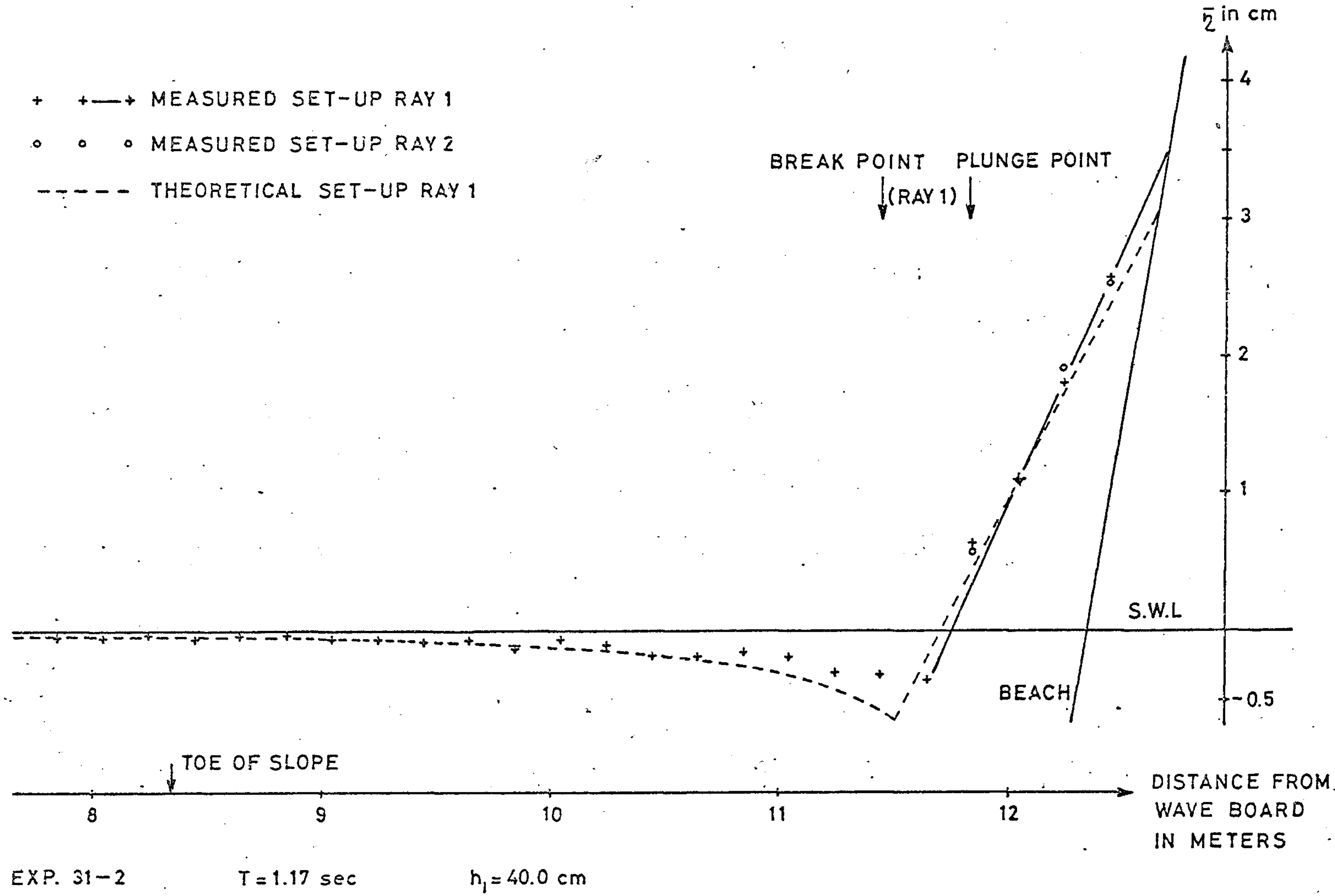


FIG. 9 : MEASURED WAVE SET-UP IN RAYS 1 AND 2 AND THEORETICAL SET-UP IN RAY 1

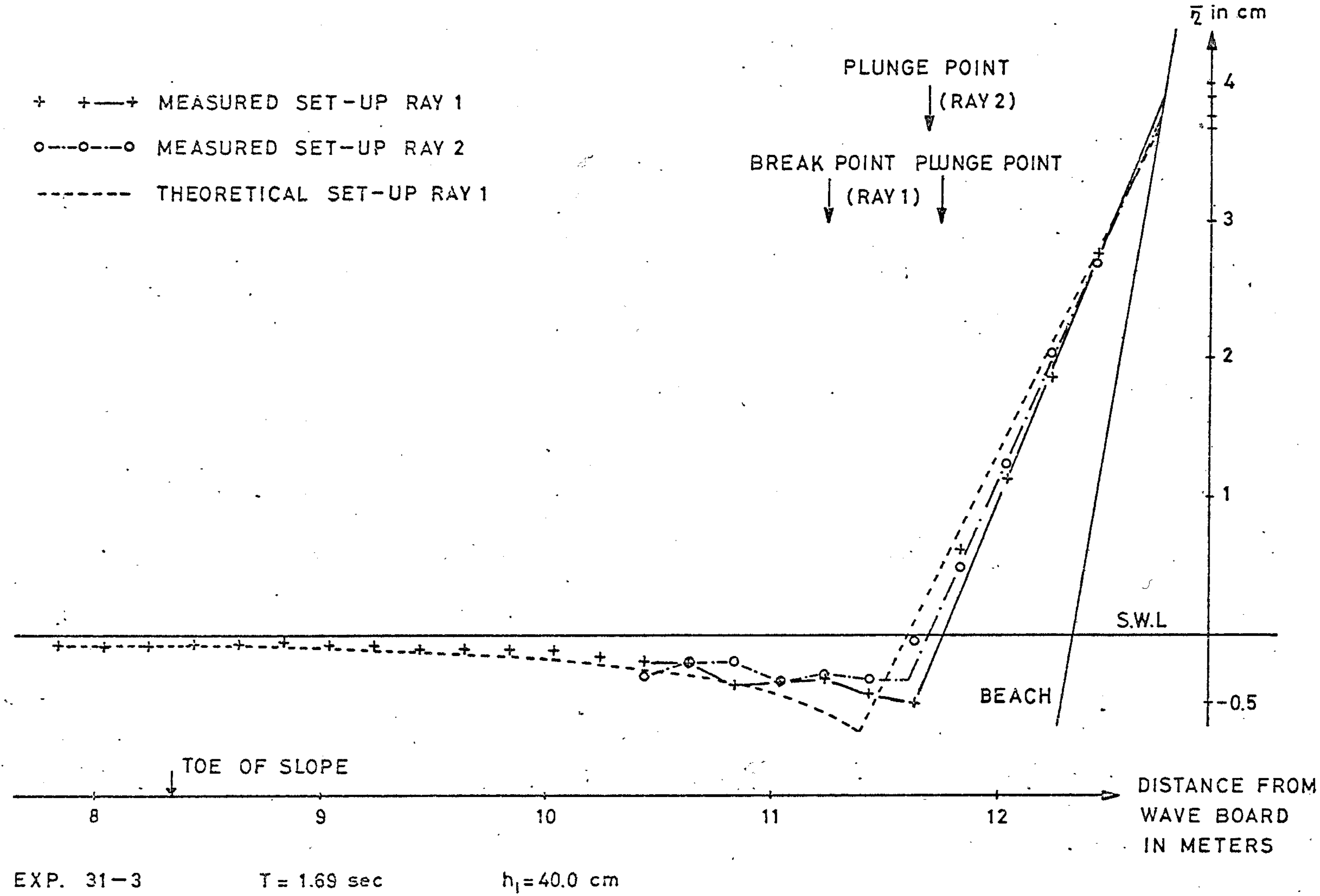
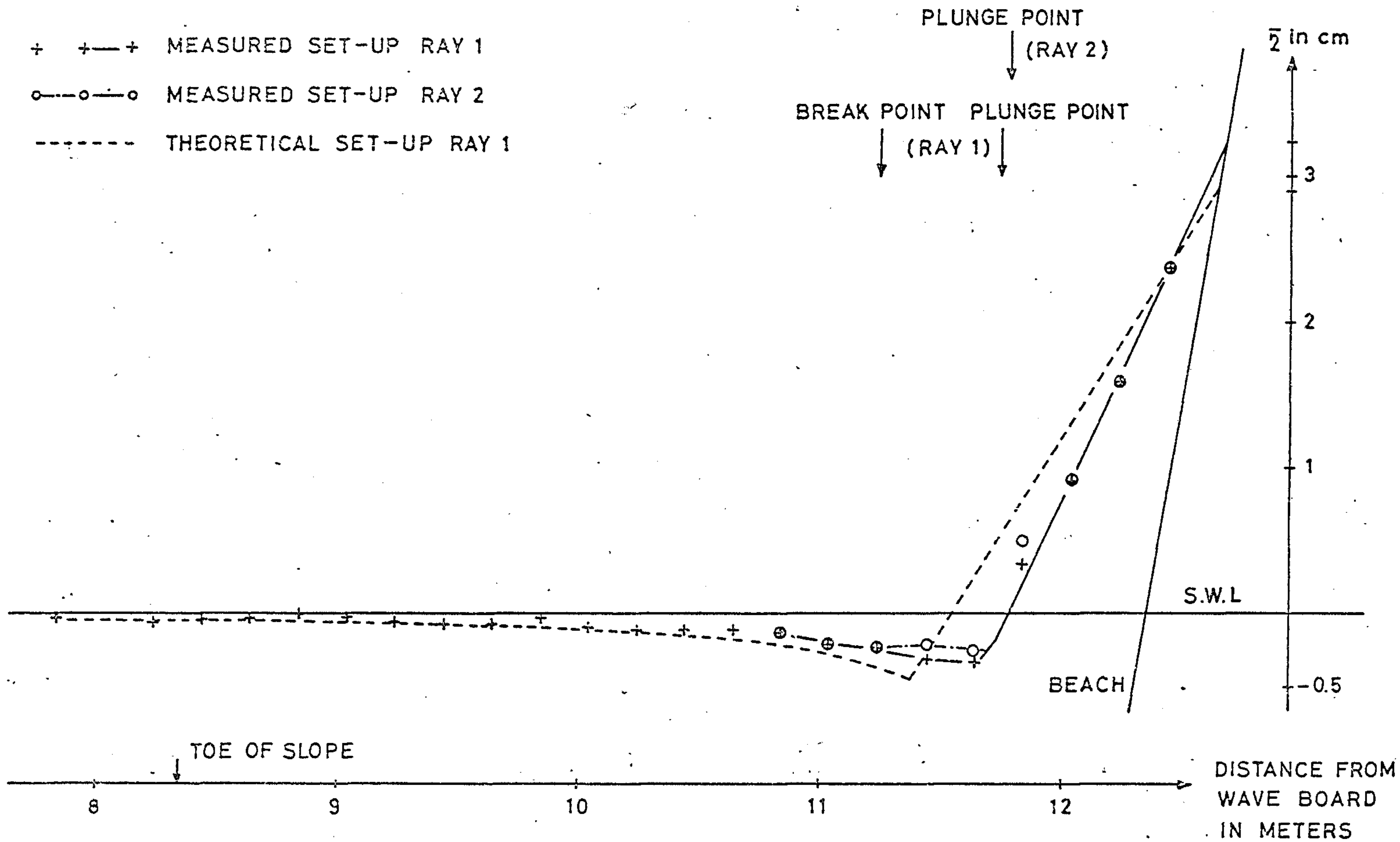
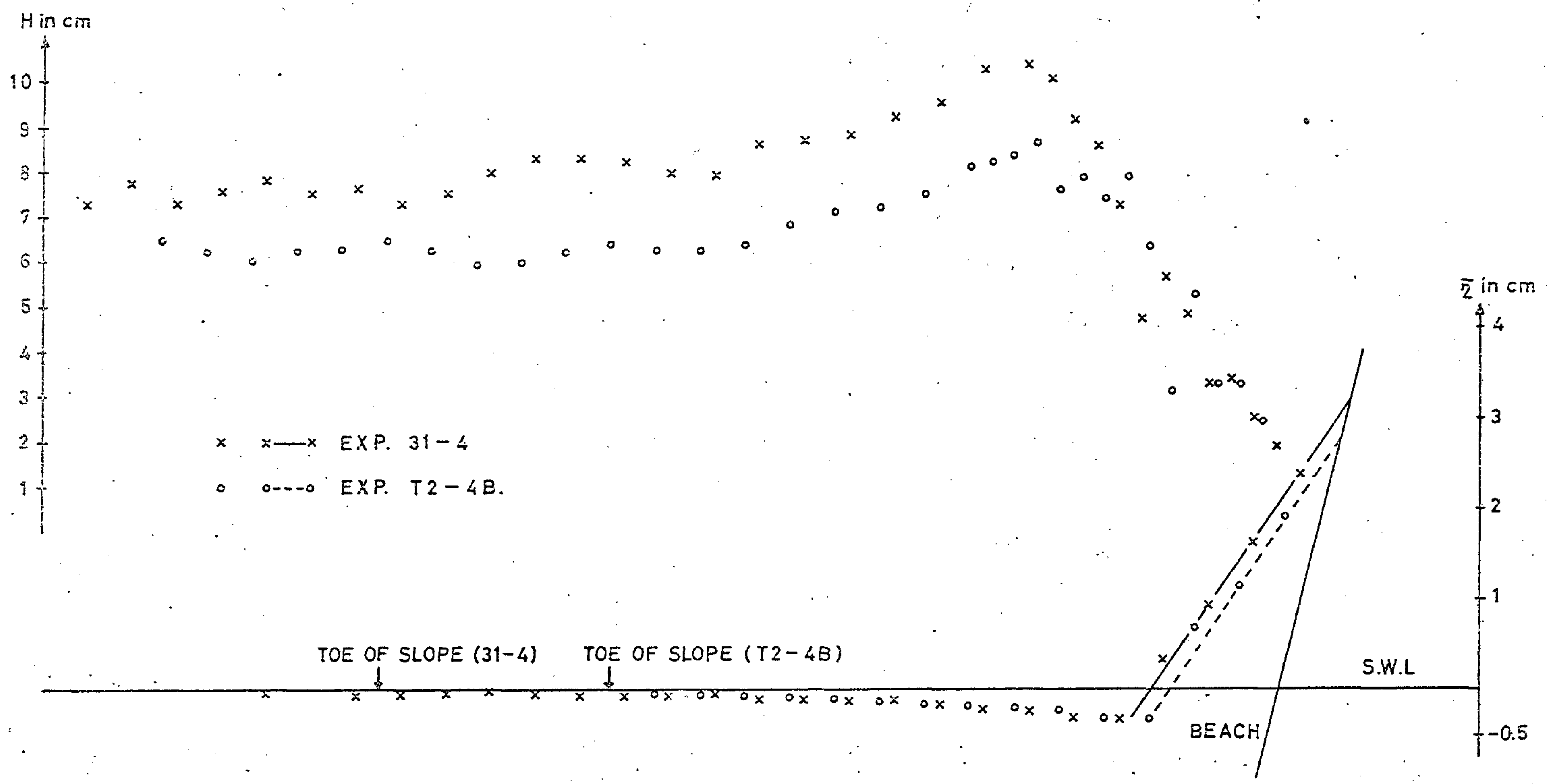


FIG. 10 : MEASURED WAVE SET-UP IN RAYS 1 AND 2 AND THEORETICAL SET-UP IN RAY 1



EXP. 31-4 $T = 1.30$ sec $h_1 = 40.1$ cm

FIG. 11 : MEASURED WAVE SET-UP IN RAYS 1 AND 2 AND THEORETICAL SET-UP IN RAY 1



EXP. 31 − 4 : T = 1.30 sec , h_1 = 40.1 cm , H_1 = 7.70 cm , TG α = 0.10 , WAVE TANK.

EXP. T2 − 4B : T = 1.28 sec , h_1 = 29.8 cm , H_1 = 6.21 cm , TG α = 0.10 , FLUME.

FIG. 12 : COMPARISON OF 2 SET-UP EXPERIMENTS IN DIFFERENT MODELS BY DIFFERENT INVESTIGATORS.