Beach and Dune Erosion Report
Delft Hydraulics Laboratory[1] M935/M936
by
Michael R Gourlay
Honorary Research Fellow
School of Civil Engineering, The University of Queensland, Australia
13 February 2015

History and scope of report

The work described in this report was carried out by the author during 1967 when he was on study leave from the University of Queensland at Delft Hydraulics Laboratory's *de Voorst Laboratory* in the Northeast Polder in the Netherlands.

The primary aim of this research project, which was funded by the Dutch Public Works organisation, Rijkswaterstaat, and overseen by Eco Bijker, then Deputy Director of Delft Hydraulics Laboratory, was to determine the influence of the height of a coastal sand dune upon the amount of recession of the shoreline during a period of increased ocean water level (storm surge).

Drafts of chapters 1 to 5 of the report were completed by me soon after I left *de Voorst Laboratory* in early January 1968. Ton van der Meulen edited these drafts and produced the text and figure volumes at the laboratory in May 1968. Subsequently, Riemer Reinalda produced the Conclusions volume (chapters 6 and 7) in June 1969, using a draft prepared by me after my return to Brisbane and additional analyses by Rijkswaterstaat engineer W. T. Bakker. For various reasons, including a lack of resources to prepare the figures in a form suitable for publication, the draft report was never formally published by Delft Hydraulics Laboratory.[2]

In July 1968 project supervisor Eco Bijker wrote to me after his coastal engineering colleagues in the Netherlands (Werkgroep 5) had reviewed my draft of chapters 1 to 5 of the report as follows: *"I like to tell you that everybody of our working group on coastal erosion appreciates your report very much. I myself am also very much impressed by the skillful way you have elaborated the tests and the way you have indicated in the report already the directions in which conclusions could be formed."*

In August 1968, following a question from one of the members of *"Werkgroep 5"* about the difference in recession between a dry and wet dune, I made a short investigation at the University of Queensland on the influence of moisture upon the strength of the model sand dunes considering both the influence of capillary moisture and rain and spray. A short unofficial report was sent to Ton van der Meulen at *de Voorst Laboratory* in September 1968.

---

[1] Delft Hydraulics Laboratory was the name under which the Dutch hydraulics laboratory operated internationally. In the Netherlands it was known as Waterloopkundig Laboratorium which simply means Hydraulic Laboratory.

[2] Readers should be aware that there are many minor uncorrected typographical errors in the text, mostly the result of Dutch typists misreading my handwritten draft. Occasionally, a word has been misinterpreted and replaced by completely different word. In other places one or more words have been omitted. These cases are generally obvious to the reader, even if the correction may not be so.
It is emphasied that the text is a draft and that readers should independently verify material before using it in professional practice.

Previous publications based on this research

Two papers concerning this research were presented to the 11th (International) Conference on Coastal Engineering in London in September 1968. Proceedings of this conference were published by ASCE in 1969.

1. Van der Meulen, T. and Gourlay, M. R, 1969. "Beach and Dune Erosion Tests" was written by Van der Meulen, using the results of Gourlay's experiments as presented in this report, and describes the experiments and some of their results. This paper was later republished as Delft Hydraulics Laboratory Publication No. 61 in November 1969.

2. Edelman, T. 1969. "Dune erosion during storm conditions" applies concepts derived from the test results to the practical problem of predicting dune erosion. Edelman was Chief Coastal Engineer in the Rijkswaterstaat at that time.

Subsequently in mid1971 I requested permission from then Head of *de Voorst Laboratory*, Jo Vinje, to publish other material from this report. After consultation with the relevant engineer in the Rijkswaterstaat this permission was given but various other commitments prevented my preparing any new publications.[3] Making the report available now (2015) on espace allows present researchers and practitioners the opportunity to study and make use of these experimental results.

Significant original work

1. The surf zone mobility parameter H/Tw and its significance are explained for the first time. H is wave height, usually deepwater wave height H_o, but sometimes breaker height H_b ; T is wave period; and w is the fall velocity of the beach sediment particles. (Section 3.3, pp. 15-21; section 7.3(e), p. 9; section 7.5(b), p. 10)

2. Comparison of equilibrium beach profiles formed by wind-generated waves and those formed by equivalent regular waves. This project was one of the earliest to use random waves in beach profile experiments. (Section 4.2, pp. 26-34; section 5.4, pp. 72-80 and figures 59 to 77; sections 5.6.2 and 5.6.3, pp. 90-104))

3. Calculation of changes in net onshore/offshore sand transport rates, both with time at a given location in the surf zone and along a beach profile at a given time, as the dune and beach erode and the nearshore profile approaches equilibrium. (Section 5.14, pp. 55-58 and figures 41 to 46; other examples in subsequent sections of report)

4. Clarification of the influence of dune height and shape upon the erosion of a shoreline and nearshore profile development and the application of these results to the design of artificial sand dunes. (Section 5.1, pp. 41-59 and figures 12 to 26; Chapter 6, pp. 1 to 5 and figures 113 to 115; section 7.1, pp. 6-7; section 7.4, pp. 9-10)

Other relevant publications by author

Subsequent experimental research at the University of Queensland involving the development of equilibrium beach profiles formed under various wave conditions for several different beach sediments ranging in median size from 0.22 mm to 2.48 mm and

---

[3] A few measurements from the report are used in Figure 7 of Gourlay 1980.

specific gravity of 2.65 and 1.34 has shown the significant influence of the sediment mobility parameter H_o/Tw in relation to relatively impermeable beaches formed in fine sediments. Accreting beaches formed in coarser sediments are more influenced by the permeability of the beach material and its fluidising velocity. This research has been published in the following two reports/papers. The first one (Gourlay 1980) also gives a review of the use of H_o/Tw by various researchers up until that date.

Gourlay, M. R., 1980. Beaches: profiles, processes and permeability. Univ. Qld., Dept Civ. Eng. Research Report CE14, 36 pp. (An expanded version of a paper with the same title published in Proc. 17th Coastal Eng. Conf., Sydney, 1980. Am. Soc. Civ. Engrs, New York, Vol. 2, pp. 1320-1339, 1981.)

Gourlay, M. R., 1985. Beaches: states, sediments and set-up. Preprints 7th Australasian Conf. on Coastal and Ocean Eng., Christchurch, New Zealand, 1985, Vol. 1, pp. 347-356.

WATERLOOPKUNDIG LABORATORIUM

RAPPORT No: M 935/M 936

BEACH AND DUNE EROSION TESTS I

TEXT

AUTEUR: M.R. Gourlay

DATUM: May 1968

CODE No:

LIST OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

C	wave celerity
C_ω	celerity of wave with frequency ω.
C_g	group velocity
D	water depth
D_b	breaker depth
D'	$\dfrac{2\pi D}{L}$
ΔD	scour depth
E	wave energy per unit crest length
E'	wave energy per unit area
H	wave height (either in general or a measured average value at a point for regular waves)
H_I	incident wave height for regular waves.
H_M	measured wave height (in same sense as for H)
H_o	deepwater wave height
H_T	theoretical wave height (i.e. shallow water height calculated from H_o).
H_{max}	maximum wave height (usually from record of 500 wind waves)
H_{rms}	root mean square wave height (based on water surface elevation relative to mean level <u>not</u> individual waves)
$H_{1/3}$	significant wave height (average of the highest 1/3 of the waves in a particular recording)
H_{15}, H_{50} etc.	wave height which is exceeded by 15,50, etc % of the waves (applies to wave height distribution at given place and time)
K	a constant
L	wave length
L_o	deepwater wave length
P	wave power per unit crest length
R	either wave reflection coefficient or wave runup height above still water level
T	wave period
T_{mean}	average period of wind wave recording calculated from number of waves and duration of record

T_o central period of wave spectrum (i.e. period with greatest amount of energy)

$U_{o_{max}}$ Maximum orbital velocity at bottom

V total volume of sand eroded from beach and dune per metre length of shoreline

V' volume of sand eroded from above storm surge water line per metre length of shoreline

X_b breaker distance (measured from initial break point to runup limit)

a a constant in dune height – water line recession relationship

b a constant in dune height – dune foot recession relationship

b' a constant in dune height – dune foot recession relationship

d_{50} median sand diameter

d_m mean sand diameter (sometimes used for d_{50})

f_w wave friction factor

g gravitational constant

h either dune height relative to storm surge level, or change in mean water level in wave action relative to deep water level

h_1 change in mean water level in wave action due to energy losses

m a constant in dune height–erosion volume relationship

n either an exponent or the ratio of group velocity to wave celerity (c_g/c)

t time

u_{max} maximum horizontal orbital velocity at a given depth

v_* shear velocity $= \sqrt{\dfrac{\tau_o}{\rho}}$

w fall velocity of sand or other sediment

x - horizontal distance usually with respect to still water line, in particular recession of still water line with respect to initial still water line.

x' recession of dune foot relative to initial still water line

x'' recession of dune foot relative to initial still water line −0.5 metres

$\bar{x}'$ position of centroid of volume eroded above storm surge level relative to initial still water line

y vertical distance usually with respect to water level

y_E wave energy level (equal to deep water level)

z distance below water level (+ upwards)

α	beach slope angle
ρ	density
ρ'	submerged density
τ_0	shear stress at bottom
ω	frequency
ω_0	frequency with which greatest amount of energy is associated, i.e. peak of spectrum
$\Delta\omega$	frequency increment

1. Introduction

1.1. The Problems

In all parts of the world where sandy coastlines of comparatively recent
origin in geologic terms occur, there is a potential danger of coastal
recession under the influence of prevailing meteorological and oceano-
graphical conditions.
In certain parts of the world such as Florida, U.S.A. and southern Queens-
land, Australia, where large scale investment in real estate and recreational
facilities has been incurred in many cases with comparatively little
consideration of the consequences for the natural environment, such
coastal recession is of great economic importance since the destruction of
the coastal beaches removes the primary natural assent of these places.
On the other hand in the Netherlands where a considerable amount of the
country lies below sea level, the recession of the coastline and the
consequent destruction of sand dunes and artificial defences inevitably
results in a national calamity as history records on many occasions.
The erosion of sand dunes during periods of high sea level accompanied
by strong wave action such as frequently occur on the North Sea under
storm conditions is thus of extreme importance in the Netherlands and full
knowledge of this process is required by those who have the responsibility
of maintaining the nation's sea defences.

Accordingly the Waterloopkundig Laboratorium was requested by Werkgroep
5-Duinen als waterkering- of the Technische Advies Commissie voor de
Waterkeringen, to investigate a number of matters related to both the
maintenance of existing sand dunes and the design of artificial sand
dunes as sea defence works. These investigations, which were commenced in
November 1966 and continued until November 1967, were concerned with the
following problems:

a) the influence of the height of sand dunes upon the amount of coastal
   recession during storm surge conditions;

b) the development of equilibrium beach profiles within the surf zone and
   immediately offshore of it and their relationship to the amount of
   coastal recession;

c) the differences in coastal recession and equilibrium profiles obtained
with regular waves and those obtained with wind waves (or other irregular
waves);

d) the influence of a current flowing parallel to the shore upon both the
amount of coastal recession and the form of the equilibrium profiles.

The results concerning items (a) to (c) above are presented in this
report while those relating to item (d) will be the subject of a separate
report.

1.2. Acknowledgements

The experiments described in the report were carried out in the Laboratory
"de Voorst" of the Delft Hydraulics Laboratory.
The experiments, which were under the general direction of Dr. ir.
E.W. Bijker, deputy director of Delft Hydraulics Laboratory, were commenced
by irs. J.P. Montas and T. v.d. Meulen, engineers of the laboratory.
The main part of the work together with the original draft of this report
were carried out by Mr. M.R. Gourlay, Senior Lecturer in Civil Engineering
at the University of Queensland, Brisbane, Australia, while on study leave
at the Delft Hydraulics Laboratory. Final preparation of this report for
publication was in the hands of ir. T. v.d. Meulen who together with
ir. G. v. Staal and G. v. Heerde gave invaluable assistance during the
investigation.

2. Review of Present Knowledge

2.1. Dune Erosion and Design of Artificial Sand Dunes

Erosion of sand dunes along the Dutch coast has occurred over a considerable period of history and much general information concerning this phenomenon is available in the records of the various organisations responsible for coast protection, etc. However relatively little systematic data were collected until after the period of the second world war and the 1953 storm surge. Since then strenuous efforts have been made to obtain quantitative information concerning changes in the beaches and coastal dunes along the Dutch coast. Profiles at numerous fixed points along the coast are surveyed regularly so that data will be available concerning the recession of the dunes under the influence of all future storm surges. Thus a comprehensive picture is being slowly built up of changes in the dunes and dry beach area. This picture is being further extended by hydrographic surveys out through the surf zone into the offshore region. The acquisition of basic data concerning coastal processes is essential for an informed and reliable approach to the design of sea defence works. In the absence of such data or if such data as are available are insufficient, it is clearly necessary that approximate methods of design be developed to meet the immediate pressing problems of protecting the country against inundation from the sea. Several such methods are described in reference 13 and are summarised below.

a) Vlissingen 1958 Method

Experimental data from the 1953 storm surge shows a relation between recession of the dune foot (assumed at N.A.P. + 4 metres) and the dune height measured above the dune foot. The product of these two quantities gives an indication of the volume eroded and appears to be approximately constant for the 1953 data (100 to 200 m^3/m). For the estimation of dune recession under different conditions, i.e. super storm surge, it is assumed that this depends upon both the duration and level of the super storm surge both of which are greater than in 1953. It is assumed that the dune recession for the super storm surge depends upon the square of the ratio of the duration of this surge and the duration of the 1953 surge for the same dune height.

The method implies that the volume of sand eroded during a given storm surge condition is constant.

b) Hoorn 1958 Method

It is assumed that the dune will erode up to the point where the extension of the slope of the dry beach cuts the storm surge level.

c) Vlissingen-Hoorn 1962 Combined Method

The dune foot position after erosion is now found by extending the beach slope to such a level that the volume of dune erosion is equal to the volume calculated for the super storm surge for the particular dune height considered.

The exterior slope is now made 1 in 4 as this is more favourable for accretion due to wind action than the eroded slope of 1 in 2. The extrapolation factor to allow for the increased duration of the super storm surge compared with that of 1953 is now taken as the three halves power of the duration ratio instead of the square as in method (a).

d) Dune Foot and Dune Height Level

A plot of dune height relative to dune foot level against the dune foot height relative to mean sea level (N.A.P.) for the 1953 storm surge indicates that dune foot recession decreases both with a higher dune height and a higher dune foot. The increased dune foot recession due to a higher water level is obtained from this graph by determining the dune foot recession for a dune foot height reduced from the existing dune foot level by the amount the water level rises.

e) Wave Runup and Storm Profile Methods

Reference 13 also suggests how estimates of dune erosion can be made from consideration of either the wave runup or a parabolic storm profile and their effect upon the position of the dune foot.

Consideration of most of the above methods shows that they suffer from the
limitation that apart from the storm surge level the factors considered are
all basically effects rather than causes. The basic cause of the dune
recession, wave action, is hardly considered at all. An attempt has been
made to remedy this recently by Edelman (reference 8). In this case it is
assumed that the beach and profile within the surf zone are constant at 1
in 50 as far as the breakpoint, defined as a depth equal to 1.3 times the
wave height. Dune erosion is calculated on the basis that the volume of
sand eroded from the sand dune is spread uniformly at a slope of 1 in 50
between the beach and the breakpoint. Such a method results in the dune
recession being greater for low dunes than for high ones, while the volume
of sand lost from the dune increases with the dune height (figures 2 and 4
of reference 8).

Since the length of the surfzone over which the eroded sand is deposited
depends upon the wave height, it is also evident that this method implies
that the dune recession increases with the wave height.

Inplicit in the simplifying assumption of a constant profile slope is the
concept that the beach profile is of the same shape under all conditions.
This of course may not be the case in reality.

2.2. Rate of Erosion and Rate of Profile Development

When available information concerning the actual rate of dune erosion and the
associated beach profile development is considered it is immediately evident
that there are very little data available. Measurements during prototype
situations are virtually non existent while most laboratory data were
obtained using relatively small waves with in many cases rather low steep-
ness which makes them more representative of swell conditions than storms.
Scale effects are therefore likely to be very important and the application
of the results to prototype situation must be made with extreme caution.
Further there are relatively few investigations which deal with situations
comparable to the erosion of sand dunes under storm surge action.

Some of the work which refers to the rate of recession of the water line
of an initially plane beach is briefly outlined in the remainder of this
section together with some investigations of similar types of problem such
as the development of stable beach slopes on inland reservoirs.

In 1957 Saville (reference 43) reported some large scale tests at virtually prototype scale in a very large flume, the initial beach slope being 1 in 15. During one test with comparatively flat waves (Ho/Lo = 0.0069) the beach eroded at an initially rapid rate which then decreased until a constant value was reached at equilibrium. During this process first one bar, then a second and a third moved seaward in succession as the beach was eroded. Similar tests with the sand size at scales of 1 to 10 and 1 to 15 gave contrary results in that the beach was built up instead of being eroded. Appreciable scale effect is thus indicated in attempting to scale such processes. Further the results of two indentical large scale tests (H = 1.28 m and T = 11 sec) give more or less similar equilibrium profiles. The suggestion is made that the rate of profile development may be a function of water temperature even though the final profile is relatively unaffected since the amount of fine sand in suspension depends upon the viscosity which is greater in cólder water (see also section 3,31). Small scale tests by Kemp (reference 23) gave the reported result that the rate of recession of the water line during the development of beach profiles was initially high but then decreased in proportion to the logarithm of the time. Tests by Sawaragi and Kawasaki (reference 44) on scour at sea dikes indicated that this phenomenon depended upon the location of the dike relative to the break point. Several types of behaviour occurred which was shown by plotting the data in the dimensionless form with $\frac{\Delta D}{Ho}$ as a function of $\frac{t}{T}$ where ΔD is the scour depth, H the deepwater wave height, t the time and T the wave period. The question of the development of equilibrium profiles on the shores of inland reservoirs appears to have received considerable attention in Russia (references 25 and 39). Under such conditions the size of the waves is relatively small but their steepness can be quite large. The initial profile slope is generally quite steep and profiles develop until sufficient length of surf zone is formed to completely dissipate the wave energy by the time it reaches the base of erosion scarp (analogous to the dune foot). Similar investigations have been made by the U.S. Bureau of Reclamation (reference 48). In this latter case plots of the dimensionless water line and dune foot positions $\frac{X}{L_o}$ and $\frac{X^1}{L_o}$ as a function of the number of waves $\frac{t}{T}$ gave similar curves of logarithmic form for two different waves. Somewhat similar curves were also found for the dimensionless erosion volume $\frac{V}{L_o H_o^2}$ as

a function of $\frac{t}{T}$ [*]. In these latter tests the sand used was comparatively coarse while the initial slope was very steep (1 to 1.5). More extensive investigations of shoreline recession have been made by Iwagaki and Noda (reference 21) in which the wave characteristics, sediment size and initial slope were varied. Results indicated that the parameter $\frac{x}{Lo}$ was logaritmically related to $\frac{t}{T}$ up to a certain value after which it became constant as equilibrium was attained. The relationships were however somewhat irregular. Considering the equilibrium situation it was found that for a given wave steepness recession of the water line occurred when the ratio $\frac{Ho}{d_{50}}$ (d_{50} is median sand size) exceeded a certain value.

For a fairly steep initial slope of 1 in 10 this critical value of $\frac{H_0}{d_{50}}$ is rather variable but tends to decrease as the steepness increases. This variation of the critical value of $\frac{Ho}{d_{50}}$ with $\frac{Ho}{Lo}$ is much smaller when the initial slope is flatter (1 in 30). The criterion for the occurrence of erosion or accretion as measured by the displacement of the water line is also associated with the occurrence of bar or step type profiles and the change in profile form is assumed to be related to a change in the relative importance of bed load and suspended load movement. The former is to be associated primarily with small values of $\frac{Ho}{d_{50}}$ and step profiles, the latter with large values of $\frac{Ho}{d_{50}}$ and bar profiles. These investigations also observed changes in the characteristics of breaking waves during the development of profiles and state that erosion will occur with spilling breakers and accretion with plunging breakers. Further the breaker crest angle apparently tends to become constant before the equilibrium profile is reached.

It has been shown by Shinohara, Tsubaki and Saito (reference 45) that the amount of movement of the shoreline is determined by the relation between the initial wave steepness corresponding to the original profile and that of the waves causing the movement.

[*] Since volume V must be volume per unit length in two-dimensional tests, the parameter $\frac{V}{L_o H_o^2}$ is not dimensionally correct.

2.3. Equilibrium Profiles

While a great many beach profiles have been measured in many different parts
of the world under widely differing conditions, it can be safely said that
in the vast majority of cases virtually no information is known about the
wave conditions causing them. Even when wave information is available there
is no guarantee that the profile measured is in fact in equilibrium under
the observed wave conditions. Thus most information concerning equilibrium
profiles has been obtained from laboratory experiments. Most of the early
work is summarised by King (reference 24). From this it is clear that a
distinction must be made between the portion of the profile above the water
line (the dry beach) and that below it. While it is found that both parts
of the profile are affected by the same factors such as sand size, wave
steepness and the absolute size of the waves expressed in terms of wave
length, there is an important difference in that the slope of the two
sections of the profile is affected differently by changes in wave steep-
ness. The underwater profile tends to increase in slope with increasing wave
steepness while the beach slope apparently tends to decrease. In both cases
an increase in sand size causes an increase in profile slope which is also
caused by a reduction in wave length. Some care has to be taken in applying
such trends to prototype sand beaches, both with and without wide surf zones,
as the results of Saville's large scale tests show (reference 43).
Many authors (references 21, 22, 27, 45 and 48) have expressed beach profiles
in dimensionless form by dividing both horizontal and vertical ordinates
generally referred to the position and level of the still water line, by
the deep water wave length. One such formulae is that of Larras (reference
27) which while based upon laboratory tests has also been found to represent
certain prototype profiles. Since reference is made of the formula in a
later section it is quoted in full below:

$$\frac{y}{L_o} = K \left(\frac{x}{L_o}\right)^m$$

in which   x is the distance referred to the still water line,

                y is the depth below still water level,

                L_o is the deep water wave length,

$$K = \frac{H_o}{L_o} + 0.039 \frac{\sqrt[2]{d_m}}{\sqrt[3]{\rho'}} \quad ,$$

$$m = 11.5 \frac{H_o}{L_o} + 0.275 \frac{1}{\sqrt[3]{\rho'}} - 0.05 \quad ,$$

Where H_o is the deep water wave height,

$\quad$ d_m is the mean sand diameter,

$\quad$ ρ' is the submerged density of the sediment.

This formula indicates that the underwater profile follows the trends indicated in the preceding paragraph.

Basically it appears that the underwater profile may be divided into two sections, the offshore zone and the surf zone.

In the offshore zone the form of the profile appears to be largely determined by a dynamic equilibrium between the landward transporting current of the waves at the bed and the influence of gravity tending to move particles seaward (references 7, 8 and 52). The more bed load motion predominates the more this process applies. Thus profiles based upon this concept or variants of it are generally found to agree with prototype coarse material profiles or small scale model profiles. Onoszko has shown that for the equilibrium profile there is a constant relation between the maximum orbital velocity and the fall velocity (reference 38). However conditions are different in the surf zone in that very often there is a tendency to form one or more bars which disturb the smooth parabolic profile given above. Various authorities (references 14 and 24) have distinguished between the step profile formed by flat waves and the bar profile formed by steep waves. The former is generally characteristic of relatively calm conditions and/or coarse material while the latter usually but not always develops after periods of heavy wave motion and is more characteristic of sand beaches. As already noted in section 2.2. Iwagaki and Noda (reference 21) have shown that the occurrence of a step or a bar profile depends upon the wave steepness $\frac{H_o}{L_o}$ and the parameter $\frac{H_o}{d_{50}}$ indicating the relative size of the bottom material.

Large values of $\dfrac{H_o}{d_{50}}$ indicate that sediment suspension dominates within the surf zone and that a bar profile will occur. Apart from this it appears that relatively little is known of the exact nature of the hydraulic processes occurring within the surfzone, nor is there as far as we are aware, any means of definitely predicting the shape of the profile and location of the bars within the surf zone, apart from the widely recognised fact, that a bar usually coincides with a break point generally of the plunging type. Priest (reference 40) has found that changes in the wave height at constant period generally result in profile changes in the horizontal direction, i.e. wider surf zone, while changes in the wave period at constant wave height generally result in profile changes in the vertical direction, i.e. higher bars and deeper troughs.

3. Model Investigation

3.1. Outside Model (M 936)

3.1.1. General Layout

The model was basically a very simple one as figure 1 indicates.
It was essentially a 20 metre square basin located in one of the model
sites of the laboratory. Four wave machines were placed along one side of
this basin and generated waves which approached the beach and sand dune
at the opposite side of the model in a normal direction. A wave filter was
placed in front of the wave machines to reduce the effect of unnatural re-
flection from the wave machines, while diffraction at the edges of the
model was prevented by side walls of hardboard on timber frame construction.
Originally the basin was a full 20 metres wide but was subsequently (see
section 4.1.3) divided into two parts, one 4.3 metres wide, indicated as
small basin or flume on figure 1 and the other 15.9 metres wide, indicated
as large basin on the same figure.
The bed of the model consisted of dune sand (d_m = 0.22 mm) which was
formed to the required initial profile before each test. In the last test
in the small basin (test T 25) this sand was replaced by finer sand
(d_m = 0.15 mm).
A movable measuring bridge 16 metres long spanned the model, its axis as
shown in figure 1 being at right angles to the beach and wave machines
to facilitate measurement of beach profiles.

3.1.2. Measurements

The basic measurements made were beach profiles from the crest of the
uneroded sand dune seaward through the surf zone to a point just in front
of the wave filter. These were made by ordinary level and staff at 10 cms
intervals up to the 5 metres distance mark* and 20 cms thereafter along
each profile. The exact location and number of profiles measured during
each test varied to some extent.

* The datum for distance measurements along the beach profiles was
arbitrary from a hydraulic point of view but was in fact the outer edge of
the measuring bridge track on the beach side of the model.

The exact location and number of profiles measured during each test varied
to some extent. Details are given in section 4. In all tests in the out-
side model over 800 different profiles each of about 100 separate levels
were measured, while a further 400 profiles were obtained in the wind flume
tests.

The location of the profiles was indicated by a number of plastic lines
with coloured distance marks. They were suspended over the model parallel
to the measuring bridge and, besides indicating the location of profile
measurement points, were also used to make direct observations of the
positions of the dune foot, water line, break point, etc. Additional obser-
vations were made between profiles using a similar line attached to the
measuring bridge.

Wave heights and reflection coefficients were measured using the laboratory's
own design of temperature compensated parallel resistance wave height
meter, recording the output on a Sanborn penrecorder.

The standard procedure was to measure at 13 points spaced over a distance
of one wave length in the direction of wave propagation and located on the
deeper part of the beach profile near the wave machines (i.e. in most
cases at a depth of roughly 50 cms). From the envelope of these wave re-
cords, the two maxima and the two minima were obtained and each averaged.
The incident wave height was then calculated by taking half the sum of the
average maximum and the average minimum wave height while the reflected
wave was calculated from half their difference. The reflection coefficient
was then simply the ratio of reflected wave over incident wave expressed
as a percentage.

On certain occasions horizontal orbital velocities were measured at various
points within the model using a miniature currents meter (micrometer)
with sufficiently high frequency response. The output was recorded, generally
with a corresponding wave height measurement, on a Sanborn recorder and/or
magnetic tape to facilitate detailed analysis.

In certain tests the variation of sediment properties was measured at the end
of a test. Size distribution of the surface sand layer was obtained by
normal sieve analysis while the in situ or bulk density was measured using
a small open ended brass cube 5 x 5 cm in area and 3 cm high which was
gently pushed into the wet sand until completely full.

It was then carefully removed, the upper and lower surfaces cut smooth, and the contents dried and weighed. Finally control of the water level was obtained by careful adjustment of the inflow and outflow weirs so that a very small flow into the model balanced leakage from it. The water level itself was measured by a pointer gauge in a well outside the model basin and connected to it by a narrow tube and a piezometer outlet behind the wave machines.

3.2. Wind Flume Model (M 935)

3.2.1. General Layout

In this case a sand beach was placed at the downwind end of the 4 metre wide, 100 metre long wind flume where a temporary brick wall was constructed to retain the back of the sand dune. The sand was formed to the same initial profile as in the outside model (see section 4.1.) and there was 15 cms of sand above the flume bottom at the lowest and most seaward portion of this profile (16 metres on outside model distance datum). Seaward of this point the sand sloped at 1 in 20 to the floor of the wind flume.

Temporary timber walkways were constructed along the side of the flume so that access was possible for levelling the five profiles which were located at 0.75 metre spacing symmetrically about the centre line. Waves were generated both using the mechanical wave paddle (regular waves) and the wind fan (wind waves) or the two in combination. To prevent possible damage to the fan by sand blown from the dune above water level, provision was made to spray the surface of the latter with fine jets of water to prevent it being blown away. This was not however always necessary. For instance in test T 8 with high wind velocity, the wind itself generated sufficient spray to maintain the sand dune in a saturated condition.

3.2.2. Measurements

Measurements were basically the same in the wind flume as in the outside model. However profile measurements were more difficult and slower in the wind flume due the restricted headroom and artificial lighting.

Thus their accuracy is not as good which fact can also be attributed to a somewhat lower efficiency of working during the night shifts which were necessary in the wind flume work. Observational difficulties also precluded in most cases the making of detailed visual observations as was done in the outside model.

The principal difference in the wind flume measurements concerned those relating to the wave characteristics. For regular waves the same procedure was used as in the outside model (section 3.1.2.) but obviously this was not applicable for irregular waves. For the latter waves were measured at a fixed point over a period of at least 500 waves every half hour during the test. Records were made upon both Sanborn recorder and magnetic tape. From the former were obtained information concerning the wave height distribution such as the maximum wave height in the 500 wave sample*, the heights exceeded by 15 % and 50 % of the waves together with the ratio of these two heights and the average wave period. The latter were used to produce a punched paper tape from which the energy density spectrum was calculated using the digital computer at the University of Groningen. Use was also made of a wave height analyser to obtain rapid information concerning the wave height distribution. The results were not as consistent as those obtained from the Sanborn recorder nor was it possible to use this instrument during very high wind velocity both because of spray and vibration. No results based upon the wave height analyser are included in this report. An analogue root mean square analyser was also used in the wind wave tests to obtain a rapid evaluation of the root mean square wave height which values generally compared favourably with those calculated from wave spectra. Finally, water level was measured as in the outside model using a piezometer connection. In tests with wind the quantity of water within the flume was adjusted by trial and error before the test so that the water level within the surf zone of the model was equal to the required model level.

* The determination of the number of waves was partly subjective in that very small waves were ignored and only waves of approximately the general average period were counted. The average period was obtained by dividing the appropriate length of record by the number of waves, usually 500, occurring during this time.

3.3. Model scales

3.3.1. General Considerations

The question of the correct selection of scales for coastal models involving sand movement under wave action is a difficult one for which no definite answer has yet been obtained. Some progress has been made in this subject when the beach material is sufficiently large for the effects of viscosity to be neglected, i.e. shingle beaches with predominate bed load movement (reference 51). Similarly the question of model scales under the combined action of waves and currents has been under study at this laboratory (reference 2) but the results to date are strictly only applicable to the offshore zone seaward of the break point where sand movement is predominately in the form of bed load. The question of model scales within the surf zone, or indeed for that matter as noted earlier (section 2.3) the form of equilibrium profiles and the general hydraulic conditions within this zone, are all at the time of writing an open question.

From the various works mentioned in sections 2.2 and 2.3 it is possible to discern some general trends in the form of equilibrium beach profiles under wave action. For instance if the empirical equation of Larras (reference 27) is considered the general trend of a beach profile depends upon the size of the sand d, the wave steepness $\frac{H_o}{L_o}$ and the absolute size of the waves expressed in terms of deep water wave length L_o. Furthermore this equation indicates that for a constant value of L_o the slope of the profile increases as the wave steepness increases. The slope of the dry beach is also found to depend upon the same variables (chapter 10 of reference 24) with the important difference that there is a tendency for the beach slope to decrease with increasing wave steepness. The effect of a change in wave length L_o or wave period T is however the same in both cases. For a constant value of steepness $\frac{H_o}{L_o}$, the slope increases as the wave length or absolute size of the waves decreases. Model beaches must therefore be regarded as distorted scale models of their prototype in much the same way as small self formed channels in alluvium can be considered as small scale distorted models of large alluvial rivers.

The greater the reduction in absolute size of the waves, i.e. the smaller the model scale, the greater the amount of distortion required to produce a model which ressembles the prototype in the form of its equilibrium profile.

In practice some more conditions can be applied which assist in arriving at suitable model scales. For instance as indicated by the results given in sections 5.62.1 and 5.62.2 together with those of other investigators, the breaking of waves is determined to a great extent by either of the two parameters $\frac{H}{L}$ and $\frac{H}{D}$ and the relative depth $\frac{D}{L}$ or $\frac{L}{D}$.

This being so, there is good reason for maintaining, at least to the first approximation, the same values of these parameters in model and prototype if this is at all possible, since the hydraulic conditions within the surf zone are largely the result of the breaking process. In a distorted scale model this results in the waves being undistorted in shape, i.e. same steepness as in prototype, and in absolute size being scaled in accordance with the vertical scale so as to give the same values of $\frac{H}{D}$ in model as in prototype.

For this to be achieved the scale for wave period must be taken by analogy with the usual Froude law similarity for distorted river models as the square root of the vertical scale of the model.

The above considerations are of course approximate since the breaking process is also affected by the bottom slope which changes once the model is distorted. In general it can be said (reference 20) that for a given $\frac{H_o}{L_o}$ a wave will break in deeper water on a steep beach than on a flat one.

This suggests that some departure from the scales suggested in the proceeding paragraph will be necessary in practice. However insufficient information is available to check this point and other factors are also relevant. For instance there appears to be a scale effect in the actual breaking process when the absolute size of the waves is reduced below a certain value (references 5 and 28). Thus when the wave period is less than about 2.0 secs it appears that for a given slope waves of the same steepness break earlier, i.e. in relatively greater depths, than waves of larger period. Thus consideration of scale effects due both to the distortion and the size of the waves indicates that for waves of the same steepness reproduced to the vertical scale of the model it is likely that the surf zone is

somewhat wider than it should be [*].

So far no reference has been made to the influence of sand size upon the selection of model scales. That this is important has already been noted (section 2.3) since other investigators have observed that many model sand beaches exhibit the characteristics of shingle beaches in prototype. This was particularly the case for the transition conditions between step and bar type profiles which are basically dependent upon the relative predominance of bed load and gravitational effects in the first instance and suspended load and general water circulation in the second. It is therefore quite possible for a model sand beach with similar sand to the prototype to produce an equilibrium profile of quite different form from that of its prototype.

As indicated in section 2.3 Iwagaki and Noda (reference 21) have presented data which indicate that the form of the beach profile depends upon the ratio $\frac{H_0}{d_{50}}$, i.e. the deepwater wave height and the median sand size, and the deep water wave steepness $\frac{H_0}{L_0}$. Considering the first parameter further it can be shown that it can be replaced by $\frac{H_0}{w}$ where w is the fall velocity of the sand particles. In this form it represents the time taken for a sand particle to fall a distance equal to the wave height. If this time is large compared with the wave period, any material stirred up by the breaking waves is likely to remain is suspension and to move as suspended load. If it is of the same order of magnitude or less than the wave period, bed load motion will predominate. Hence it may be deduced that for models requiring similarity of surf zone processes on sandy shores under storm conditions (i.e. suspended load conditions) the following condition must apply:

$$\frac{H}{Tw} \gg 1$$

In a given situation where $\frac{H}{Tw}$ is too small which can be the case when comparatively flat waves are reproduced in a small scale model the situation can be rectified by reducing the magnitude of the fall velocity w.

[*] This is when the surf zone is measured in terms of a horizontal distance to the horizontal scale. It is obviously not the case in terms of wave lengths or number of waves, which have been based upon the vertical scale.

This in practice means using a ligher and/or smaller sediment in the model which may not always be practical.

Alternatively the period of the waves can be reduced to increase their steepness. In this case the data of Iwagaki and Noda (reference 21) indicate that a bar profile and hence presumably suspended load transport will always occur when $\frac{H_o}{L_o} > 0.04$. Of course such a distortion in wave characteristics, while it tends to compensate for the scale effects due to incorrect sand movement, introduces other problems particularly with respect to three dimensional models in which wave refraction is important. The above criterion for suspension conditions within the surf zone can be related to the usual parameter influencing suspended sediment distribution in a unidirectional flow, $\frac{v_*}{w}$, where v_* is the shear velocity which is defined as $\sqrt{\frac{\tau_o}{\rho}}$ where τ_o is the shear stress on the channel bottom and ρ the fluid density. This is seen from the following relationship:

$$v_* = \sqrt{\frac{\tau_o}{\rho}} = U_{o_{max}} \cdot \sqrt{\frac{f_w}{2}}$$

where f_w is the friction factor due to wave action

and $U_{o_{max}}$ is the maximum orbital velocity at the bottom given by the following equation:

$$U_{o_{max}} = \frac{\pi H}{T \sinh \frac{2 \pi D}{L}}$$

Whence
$$\frac{v_*}{w} = \frac{\pi H \sqrt{\frac{f_w}{2}}}{wT \sinh \frac{2 \pi D}{L}} \propto \frac{H}{Tw}$$

if $\frac{D}{L}$ and f_w do not change significantly.

Applying this criterion to several of the model tests made during this investigation it can be seen from table 3.31-1 below, that in all cases the ratio $\frac{H_o}{Tw}$ was greater than 1 while inspection of the various equilibrium profiles presented later on in this report, together with others not included due to lack of space, reveals that in all cases bar type profiles were formed.

The location of the bar was however different and it is evident from the test profiles (figures 56, 64, 66 and 68) that in tests with relatively large values of $\frac{H_o}{Tw}$ the bar is located further seaward and/or is higher than those with lower values of this parameter.

TABLE 3.31-1

Values of parameter $\frac{H_o}{Tw}$ for various model tests

Test number	Wave height H_o – cm	Wave period T – sec	Sand size d_{50} – mm	Fall velocity* w – cm/sec	$\frac{H_o}{Tw}$
T14-T17 T26, TO	19.5	1.6	0.22	2.5 *27 mm/s From E2H curved graph 13°C*	4.9
T25	19.5	1.6	0.15	1.4 *13 mm/s*	8.7
T24	18.2	1.3	0.22	2.5	5.6
T22	9.8	1.0	0.22	2.5	3.9
T20	10.7	1.6	0.22	2.5	2.7
Prototype	450	8.0	0.22	2.5	22.5

No consideration has been given to the question of time scale for the development of equilibrium profiles. For the suspended load regime within the surf zone this will obviously depend among other things upon the absolute value of $\frac{H}{Tw}$. When this is comparatively small as in test T 20 (table 3.31-1) the time to reach equilibrium may be quite long (see section 5.2). When it is large as in test T25, equilibrium is attained somewhat more rapidly (see section 5.5). The implication here is that in prototype equilibrium may be attained relatively more quickly in terms of the number of waves $\frac{t}{T}$, although not necessarily in absolute time, than in the model.

* Fall velocities are for water at 60° F (13° C) and are obtained from figure 2 in chapter XII of reference 41.

Outside of the breaker zone it is obvious that the wave action within the
model must be capable of moving the sediment over the portions of the
profile where this motion is significant. An indication of whether or not
sand movement will occur in a model under wave action can be obtained from
the experimental data and monograph of Bonnefille and Pernecker (reference
3) while an estimate of the time scale for bed movement can be obtained
from an empirical equation of Larras (reference 26) which shows that the
bed load transport towards the shore upon a level bottom is a function
of the maximum orbital velocity at the bottom and independent of the
sediment size.

3.32. Scales for present Investigation

In the light of the preceding section it can be said that the beach studies
of this report must be regarded as distorted scale models of prototype sandy
beaches, the wave conditions being reproduced approximately in an undis-
torted form to the vertical scale. Scale effect due to incorrect re-
production of the breaking process will be reduced if the model wave period
is of the order of 2 seconds. Sand movement in suspension in the surf zone
will occur if $\frac{H}{Tw} > 1$. No definite conclusions can be reached concerning
time scale for profile development. An estimate of the linear scales applying
to the test was obtained by comparing the initial starting profile obtained
from preliminary tests at normal water level (N.A.P.) (see section 4.1) with
certain prototype profiles with a similar bar form measured on the Dutch
coast. An example of this comparison is shown on figure 2. From a knowledge
of the comparative scales of the two profiles it is deduced that the model
initial profile schematises the prototype profile when the former is regarded
as a distorted model with a horzizontal scale of 1 in 125 and a vertical
scale of 1 in 25. Assuming a time scale for wave period of 1 in 5 which
is consistent with undistorted waves scaled in accordance with the vertical
scale and knowing that the model waves which caused this profile had a
period of about 1.6 seconds and a height of 14 cms, equivalent prototype
values of 8 seconds and 3.5 metres are obtained. There is no evidence
whatever to say that waves of these dimensions did in fact cause the
prototype profiles shown on figure 2. On the other hand such waves are
typical of average storm conditions along the Dutch coast.

On the basis of these scales the storm surge height used in the tests, 12 cm in the model, represents a 3 metre surge in prototype, which is the same order of magnitude or a little higher than the highest surge which occurred during November-December 1965 which had an exceedance value of 0.09 in any given year. The model storm surge waves of 18 cms height in 50 cms depth represent prototype waves 4.5 metres high in 12.5 metres of water which is the same order of magnitude as the highest significant wave heights observed offshore at a depth of N.A.P. - 15 metres during the 1965 prototype storm surges (reference 53). It is however impossible to say much more than this concerning model scales for this investigation. Therefore no attempt has been made to express the results in terms of prototype values, and all dimensions in the text and figures refer to model values unless it is specifically stated to the contrary. Estimates of possible prototype values can be obtained by multiplying horizontal distance by 125[*], vertical distance by 25, volumes by 3125 and slopes, when expressed as 1 in n, by 5. It should however be clearly understood that such factors are approximate and that they only apply to those tests where the initial profile does in fact represent the condition described above. This means that the tests where the wave period was significantly different to 1.6 secs (tests T6 to T8 and T22 to T24) cannot be scaled in this manner. Any test results using data from these tests, the most important of which are those comparing the action of wind waves and regular waves, must be regarded on a comparative basis only and absolute values may not be scaled up using the scales given above. Of course where such data are presented in dimensionless form, even though the parameter is still expressed in model dimensions due to the omision of the gravitational constant, some generalisation of the result is possible provided due allowance is made for possible scale effects.

Finally the actual process of collapse of the sand dune is a complex matter which will be affected by scale effects due to capillarity influencing the moisture content and hence the dune stability.

In this case extreme caution must be exercised in scaling all results concerned with the actual erosion of the dune. In all probability the dune erosion cannot be reliably scaled in a distorted model since as in other cases of local scouring or erosion it is impossible to distort the natural slopes of a granular material such as sand.

[*] Except wave lengths which should be multiplied by 25.

4. Model Tests

4.1. Outside Model-Large Basin

4.1.1. Preliminary tests for Initial Profile

In view of the fact that it was intended to reproduce dune erosion under
storm surge conditions, it was considered desirable that the initial
starting profile be related to conditions which might exist before a storm
surge. Such conditions are of course variable but it appeared to be
reasonable to start with a profile approximating that which would be formed
under storm waves without a storm surge, i.e. water level at mean sea level
(N.A.P.). Accordingly the first tests were made with a water level of - 12
cms* and an original profile as shown in figure 3. Several wave height and
period combinations were tried and the development of beach profiles
measured. From these preliminary tests it was concluded that a 1.56 second
period wave, 14 cm high, gave an equilibrium profile (figure 3) which
could be taken to represent a typical prototype profile on the assumption
of a scale distortion of 5 as discussed in section 3.3.
In practice, the initial profile was simplified as shown on figure 3 to
facilitate model rebuilding and each test was preceeded by a period of two
hours of the initial wave conditions which reshaped the profile to some
extent into a more natural form**. A typical average profile for this
condition, is shown for comparison on figure 3. In all tests this
condition was measured and formed the initial profile with which profile
changes during storm surge conditions were compared.

---

* Since virtually all subsequent tests were at the same storm surge level
which was 12 cms above normal mean water level, all vertical measurements,
both depth and heights are referred to <u>storm surge level</u>. Horizontal
distances are measured either with respect to the storm surge water line on
the adapted initial profile, i.e. dune foot recession, etc., or to an
arbitrary reference point lying 2.1 m landward of this point. All profiles
are plotted with respect to the latter origin.
** This procedure was followed for all tests where the wave period was 1.56
to 1.63 seconds. It was not followed for the tests where the period was
significantly different from this value, i.e., the wind wave tests (T6 to T8)
and their corresponding regular wave tests (T22 to T24) as the relation
between the initial condition and the storm surge waves was then quite arbitrary.

4.12. Initial tests in wide basin

The first series of tests were made in the three dimensional model
basin with a water level 12 cms above normal level as used in the
preliminary tests. The wave period was maintained constant at 1.56
seconds and the wave machine eccentricity was unaltered.
Since the water depth was now greater the wave height produced by
the wave machines was also larger, now being about 18.0 to 18.5 cm.
A similar effect will occur in prototype when the offshore bottom is
relatively shallow due to the change in water depth affecting the
height of the storm waves. However the relationship between the two
wave heights could well be different in the model from that in
prototype. It was however more convenient to operate the model in
this way. The forms of the sand dunes tested are shown in figure 4.
In brief it can be seen that T11 represented an average height dune
with narrow crest and a shape approximating that of a real sand dune.
T12 represented a condition without any sand dune at all and was
intended to give an indication of the maximum erosion which could be
expected, while T13 represented a relatively high sand dune of
indefinite width. The general tests conditions and a summary of the
measurements made for both this series of tests and all subsequent
ones are given in Table 4.12-1.
For these tests beach profiles were measured on five lines spaced
at 2,5 m and located symmetrically about the centreline of the 20 m
wide basin. Measurements were made before commencing operation at
the storm surge water level and $\frac{1}{2}$, 1, 2, $3\frac{1}{2}$, $5\frac{1}{2}$, 8, 11 and $14\frac{1}{2}$
hours after commencement of the test. After $14\frac{1}{2}$ hours it appeared
that the sand dune erosion had reached a relatively constant value.
These tests yielded a great deal of general information concerning
the process of dune erosion.

TABLE 4.12-1   Summary of test conditions and Quantities measured

Test Number	Model	Dune Height-cm	Dune Slope	Type of Waves	H_incident	H_15	H_rms	Deepwater Wave Height	Wave Period-sec	Sand Size-mm	Water level	Duration of Test-hours	No. of profiles	No. of Times	Wave Height; Reflection	Spectra Inshore	Spectra Offshore	W. height Inshore	W. height Off
TO	Wind Flume	40	1 to 1¾	Regular Waves	17.9	-	-	19.5	1.63	0.22	Constant	2 + 19	5	10		-	-	-	
TO'	"	"	"	"	18.0	-	-	19.5	"	"	"	"	"	"	Every ½ hour	-	-	-	
T1	"	"	"	Irregular Waves	-	16.5	8.8	-	"	"	"	"	"	"	" " "	-	-	-	
T2	"	"	"	"	-	17.7	9.8	-	"	"	"	"	"	"	- - -	-	9	-	1½
T3	"	"	"	Regular Waves	19.5	-	14.0	21.2	"	"	"	2½	-	-	- - -	-	9	-	
T4	"	"	"	"	16.2	-	10.4	17.6	"	"	"	2 + 19	5	10	Every ½ hour	-	4	-	
T5	"	"	"	Wind Waves	-	20	-	-	1.12	"	"	2½	-	-	" " "	-	9	-	
T6	"	"	"	"	-	19.0	9.4	-	1.11	"	"	19	5	10	- - -	-	-	-	16 at 5
T7	"	"	"	"	-	13.4	6.7	-	1.00	"	"	"	"	"	- - -	5	9	Every ½ hour	1½
T8	"	"	"	"	-	21.0	11.2	-	1.29	"	"	"	"	"	- - -	9	9	"	1½
T11	Original Basin Outs.	24	1 to 3	Regular Waves	18	-	-	19.7	1.56	0.22	"	2 + 14½	5	9		8	8	"	
T12	"	15	1 to 10	"	"	-	-	"	"	"	"	"	"	"	Occasionally	-	-	-	
T13	"	33 to 40	1 to 2	"	"	-	-	"	"	"	"	"	"	"	"	-	-	-	
T14	Large basin Outside	40	1 to 1¾	Regular Waves	18	-	-	19.7	1.56	0.22	"	2 + 19	7	10	Occasionally	-	-	-	
T15	"	30	"	"	"	-	-	"	"	"	"	"	7	"	Occasionally	-	-	-	
T16	"	20	"	"	18.0	-	-	"	"	"	"	"	9	"	"	-	-	-	
T17	"	10	"	"	18.3	-	-	20.0	"	"	"	"	10	"	"	-	-	-	
T18	Small basin Outside	40	1 to 1¾	Regular Waves	16.3	-	-	17.8	1.56	0.22	"	2 + 19	5	2	Approx. every 2 hours	-	-	-	
T19	"	"	"	"	14.1	-	-	15.4	"	"	"	"	"	2	Occasionally every ½ hour	-	-	-	
T20	"	"	"	"	9.8	-	-	10.7	"	"	"	2 + 26½	"	3	Every ½ hour	-	-	-	
T21	"	"	"	"	18.4 H.W. / 17.3 L.W.	-	-	20.1 H.W. / 18.9 L.W.	"	"	± 2½	2 + 19½	"	5	" " "	-	-	-	
T22	"	"	"	"	9.3	-	6.6	9.8	1.04	"	Constant	19	"	3	" " "	-	-	-	
T23	"	"	"	"	12.5	-	8.9	13.4	1.16	"	"	19	"	3	" " "	-	-	-	
T24	"	"	"	"	16.7	-	10.9	18.2	1.29	"	"	"	"	10	" " "	-	-	-	
T25	"	"	"	"	18.6	-	-	20.3	1.56	0.15	"	2 + 19	"	10	" " "	-	2	-	
T26	Large basin Outside	80	1 to 1	Regular Waves	19.9	-	-	21.7	1.56	0.22	"	2 + 19	10	10	After test	-	-	-	

sured

Deepwater Wave Height	Wave Period-sec	Sand Size-mm	Water level	Duration of Test-hours	Beach Profiles No. of profiles	Beach Profiles No. of Times	Wave Height; Reflection	Wave Spectra Inshore	Wave Spectra Offshore	W. height dist. Inshore	W. height dist. Offshore	Orbital Velocity	Sand Density	Sand Size Distribution	Visual Observations Dune	Visual Observations Breakers	Water Temp.
19.5	1.63	0.22	Con-stant	2 + 19	5	10	Every ½ hour	-	-	-	-	-	After test	-	-	Every ½ hour	-
19.5	"	"	"	"	"	"	" " "	-	-	-	-	-	"	-	-	"	-
-	"	"	"	"	"	"	- - -	-	9	-	½ Every hour "	-	"	-	-	"	several times
-	"	"	"	"	"	"	- - -	-	9	-	-	-	-	-	-	"	-
21.2	"	"	"	2½	-	-	Every ½ hour	-	4	-	-	-	-	-	-	-	-
17.6	"	"	"	2 + 19	5	10	" " "	-	9	-	-	-	-	-	-	Every ½ hour	several times
-	1.12	"	"	2½	-	-	-	-	-	-	16 Points at 22 cm Every ½ hour	-	-	-	-	Every ½ hour	several times
-	1.11	"	"	19	5	10	- - -	5	9	Every ½ hour	½ Every hour	9 times at inshore point	After test	-	-	Every ½ hour	several times
-	1.00	"	"	"	"	"	- - -	9	9			"	-	-	-	"	"
-	1.29	"	"	"	"	"	- - -	8	8	"	"	"	After test	After test	-	"	"
19.7	1.56	0.22	"	2 + 14½	5	9	Occasionally	-	-	-	-	-	-	-	-	-	-
"	"	"	"	"	"	"	"	-	-	-	-	-	-	-	-	-	-
"	"	"	"	"	"	"	"	-	-	-	-	-	-	-	-	-	-
19.7	1.56	0.22	"	2 + 19	7	10	Occasionally	-	-	-	-	-	-	-	at each levelling	occasion-ally	-
"	"	"	"	"	7	"	"								"	"	
"	"	"	"	"	9	"	"	-	-	-	-	-	-	-	"	"	-
20.0	"	"	"	"	10	"	Approx.every 2 hours	-	-	--	-	-	After test	After test	"	Approx. 2 hours	-
17.8	1.56	0.22	"	2 + 19	5	2	Occasionally every ½ hour	-	-	-	-	Along 3 profiles after t.	After test	After test	Occasion-ally	Occasion-ally	-
15.4	"	"	"	"	"	2	Every ½ hour	-	-	-	-	-	-	-	Every ½ hour	Every ½ hour	Thrice Daily
10.7	"	"	"	2 + 26½	"	3	" " "	-	-	-	-	-	-	-	"	"	"
20.1 H.W. 18.9 L.W.	"	"	± 2½	2 + 19½	"	5	" " "	-	-	-	-	-	-	-	"	"	"
9.8	1.04	"	Con-stant	19	"	3	" " "	-	-	-	-	-	-	-	"	"	"
13.4	1.16	"	"	19	"	3	" " "	-	-	-	-	-	-	-	"	"	"
18.2	1.29	"	"	"	"	10	" " "	-	2	-	-	-	-	-	"	"	"
20.3	1.56	0.15	"	2 + 19	"	10	" " "	-	-	-	-	-	Before After test	Before After test	"	"	"
21.7	1.56	0.22	"	2 + 19	10	10	After test	-	-	-	-	-	Before test	Before test	at each levelling	Every ½ hour	"

They also indicated that changes in measurement techniques would be
necessary if reliable quantitative comparisons were to be made
between different conditions. In particular it was observed that
large variations occurred between different profiles measured at the
same time in the same test due to the fact that conditions within the
surf zone did not remain two-dimensional. Indeed the surf zone was
covered with irrigular shoals and bars while the beach and dune line
exhibited a cusp like appearance with relatively large differences
in position from profile to profile. As the variations in beach
position were quasi-periodic it was evident that care had to be taken
in the spacing of the measuring profiles if a reliable average value
for the dune erosion was to be determined. Since all the conclusions
derived from these tests can also be made from the subsequent tests,
the results of tests T11 to T13 with one or two small exceptions are
not reproduced or discussed further in this report.

4.13. Varying dune height tests in large basin

In the light of the experience gained during the earlier tests a new
series of tests was made. The purpose of these tests was basically
to establish the relation, if any, between sand dune height and dune
erosion when all other factors were maintained constant. To this
end the geometry of the sand dune was controlled so that the shape
of the sand dune was similar in each test, with a constant front
slope of 1 on $1\frac{3}{4}$ and a level crest of indefinite width in each case
(see figure 4)*. The sand dune height was varied in increments of
10 cms from 40 cms above storm surge level (T14) to 10 cms above
storm surge level (T17).

*It was intended that the front slope be I on 2 which would have made
test T 14 almost indentical with test T 13 as far as dune geometry
was concerned. However a mistake was made in setting out of the dune
slope in the model for test T14 and this was not so. In the interest
of comparison of the effects of dune height only, the changed front
slope was adopted for the remainder of the tests.

The choice of front slope of the dune was arbitrary and cannot be related to prototype. For example if we assume a prototype seaward slope of 1:4 as recommended by Studiedienst - Vlissingen (reference 29) the distortion of 5 results in a model slope of 1 on 0.8 which is impossible to maintain in the model. For these tests the model basin was divided into two sections, a large basin 15.6 m wide and a small basin or flume 4.3 m wide. Initially the intention was to compare conditions in the two basins in tests T14 and then to subdivide the main basin into three more flumes so that several tests with the same wave conditions but different sand dunes could be made simultaneously. However it was found that dune erosion was significantly different in the flume to the main basin and this idea was not proceeded with. Consequently all tests with different dune heights were made in the large basin *. In tests T14 to T16, seven profiles were measured at each levelling. These were spaced at 1.5 m and were located symmetrically about the centre line of the large basin (figure 1). In test T16 two more profiles, making nine in all, were measured with the intention of obtaining a more uniform coverage of the model basin and hence a better average value of both the dune erosion and the beach profile. The number of profiles measured was increased to ten in test T17 and the wave filter was altered to give a more uniform wave height distribution along the basin.

Subsequently a further test T26 was made in the large basin with a very large dune height, 80 cm above storm surge level and a steeper seaward dune slope of 1 on 1. It was intended that this test should indicate the influence of a very large sand supply close to the shore upon both the rate and amount of dune erosion as well as on the form of the equilibrium profile.

---

* It was at first assumed that the reason for the differences between the results from the flume and large basin was due to cross oscillations in the former and wave height measurements appeared to confirm this conclusion. Subsequent investigations showed that this was not necessarily the only reason and that the variations in wave height across the flume were increased owing due to non uniformity of the wave filter used in these tests (see section 4.31).

The conditions of this test were similar to T17 and a total of ten
profiles at a spacing of 1.5 m was surveyed thus giving uniform
coverage of the entire basin. In all these tests the beach profiles
were measured at the same time intervals as in the previous series
of tests, i.e. $\frac{1}{2}$, 1, 2, $3\frac{1}{2}$, $5\frac{1}{2}$, 8, 11, $14\frac{1}{2}$ hours with the addition
of an extra levelling at 19 hours. The positions of the dune crest,
dune foot and water line were observed directly at the same time
intervals at each profile and midway between profiles.

4.2. Wind flume

4.21. Regular waves for comparison with outside model

The first tests made in the wind flume were with regular waves and
were intended to show what difference, if any, existed between
profiles made in the wind flume and the outside model under comparable
conditions. To this end the initial test in the wind flume TO was
indentical to test T14 with respect to shape and height of sand dune,
initial profile, testing procedure and wave height and period[*]. For
all dune erosion tests in the wind flume five profiles spaced at
0.75 m distances and symmetrical with the centre line were measured
at the same times as in the outside model, i.e. $\frac{1}{2}$, 1, 2, $3\frac{1}{2}$, $5\frac{1}{2}$, 8,
11, $14\frac{1}{2}$ and 19 hours. Wave heights and reflection coefficients were
measured for regular waves on the centre line in the deepest part
of the profile, every half hour during operation. As the results of
test TO were at variance to some degree with those of test T14, the
former test was repeated so as to obtain information on the degree
of reproducability of the test. This second test TO' agreed reasonably
well with test TO as can be seen from data 5.21-1 for dune recession
and table 5.22-1 for total sand volume eroded as well as figure 5
where the final profiles at 19 hours are compared.

[*] In fact the wave period was slightly different, being 1.63 seconds
in the wind flume tests and 1.56 seconds in the outside model. This
difference, which results in a difference in deepwater wave length
of about 9% was due to the fact that the period of the waves produced
by the outside model wave machines for a given speed setting was not
equal to the nominal calibrated value. This was not discovered until
after the wind flume tests had begun.

Both tests TO and TO' differed from test T14 in the form of the final
equilibrium profile (figure 5); the reasons for this difference are
discussed in section 5.13. Subsequently a third regular wave test T4
was made in the wind flume. This test was indentical with TO and TO'
with the exception that the wave height was about 16 cm. It produced
a final profile at 19 hours very similar to that from test T18 made
in the small basin of the outside model (figure 6).
The wave height in this latter test was also about 16 cm. On the
basis of the above results it was concluded that profiles made in the
wind flume could be compared with those made in the outside model.
Such significant differences as there were could be explained in terms
of different model conditions (section 5.13).

4.22. Mixed irregular waves

To achieve the objective of comparing the effects of regular and irre-
gular waves upon the erosion of sand dunes and the development of
beach profiles it was necessary to reproduce in the wind flume irregular
waves which could be compared with the regular waves of the outside
model. Since the capacity of the wind flume is such that waves with
periods greater than 1,2 to 1,3 secs cannot be generated by wind action
only, it was necessary to produce the required irregular waves using
both wind and wave paddle. This process is one which has been standard
in this laboratory for tests on dikes and breakwaters for many years.
Accordingly test T1 was made with a sand dune the same as T14, as in-
deed were all tests in the wind flume. The wave machine was set at
a period of 1.63 secs, equivalent to what was then believed to be the
period of the waves in the outside model, and the wave machine
eccentricity and wind velocity adjusted until the wave height which
was exceeded by 15% of the waves (H_{15}) was equal to that of the regular
wave tests, i.e. 18 cms approximately.
The wave height measurement was made at a position approximately in
the centre of the distance over which the regular wave incident and
reflected wave heights were measured.

The test results showed a considerably smaller amount of dune erosion at a given time compared with the regular waves and so a further test T2 was made in which both the wind velocity and wave machine exentricity were increased so that H_{20} was now equal to the regular wave height of approximately 18 cm. The test results however were similar to T1 in that the dune erosion was considerably lower than with the regular wave tests. Consideration of the results of tests T1 and T2 indicated that considerable difficulty could be expected in obtaining irregular waves equivalent to the regular wave tests already made. Several important problems were immediately evident. Firstly the waves were far too regular in shape and were in fact regular waves of 1.63 secs period with a relatively small amount of wind generated wave energy (about 10% of total) super-imposed upon them. As the spectra shown on figure 7 indicate the wave height distribution could not be expected to be a realistic one and this was confirmed by the values of the ratio $\frac{H_{15}}{H_{50}}$ which were of the order of 0.85. A value somewhat less than 0.7 would have been more representative of natural wind waves. Secondly the total wave energy attacking the beach in tests T1 and T2 was appreciably smaller than in the regular wave tests. Figure 7 shows this fact quite clearly[*]. Thus it is not surprising that the dune erosion is also appreciably smaller for tests T1 and T2. A possible means of making use of the data from T1 and T2 was to repeat the regular wave tests with lower wave heights and obtain a condition, by interpolation if necessary, where the wave energy was equal to that of either test T1 or T2. For this reason test T4 was made with a regular wave height of 16 cms but the dune erosion was substantially the same as in tests TO and TO'. Since the wave height distributions of tests T1 and T2 were not truly representative of real conditions this plan was not proceeded with further at this time. Other tests with (the) approximately same period and lower wave heights were subsequently made in the outside model (see section 4.31) but uncertainties in the results of one of these tests make a reliable comparison of the irregular waves of tests T1 and T2 with regular waves impossible.

[*] The spectra for the regular wave tests were made in a separate measurement from the original tests TO and TO' and are hence designated as test T3.

A further problem encountered which was particularly pronounced with partly paddle generated waves, although subsequent work showed that it also occurred with purely wind generated waves was, that the average wave heights at a fixed point offshore were not constant in time, even when determined from waves records containing 500 waves. Quite definite trends in wave height were evident and comparison with similar measurements made during regular wave tests, e.g. T4, indicated that this was due both to the shifting of the point of reflection on the beach profile as the sand dune was eroded and also to changes in the reflection coefficient during the development of the beach profile (figure 8). The causes and significance of the latter effect on the development of the beach profile will be discussed in section 5.61. However it is immediately evident that control of a test involving the erosion and build up of a beach under irregular waves is very difficult since if the wave height is measured at a fixed point quite large variations may occur due to reflection, of the order of 20% in tests T1 and T2. For instance it was started earlier that in test T1 H_{15} was equal to 18 cms and in test T2 H_{20} was equal to 18 cms. These measurements were made before the commencement of the actual tests on the beach profile left from the preceeding test. The actual wave heights during the test were in fact lower than 18 cm as the values given in table 4.12-1 show. Moreover, since the waves are irregular relatively long measurements (at least 100 waves, preferably 500) must be made at a point so it is impossible to assess the reflection effect by measuring at several points over a wave length since significant changes would occur in the beach profile and hence in the reflection characteristics, during the measurement. Consideration of the above problems lead to the conclusion that it would be better to use a different approach for determining the relative effects of regular and irregular waves upon beach erosion processes.
This is discussed in section 4.23 following.

4.23. Wind waves

In the light of the problems described above it was decided to generate
irregular waves by wind action only. These advantages of this proce-
dure were that both the shape of the waves and the form of the wave
spectrum would be more in agreement with storm surge conditions and
the bottom return current due to wind stress could be reproduced.
Further, because the wave energy would be spread over a relatively
wider range of periods, it was not so likely that reflection, or more
precisely the clapotis effect, would be so prominent as it was with
the partly paddle generated waves. A brief test (T5) was made to
check this point but the results were somewhat inconclusive (figure 9a).
Subsequent experience showed that such effects were indeed present
with wind generated waves, particularly when the wave spectrum (or
wave height distribution) was comparatively narrow. Finally it was
anticipated that it would be easier to produce a regular wave which
was equivalent to a previously produced wind wave, since greater ∞
control of the output of the wave paddle was possible compared with
that of the wind fan. A disadvantage of this procedure was that the
wind waves could not duplicate the test conditions of the outside
model since the maximum periods which could be obtained in the wind
flume were of the order of 1.2 to 1.3 secs. Thus it was necessary
to reconsider the conditions to be imposed upon the model, in parti-
cular the initial beach profile. If this were to have the same phy-
sical interpretation as in the previous tests it would have been
necessary to have made two tests each time, one at normal level to
obtain the normal storm profile (if such a thing exists) and one
at storm surge level to study dune erosion. If the same thing were done
for the equivalent regular waves two more tests would be necessary
and then the initial profiles for the start of dune erosion would
in all probability not be the same. Thus comparison of the regular
and irregular waves effects might not be too easy. It therefore
seemed desirable that a common initial profile be used for the

regular and irregular wave tests. Moreover the comparison should be
made with several wind velocities. Simplicity suggested and economy
demanded that the initial profile be the same in all these tests,
thus eliminating extra tests for its determination. In the absence
of any definite reason for choosing any other profile, and to
facilitate possible comparisons with earlier tests, the initial
profile for the wind wave tests was therefore taken as the same
as in the previous tests with the exeption that the two hours of
preparatory waving at normal water level were omitted. An important
point which had to be settled was the basis on which the regular
and irregular waves were to be compared. This could be done by
comparing the regular wave height with some arbitrarily chosen height
from the wind wave height distribution, ie H15 or H20, as had been
attempted in tests T1 and T2. On this basis the result of the comparison
could be quite different depending upon which wave height frequency
was compared. Thus if the regular wave height were compared with H50
then it was almost certain that the wind waves would show greater
dune erosion than the regular waves. On the other hand if the regular
wave height were compared with H15 or H10 the difference could be
reversed as the previous tests had shown.

Further such a comparison, even supposing that a suitable equivalent
wave height could be selected, was dependent on the wave height
distribution being the same for different wind velocities which was
not, as it turned out, the case.

A more suitable basis for comparison appeared to be to make the root
mean square wave heights of the regular and irregular waves the same.
This in fact amounts to making the areas of the power spectra diagrams
the same in each case. Referring to figure 7 we see that the area of
the power spectrum diagram is equal to

$$\sum_{\omega=0}^{\infty} E'(\omega)\Delta\omega$$

where ω is frequency in c.p.s.

E' is the energy per unit area associated with a given frequency interval

$\Delta\omega$ is the increment of frequency at which the calculation is made.

The value of the above summation represents the total energy per unit area of water surface which is proportional to the wave height squared. The square root of the above expression gives the root mean square amplitude which, when multiplied by 2 gives the root mean square wave height, Hrms[*]. If the regular wave is a sine wave or closely approximates to one then it can be shown theoretically that

$$Hrms = 0.707 \ H.$$

where H is the height of the equivalent sine wave.
This fact was approximately verified using data from tests T3 and T4 (figure 9 b) where H is taken as the average wave height at the point where Hrms was measured. If the wave is not a sine wave, ie has relatively sharper crests as is the case for most waves in practice, then the actual value of Hrms will be less than 0.707 times the wave height. It may be argued that a more suitable basis for comparison is to make the wave power or rate at which energy is transmitted towards the shore the same for both regular and irregular waves. This may indeed be so but its computation is more difficult since

$$P = \frac{n \ E}{T}$$

where P is the wave power per unit length of wave crest,

n is the ratio of group velocity Cg to phase velocity C,

and E is the energy per wave per unit length of wave crest.

Now $E = \dfrac{\rho g \ H^2 \ L}{8}$

whence $P \propto \dfrac{H^2 \ n \ C}{T}$ since $L = C \ T.$

where both C and n are functions of the relative depth $\dfrac{D}{L}.$

[*] The computed values of E' on figure 7 are based upon amplitudes relative to mean water bevel, hence the need for the factor 2.

The total wave power of an irregular wave can therefore by analogy be indicated by

$$P \propto \sum_{\omega=0}^{\infty} \left[E'(\omega) \, n_\omega \, C_\omega \right] \Delta_\omega$$

where n_ω and C_ω are the values of n and C at a given frequency ω. If the spectrum is measured in deep water n_ω is constant and equal to 0.5 while C_ω is proportional T or $\frac{1}{\omega}$ and the calculation is simplified. However the dimensions of the wind flume are such that this is not possible and a suitable computer program was not available. Further the practical requirements of the testing program were such that it was not possible to make such calculations with sufficient rapidity to prevent substantial expensive hold ups in the program. On the other hand Hrms could be evaluated on the spot at any time desired using available electronic analogue equipment. On the basis of the above considerations it was decided to make the comparison between the regular waves and irregular waves using waves of the same root mean square wave height and as a first approach the period was made equal to the period equivalent to the central frequency ω_o, or frequency with the greatest energy, of the wind wave spectrum.

Three wind wave tests (T6 to T8) were made, in each case a different wind velocity was used which resulted in waves with different characteristics *(figure 10 a). As explained earlier the initial profile was the same as for previous tests and the sand dune was identical with that used in the other wind flume tests, ie, the same as in test T14. Levellings were made along the same profiles and at the same time intervals as in other wind flume tests while wave heights were measured at two points as shown on figure 10 b.
Also measured were horizontal orbital velocities at various depths adjacent to the inshore wave height meter.

*It should be noted that the test with the medium wind speed was made first and is thus designated as T6. It was followed by the low speed test T7 and then the high speed one T8. The logical order of these these tests in terms of the conditions imposed in thus T7, T6, T8.

4.3. Outside model - small basin

4.31. Wave filter tests

During the three tests in the large basin T14 to T16 some trouble was experienced with the "steengaas" wave filters used in the model[*]. Continual repairs were required which, since it required emptying of the model each time, was inconvenient, particularly during a test, as well as costly. Further there was reason to believe that the filters were becoming increasingly more non uniform with time as repairs were made, which fact could be expected to influence the magnitude of the wave heights in the model and so presumably the erosion of the sand dune and the development of the beach profile. Indeed it had been noticed in tests T14, T15 and T16 that the position of the offshore bar was inclined at an angle to the beach and the wave machines which fact was apparently the reason for the differences between test T14 and the wind flume tests T0 and T0' (see sections 4.21 and 5.13). Accordingly investigations were made in the small basin (or flume) to see if a better filter material could be obtained. Plastic mesh, nylon mesh and expanded metal mesh as well as "steengaas" were all tested with one or more layers of material standing vertically in front of the wave machines parallel to the wave crests.

The wave height was measured in approximately 50 cm of water after passage through the filter at 9 positions across the flume. The effect of reflection from the beach was removed in the usual way (see section 3.12). In each case the filter is compared with conditions without any filter and the transmission coefficient calculated. The maximum difference in wave height in front of the filter was also determined and compared with the average wave height to give a variability coefficient.

[*] "Steengaas" is a type of wire mesh reinforced plaster with about 60% of its surface as holes. Its surface is quite rough which facilitates its use in building as a base for plaster which is its primary use. It is this rough surface which results in its being an effective wave filter.

The results are given in table 4.31-1 below and it can clearly be seen that the original "steengaas" filters were indeed making the waves more irregular since their variability coefficient is twice that with no filters at all.

TABLE 4.31-1

Results of wave filter tests
(T = 1.56 sec)

Type of filter	Number of layers	Av. wave-height after filter H_{av} -cm	Transmission coefficient H_{av}/H_{avo}	Wave-height variation $H_{max}-H_{min}$ (cm)	Variability coefficient $\dfrac{H_{max}-H_{min}}{H_{av}}$
No filter	-	27.7	100 %	2.8	10 %
Original "Steen-gaas"		18.0	65	3.5	20
"Steengaas"	1	22.0	79	1.6	7
"	2	18.2	66	1.0	6
" (new mat.)	2	16.2	59	1.4	9
Plastic mesh	1	26.4	95	3.5	13
	2	24.7	89	2.0	8
	3	23.5	85	2.0	9
Nylon mesh	1	25.7	93	2.2	9
	2	23.8	86	3.7	16
Expanded metal mesh	1	26.0	94	2.6	10
	2	24.0	87	3.5	15

With regard to the various filter materials it was concluded that none of the more durable materials were as effective as "steengaas", at least not at a reasonable cost.

Since the same transmission coefficient could be obtained at lower
cost with the simple arrangement of two parallel layers of "steengaas",
this latter type of filter was adapted for the remainder of the out-
side tests*.

4.32. Tests with different wave heights and constant period.

The first test T18 represented a repeat of the conditions imposed in
test T4. It was operated continuously over night and levellings of the
beach profiles, of which there were five spaced at 0.75 metre intervals
as in the wind flume, were made before the commencement of storm surge
level waves and after 19 hours, Comparison of the final profile of
this test with that from the wind flume test T4 was favourable (figure
6) so it was concluded that tests in this basin could be compared
with those in the wind flume.
Two further tests were made in a similar manner with the same wave
period (1.56 seconds) and different wave heights, T19 with H = 14 cm
and T20 with H = 10 cm. Levellings were made at the beginning of the
test and after 19 hours and for T20 also at $26\frac{1}{2}$ hours since equilibrium
had obviously not been reached at the earlier time. Visual observations
were made every half hour of a number of phenomena characterising the
sand dune erosion (dune foot and dune crest position, also still water
line at less frequent intervals) and conditions in the surf zone
(initial break point, end of surf zone and wave runup distance). Wave
height and reflection coefficients were also measured every half hour.
The purpose of these tests was to obtain more information on the
formation of equilibrium beach profiles and also to provide some
information on regular wave effects which might be compared with wind
flume tests T1 and T2. Unfortunately the results of test T19 contain
several apparent inconsistencies which make it difficult to draw firm
conclusions from them.

* For reasons that have never been explained, the actual rebuilt
filters in the model were more efficient than the tests had indicated.
Since the wave machines were operating at maximum eccentricity, it was
necessary to remove one layer of filter material so that the original
test wave height of 18 to 18.5 cm could be maintained. This was the
situation for tests T17 and T26 in the large basin and for all tests
in the small basin.

4.33. Test with changing water level

Test T21 reproduced the conditions of test T0 with the important difference that the water level during the test was alternated at half hourly intervals by $\pm$ 2.5 cm about the storm surge water level. This variation would correspond at the assumed vertical scale of 1 in 25 to a prototype tide range of 1.25 m which is a reasonable value for the Dutch coast. The test was thus intended to give an indication of the effects of normal tide level variations upon dune erosion and equilibrium beach profile form. Levellings were made after both a high water and a low water period at an early stage of the test (4 and $4\frac{1}{2}$ hours) as well as at its end (19 and $19\frac{1}{2}$ hours). Half hourly visual observations and wave height measurements were also made.

4.34. Tests with same H_{rms} and T_0 as wind waves tests

The basis adopted for comparing the regular and wind wave tests was described earlier (section 4.23). Unexpected difficulties were however met in producing in the wind flume regular waves equivalent to wind wave test T6. It was found that it was possible to obtain regular waves with a period of 1.11 sec corresponding to test T6. The waves formed groups of large waves, which broke as they travelled along the flume, separated by waves of smaller height with the result that the waves measured in front of the beach were quite irregular[*]. The regular wave tests were therefore not made in the wind flume but in the small basin of the outside model. The much shorter length of this basin apparently did not give the waves time to degenerate and so it was possible to obtain reasonably regular waves. Three tests were carried out, T22, T23 and T24, which were comparable to wind wave tests T7, T6 and T8 respectively in that the periods were equal to the central period of the wind wave spectra, and the wave heights were such that H_{rms} was the same for each pair of tests.

[*] Subsequently it was learnt (ref. 36 and personal discussion with Dr. C. Galvin) that this phenomenon had been observed by the U.S. Coastal Engineering Research Centre and that the limits over which generation of stable regular waves were possible had been determined experimentally. Theoretical justification also appears to forthcoming for this phenomenon.

Since the values of H_{rms} determined in the wind wave tests were not particularly accurate this quantity was not measured directly in the outside model. Instead the incident wave height was made equal to the height of the sine wave with the required root mean square wave height. As indicated in section 4.21 this procedure gives reasonable results which was justified by a check measurement of H_{rms} at the end of test T24 (figure 9). Moreover wave height measurements across the flume indicated that cross oscillations were present in certain cases and it was necessary to make some allowance for these in adjusting the wave height measured on the centre line.

In these tests reflection coefficients and visual observations of dune and break point positions were made every half hour while profiles were measured after 11 and 19 hours in tests T22 and T23 and at $\frac{1}{2}$, 1, 2, $3\frac{1}{2}$, $5\frac{1}{2}$, 8, 11, $14\frac{1}{2}$ and 19 hours in test T24.

4.35. Test with different sand size

It was suggested that the rate of dune erosion and the form of beach profile might be significantly different if the size of the sand were reduced. Test T25 was therefore made with sand of median size 0.15 mm as compared with 0.22 mm used for all the other tests. This represented the finest sand available. Unfortunately however it was not particularly clean, containing both some very fine material and a proportion of relatively large particles of organic origin, probably peat.

During this test, which was the last one made, all quantities measured in previous outside model tests, i.e. wave height, reflection coefficient, beach profiles, visual observations, sand density and grading, were observed so that the maximum amount of data could be obtained during one test. In this way it was hoped to relate as many as possible of the trends and relations previously observed, to one another.

4.36. Velocity and wave height measurements in surf zone

During the conduct of the investigation some observations of horizontal orbital velocities and wave heights were made along certain beach

profiles from the offshore zone, seaward of the initial break point, shoreward into the surf zone as far as instrument limitations would allow. These observations were made a few hours after the end of test T18 and indeed, were not part of the original investigation as such. However as they are useful in interpreting the processes occurring during dune erosion and profile adjustment use of them has been made in the interpretation of results.

The observations were made with beach profiles approximating equilibrium conditions for 1.56 second waves of 18 cm height. Two series of measurements were conducted, one in which the wave form and the orbital velocities at various depths were measured at 0.5 to 1 m intervals along the profile, and one in which wave heights and their relative phase relation to one another were measured at 10 cm intervals along three separate profiles.

5. Model results

5.1. Influence of dune height and shape upon erosion and profile development

5.11. Water line and dune foot recession

The erosion of a sand dune can be described in two ways. Firstly it can be measured as the horizontal displacement from a fixed reference point of some indentifiable feature such as the still water line, dune foot or dune crest. Secondly the dune erosion can be measured in terms of the volume of sand eroded from the dune above some fixed reference level. In this section we consider the effect of dune height upon the horizontal recession of the dune while volume considerations are dealt with in the following one (5.12).
In these tests the dune recession has been measured by the recession of both the storm surge still water line and the dune foot with respect to the original position of the storm surge water line before commencement of the test. These two points are generally quite well defined and both have a definite hydraulic significance, the water line by its very nature and the dune foot because it normally corresponds in these tests to the extreme limit of wave runup, i.e. the limit of the wave formed profile. Measurements were also made of dune crest position but as this point is dependent upon the dune height which was a fundamental variable in the tests and upon the slope of the dune face which is subject to considerable scale effect, these results are not presented in this report. For comparison of the effects of various variables it has been found essential to use the average values of the dune erosion parameters. Both visual observation and measurements indicate that the water line and dune foot positions at different profiles at the same time in the same test very often vary by amounts of the same or a greater order of magnitude than does their average value due to changes in the dune height or other independent variables. However as figure 11 shows, the scatter bands indicating the maximum and minimum positions of the dune foot and water line at any given time are in general consistent with their average values.
The effect of the dune height upon dune erosion is given by the results of tests T14, T15, T16, T17 and T26, all made in the large basin of the outside model. The average values of the water line and dune foot recession are given in table 5.11-1. In this table all distances are measured in metres from the original storm surge still water line and the height is measured relative to the storm surge water level.

TABLE 5.11-1

Dune recession as function of dune height
(metres)

	Test Number	dune height	Time - hours									
			$\frac{1}{2}$	1	2	$3\frac{1}{2}$	$5\frac{1}{2}$	8	11	$14\frac{1}{2}$	19	$27\frac{1}{2}$
Water line recession m	T14	40 cm	0.20	0.27	0.39	0.42	0.51	0.59	0.61	0.63	0.64	-
	T15	30	0.22	0.33	0.45	0.54	0.61	0.66	0.71	0.72	0.74	0.83
	T16	20	0.25	0.36	0.49	0.58	0.64	0.72	0.76	0.86	0.89	-
	T17	10	0.43	0.53	0.68	0.81	0.96	1.09	1.12	1.22	1.27	-
	T26	80	0.18	0.07	0.13	0.21	0.24	0.24	0.23	0.24	0.32	-
Dune foot recession m	T14	40	0.61	0.68	0.79	0.86	0.93	1.02	1.05	1.10	1.21	-
	T15	30	0.71	0.78	0.88	0.97	1.04	1.11	1.19	1.23	1.24	1.31
	T16	20	0.70	0.79	0.90	1.01	1.11	1.21	1.28	1.34	1.43	-
	T17	10	0.91	1.03	1.15	1.30	1.44	1.58	1.64	1.79	1.96	-
	T26	80	0.42	0.58	0.60	0.61	0.68	0.73	0.74	0.79	0.82	-

The data from table 5.11-1 are plotted on figure 12 for water line recession and figure 13 for dune foot recession. It is immediately evident, even when test T26 is ignored since the dune slope in this test was different to that in the other tests, that the amount of dune recession at a given time increases as the sand dune height is reduced.

When the development of the dune recession with time is considered it can be seen that in all tests, except possibly test T17 with the low sand dune, an approximate equilibrium or limiting recession has been reached after 19 hours. To a first approximation, it appears that the dune recession, in terms of water line position, varies logarithmically with time. However it is also apparent that there are certain discontinuities in this relationship. Moreover observations at more frequent time intervals in later tests T19 to T25 indicate that these discontinuities do in fact represent actual conditions and are not, in general, observational errors. They are dealt with further in section 5.61; here only the general trends of the results are considered.

The recession of the water line and dune foot for various dune heights is shown on figures 14 and 15. Again it is difficult to draw a smooth curve through the points but the trend is clear, the recession of the dune is inversely proportional to some function of the dune height. The inconsistency of the results for tests T15 and T16 (30 and 20 cm height dunes) is probably due to the occurrence of a definite cusp like formation of the beach during the first half of these tests. It is possible that this formation in itself may influence the rate of dune erosion while it is certain that it will affect the values of the dune erosion measured at fixed points along the beach, However when the water line data are plotted on double logarithimic paper it is possible to detect a general trend (figure 16) and for each time to draw a series of parallel straight lines. Evaluation of the intercepts between these lines is found to give a logarithmic relation for the water line position with respect to time while their slope indicates that the water line recession is inversely proportional to the 0.5 power of the dune height (figure 17). The relationship obtained is expressed by the following equation

$$x = \frac{0.41 \log t + 1.71}{h^{0.5}}$$

where x is the recession in metres of the water line, from the initial storm
   surge water line position,

   t is the time in hours,

   h is the dune height in centimetres above the storm surge level.
Applying the same procedure to the dune foot position, measured relative to the original still water line, a power relation with respect to time is found while the dune foot recession is inversely proportional to the 0.3 power of the dune height (figures 18 and 19). The relationship in this case is expressed by the equation

$$x' = \frac{2.07 \, t^{0.19}}{h^{0,3}}$$

where x' is the recession in metres of the dune foot from the initial storm
   surge still water line position.

The general agreement of the experimental points with these equations is shown on the lower graphs of figures 17 and 19 where $x\,h^{0.5}$ and $x'\,h^{0.3}$ are plotted as a function of time. It should be clearly understood that they are completely empirical and depend upon the particular geometry considered and hence upon the degree of distortion between model and prototype. Their transformation into prototype dimensions must await the acquisition of suitable prototype data. Further since the wave characteristics were constant during the tests no useful purpose is served in attempting an expression in dimensionless form. The geometrical effects will be revealed if a different initial profile is used or if the dune geometry changes. Under these conditions the relationships between dune foot or water line recession with dune height and time will change. For instance on figure 17 are shown points from tests T12 and T26 in which the dune has different front slopes to that in tests T14 to T17 but which are otherwise similar in shape. The points scatter considerably but nevertheless clearly indicate that if the dune face is flatter than as in test T12 (1:10 as compared to $1:1\frac{3}{4}$) then for the same initial dune foot position, the erosion at a given time as measured by the water line recession increases. On the other hand if the dune face slope is increased as in test T26 (1:1 as compared to $1:1\frac{3}{4}$) then the dune foot recession at a given time is reduced. The influence of purely geometrical factors upon the relation for the dune foot position is also evident when the reference point is changed. For instance if the data for water line and dune foot position in table 5.11-1 are compared, it is found that the dune foot is, on the average, about 0.5 m or a little less behind the still water line at any instant. When the dune foot recession is referred to a point 0.5 m landward of the initial still water line, a double logarithmic plot of dune foot recession versus dune height for various times (figure 20) indicates that except for times less than 2 hours, the dune foot recession at a given time with respect to this reference point, is inversely proportional to the 0.5 power of the dune height. This is of course the same relation as was found previously for the water line recession with respect to the original still water line. The time relationship however remains a power one and does not become logarithmic as it is for the water line position. The new equation is:

$$x'' = \frac{1.51\ t^{0.37}}{h^{0.5}}$$

where $x'' = x' - 0.5$ metres.

5.12. Sand volumes eroded

The erosion of sand dunes may also be expressed in terms of the volume of sand removed from the shore during a given situation. The total sand volumes eroded from the beach and sand dune have therefore been calculated for tests T14 to 17 and T26 and are given in table 5.12-1 below.

TABLE 5.12-1

Total volume of sand eroded from beach and dune
$(\text{metres}^3/\text{metre})$

Test Number	Dune height cm	Dune slope	Time – hours								
			$\frac{1}{2}$	1	2	$3\frac{1}{2}$	$5\frac{1}{2}$	8	11	$14\frac{1}{2}$	19
T14	40	$1:1\frac{3}{4}$	0.113	0.154	0.197	0.243	0.271	0.311	0.333	0.342	0.376
T15	30	"	0.131	0.148	0.186	0.218	0.242	0.284	0.303	0.309	0.316
T16	20	"	0.091	0.123	0.157	0.180	0.213	0.228	0.245	0.268	0.282
T17	10	"	0.082	0.096	0.114	0.143	0.180	0.191	0.209	0.224	0.229
T26	80	1:1	0.117	0.164	0.202	0.249	0.306	0.323	0.377	0.400	0.467

Consideration of these figures which are plotted as a function of time on figure 21 immediately shows that the total volume of sand eroded at a given time decreases as the height of the sand dune decreases. Further, when the sand volume is plotted as a function of dune height (figure 22) it also appears that there is a linear relation between the two quantities, i.e., at a given time the total volume of sand eroded increases in direct proportion to the dune height. The relationship between total sand volume eroded and time is established using the lower graph of figure 22 in which the ordinate m is the slope of the volume dune height lines on the upper graph of figure 22 relative to the volume axis. The equation which expresses this relation over the range of time up to 11 hours is as follows:

$$V = \frac{(h + 41) \, t^{0.3}}{0.62}$$

where V is the total volume of sand eroded from the beach and dune in metres^3/metre,

    h is the dune height in centimetres above storm surge level,

    t is the time in hours.

In practice use is more generally made of the volume of sand eroded from the dune above storm surge level. Consequently this quantity has also been calculated for these tests and the values are given in table 5.12-2 below.

TABLE 5.12-2

Volume of sand eroded from dune above waterline
(metres^3/metre)

Test Number	Dune height cm	Dune Slope	$\frac{1}{2}$	1	2	$3\frac{1}{2}$	$5\frac{1}{2}$	8	11	$14\frac{1}{2}$	19
			Time - hours								
T14	40	1:1$\frac{3}{4}$	0.102	0.137	0.174	0.211	0.238	0.267	0.288	0.301	0.333
T15	30	"	0.120	0.136	0.164	0.184	0,206	0.238	0.254	0.263	0.274
T16	20	"	0.088	0.111	0.134	0.150	0.173	0.190	0.200	0.217	0.228
T17	10	"	0.068	0.077	0.089	0.103	0.119	0.130	0.133	0.143	0.145
T26	80	1:1	0.116	0.163	0.201	0.253	0.288	0.314	0.369	0.392	0.455

The data from table 5.12-2 are plotted on figure 21-b as a function of time and on figure 23 as a function of dune height. As might be expected the relation between volume eroded and dune height is different to that involving the total volume eroded. Moreover while the curves, apart from those at 0.5 and 1 hours, are generally consistent it is difficult to establish a simple relation between the volume eroded above storm surge level, the dune height and time. This is shown on the lower graph of figure 23 where the volume eroded is plotted as a function of dune height on double logarithmic paper. Obviously $V^1 = K\ h^n$ where both K and n are functions of time t. Their evaluation is of little practical importance since the sole purpose of these equations is to indicate the general trends of the data.

The relation between the water line and dune foot position and the total volume eroded from the dune and foreshore is shown on figures 24 and 25. In general the volume of sand eroded increases roughly in proportion to the distance which the water line or dune foot recedes. Thus as these two points approach equilibrium, the total volume of sand eroded tends to a constant value. However with the very high sand dune (test T26), the volume of sand eroded increases significantly over a period of time without the water line or dune foot changing position. This is due to instability of the slope itself and the development of slips in the upper portion of the sand dune for which wave action is not the direct cause. The opposite situation occurs with the recession of the dune foot of the very low sand dune. In this case there is only a very small dune cliff, the dune height being approximately equal to the run up height, and consequently not much sand can be eroded as the shoreline recedes. In general figures 24 and 25 clearly indicate that the higher the sand dune is the smaller the dune recession after a given time, but the greater the volume of sand eroded. Now the results concerning dune recession in section 5.11 indicated that the amount of dune erosion depends not only upon the height of the dune but also upon the slope of its seaward face, not to mention the location of the initial dune foot relative to the initial still water line which was not varied in these tests. Further it can be deduced from the results for different dune face slopes that the recession of the sand dune will be reduced if the bulk of the sand dune is located relatively near to the original water line. Thus it may be possible to express the dune recession at a given time in terms of a single figure (which is independent of the shape of the sand dune), such as the position of the centroid of the eroded volume relative to a suitable reference point. Accordingly the centroids of the volumes eroded at different times for the various sand dunes were calculated for both the total volume eroded and the volume eroded above storm surge water level as well as the volume eroded above the initial dune foot level (height 3 cms above storm surge water level). Consideration of these results showed that it was difficult to get a completely satisfactory representation of dune shape in this manner. However the centroid positions for the volume eroded above storm surge level at a given time were of the same order of magnitude for each of the five tests considered and are given in table 5.12-3 below.

TABLE 5.12-3

Recession of centroid of volume eroded above storm surge level for various sand dunes (metres)

Test Number	Dune height cm	Dune slope	Time - hours								
			$\frac{1}{2}$	1	2	$3\frac{1}{2}$	$5\frac{1}{2}$	8	11	$14\frac{1}{2}$	19
T14	40	$1:1\frac{3}{4}$	0.49	0.54	0.60	0.65	0.67	0.71	0.74	0.75	0.80
T15	30	"	0.52	0.55	0.57	0.65	0.65	0.71	0.74	0.76	0.77
T16	20	"	0.41	0.47	0.52	0.54	0.62	0.65	0.69	0.73	0.76
T17	10	"	0.37	0.42	0.48	0.56	0.65	0.71	0.73	0.78	0.78
T26	80	1:1	0.52	0.56	0.58	0.61	0.64	0.66	0.70	0.73	0.76

The position of the centroid of the volume eroded above storm surge level is plotted with respect to time on figure 26 where it can be seen to give a fairly consistent grouping of points from the various height sand dunes. There is however a definite tendency for the centroid $\bar{x}'$ to lie somewhat further landward for the higher sand dunes than for the lower dunes in the early stages of erosion. The scatter of the points however reduces as equilibrium is approached. Plotting the points on double logarithmic paper allows the determination of a power relation between $\bar{x}'$ and t. The equation of the mean line on the lower graph of figure 26 is

$$\bar{x}' = 4.9 \, t^{0.16}$$

where $\bar{x}'$ is the position in metres of the centroid of the volume eroded above
storm surge level relative to the original storm surge water line,
t is the time in hours.

5.13. Profile changes and development of equilibrium profile

Since both the rate and amount of dune erosion are evidently related to the differences between the initial profile and the equilibrium profile for particular waves at a given water level, considerable effort was made to measure the changes in the underwater bottom profile both within the surf zone and offshore of it.

As explained earlier (section 4.13) in each test several profiles were measured at a given time. Now if conditions in the model had remained two dimensional it would have been expected that the several profiles measured at a given time were similar. However, reference to figure 27 immediately shows that this was not in fact the case. Indeed for this particular test (T14), the variations between different profiles at a given time, i.e. 19 hours, are as great or greater than the variations in a single profile during the same test (figures 28 and 29). Study of the profiles for tests T15 and T16 (not given in this report) indicates similar wide variations between the profiles measured at a given time with considerable variations in the location of the various profile features, in particular the position of initial breakpoint bar (or outer bar). This means that when the profiles are averaged to obtain a better idea of general profile slopes as well as to facilitate volume calculations, the bar formations are largely filtered out and the resulting average profile (figure 27) is difficult to reconcile with the hydraulic conditions occurring since the outer bar largely disappears. The equilibrium profiles of tests T14, 15 and T16 which are similar to one another, are however rather different from those of both tests T17 and T26 (figure 30) obtained in the same model basin, and tests T0 and T0' (figure 5) from the wind flume. Comparison of the various profiles at 19 hours for test T14 (figure 27) and test T26 (figures 31 and 32) shows that there is not so much variability between profiles in the latter test, particularly with respect to the position and shape of the outer bar. Indeed the profiles in test T26 are essentially two dimensional up to the crest of the initial break point bar. It is only in the surf zone that significant differences between profiles made at the same time occur.

The explanation for this difference between the profiles of test T14 together with T15 and T16 and test T26 etc., is apparently to be found in certain model conditions and in particular in the characteristics of the wave filter used. As indicated in section 4.31 the original filter used in tests T14 to T16 was rather irregular and resulted in waves with nonuniform wave height which broke in different ways and places at the various profiles. This resulted in the formation of the outer bar at a angle to the wave machines.

Thus when the average profile was calculated this bar tended to be smoothed out. However when the filter was changed conditions became more uniform and the average profiles (eg., for tests T17 and T26, figure 30) became both more representative of reality and similar to those obtained in the wind flume (see figures 5 and 6).

When we consider the development of the underwater profile within the surf zone and further offshore the following general process can be observed in test T14 (figures 33 and 34). The sand eroded at the beginning of the test is deposited largely inshore of the 5 metres distance point and rapidly builds up an inshore break point bar (or inner bar) with a crest a little landward of the 4 metre point. Visual observation on the model indicated that a definite plunge point occurred in this vicinity. Built up of this bar continued until about $5\frac{1}{2}$ hours during which time the average profile slope between normal water level and storm surge level flattened from 1 in 10 after $\frac{1}{2}$ hour to 1 in 12 after $5\frac{1}{2}$ hours. At the same time the average profile slope of the seaward face of the inner bar steepened from 1 to 11 to 1 in 9. During this period only a comparatively small amount of sand was deposited on the outer bar. However after $5\frac{1}{2}$ hours the seaward face of the inner bar flattens, becoming 1 in 13 at $14\frac{1}{2}$ hours, as an increasing amount of sand moves seawards into the outer bar which builds up steadily during the test and at which the initial breakpoint finally stabilises. During this latter period the average profile slope between normal water level and storm surge water level changes relatively little, the final slope at 19 hours being 1 in 12.5. Thus we see that a quasi equilibrium is obtained relatively quickly within the inner surf zone due to the relatively large volume of sand eroded from the beach and dune during the early stages of the test. Indeed two thirds of the erosion volume and five sixths of the water line recession occur in the first $5\frac{1}{2}$ hours of test T14. After this time the quantity of sand deposited within the inner surf zone remains sensibly constant, the amount of sand supplied by dune erosion being approximately equal to the amount transferred to the outer bar zone (figure 35). While the final equilibrium profiles are essentially the same for the various dune heights (figure 30) if we neglect the difference in outer bar position due to model effects, the rates of development of these profiles are obviously different. Considering test T26 with an 80 cm dune (figures 36 and 37) we find that equilibrium occurs very rapidly within the inner surf zone and it is almost impossible to detect an inner bar on the average profiles. The average profile slope between normal water level and storm surge level is initially 1 in 9 at $\frac{1}{2}$ hour which is steeper than in test T14, doubtless due to the greatly increased sand supply.

This slope however flattens rapidly becoming 1 in 12 at $3\frac{1}{2}$ hours and 1 in 13 at 11 hours, i.e. slightly flatter than in test T14. Since there is no distinguishable inner bar on the average profile the slope of its seaward face cannot be measured but the general profile slope in the surf zone below mean water level flattened from 1 in 12 after $\frac{1}{2}$ hour to 1 in 15 at 2 hours and 1 in 18 after $3\frac{1}{2}$ hours. This slope finally stabilised at about 1 in 19 at 11 hours, the corresponding slope in test T14 being 1 in 17.

Since a much larger volume of sand was required to fill the surf zone profile seaward of the inner breakpoint in test T26 because of the relatively small dune recession, build up of the outer bar was not significant until 11 hours after the commencement of the test. However after this time the outer bar developed steadily right up to the end of the test.

Considering test T17 (figures 38 and 39), the test with the very low dune (10 cm), or more correctly no dune at all since the dune height was of the same order of magnitude as the run up height, the profile development is similar. Equilibrium is reached quite quickly within the surf zone since the volume of sand required is much smaller than in either of tests T14 or T26 and the dune erosion is more rapid. An inner bar appears to be present up to $5\frac{1}{2}$ hours while development of the outer bar is not significant until after 11 hours. The position of the latter is rather closer to the original shore line than it is in test T26 which fact can be accounted for by the landward displacement of the whole profile due to the greater dune recession. In general we find that the average profile slopes are slightly flatter than for tests T14 and T26. For instance the slope between normal water level and storm surge level is initially 1 in 11 after $\frac{1}{2}$ hour and flattens to a general value of 1 in 14 after 2 hours which persists for most of the test although there is a tendency for it to become still fatter near the end. This reduction in slope is presumably explained by the smaller sand supply in this test. The average profile slope below normal water level attains a value similar to that in T26 after 8 hours, i.e. between 1 in 18 and 1 in 20. The question of the recession of the storm surge water line has been dealt with in section 5.11. It is however of interest to consider what happens to the normal water line during the development of the offshore bottom profile. The relevant data are presented in table 5.13-1 below for the various tests.

The general trend is for the normal water line to move seaward during the early part of each test as the inner bar buildsup. Indeed there may in some cases (e.g. test T16) be two normal water lines if the inner bar builds up above this level (In prototype this would not occur as the inner bar would normally be flattened during the fall in storm surge level). However after some time, i.e. $3\frac{1}{2}$ to $5\frac{1}{2}$ hours, there is a tendency, at least for the three lowest dunes (tests T15, T16 and T17), for the normal water line to move landward again as the dune is further eroded.

For the very low dune (test T17) with the greatest dune recession the normal water line at the end of the test has in fact receeded relative to its original position by about 0.2 metres. On the other hand the very high dune (test T26) shows a permanent movement in the seaward direction of more than 0.5 metres. The situation on the other tests with dune heights in between these two is somewhat indeterminate which is not unexpected since the point under consideration lies in the surf zone where frequent local changes in the bottom levels are occurring throughout the test.

In general we can say that for tests T14, T15 and T16, the normal water line position at the end of the tests is approximately at the same position as it had at the beginning.

TABLE 5.13-1

Change in normal waterline position (N.A.P.) for different sand dunes
(metres relative to profile datum)

Test Number	Dune height	Time - hours									
		0	$\frac{1}{2}$	1	2	$3\frac{1}{2}$	$5\frac{1}{2}$	8	11	$14\frac{1}{2}$	19
T14	40 cm	2.84	3.07	3.02	3.00	2.95	3.00	3.06	2.94	3.04	2.79
T15	30	2.78	2.95	2.92	2.88	2.86	2.80	2.76	2.66	3.08	2.95
T16	20	2.86	3.16	3.03	2.89	2.90	2.76	3.04	3.02	2.95	2.79
			3.50	3.54							
T17	10	2.83	3.00	3.00	3.12	2.96	2.78	2.75	2.58	2.90	2.65
T26	80	2.76	3.12	3.24	3.35	3.22	3.31	3.25	3.26	3.34	3.33

The general average slopes of the final profiles from the various tests shown on figure 30 are tabulated in table 5.13-2 below.

Here is indicated the average slope of what is called elsewhere in this report the beach, that is, the section of the profile above storm surge level between the dune foot and the storm surge water line position. It has an average value of 1 in 5,5. Secondly the slope of the profile between storm surge water line and normal water line (N.A.P.) is given as about 1 in 13.5. In actual fact the general slope in this zone is somewhat flatter than this in most of the profiles (e.g. figure 30), since the beach slope extends for two or three centimetres below the storm surge water line. At this point there is a definite step in the profile which corresponds to the end of the surf zone proper where the backwash from the beach meets the next wave.

TABLE 5.13-2

Average profile slopes at 19 hours for various dune heights

Test Number	Dune height-cm	Between dune foot and storm surge level	Between S.S. level and normal level (N.A.P.)	Between N.A.P. and outer bar through
T14	40	1 in 6	1 in 11.5	1 in 21.0
T15	30	1 in 5.5	1 in 12.5	1 in 21.0
T16	20	1 in 5	1 in 14.5	1 in 21.0
T17	10	1 in 6	1 in 15.5	1 in 19.5
T26	80	1 in 4.5	1 in 13	1 in 20.5
Average of all tests	-	1 in 5.5	1 in 13.5	1 in 20.5

The average profile slope seaward of the normal water level (N.A.P.) is rather difficult to determine precisely. This is because of the inner bar which is generally located between 3 and 4 metres. The inner bar itself does not clearly show on many of the average profiles as it is filtered out to a greater or lesser extent depending upon the amount of variation in its position from profile to profile. However the average slope of 1 in 20.5 given in the last column of table 5.13-2 gives a general idea of the slope within the surf zone between normal water level and the trough on the landward side of the outer bar.

In actual fact it is difficult to describe the form of beach profiles in terms of single slopes. The general trend of the underwater profile is best expressed in terms of a continuous curve such as some form of parabola. As outlined in section 2.3 this has been done by Larras (reference [27]) who expressed the equilibrium profile form in terms of dimensionless coordinates $\frac{x}{L_o}$ and $\frac{y}{L_o}$ where x and y are referred to the still water line position, the wave steepness $\frac{H_o}{L_o}$ and the sediment size. For the particular sediment and wave conditions of these tests Larras' formula gives:

$$y = 0.0935 \; x^{0.724}$$

Plotting the final profile from test T14 on logarithmic paper (figure 40) we find a similar equation:

$$y = 0.083 \; x^{0.724}$$

Checking with tests T15, T16 and T17 indicated that within the accuracy to which this line can be drawn, all profiles gave sensibly the same equation. The reason for the slight difference between the equation from Larras' formula and the model may well be that model depths seaward of the offshore bar are somewhat shallower than those required for equilibrium since the Larras profile lies generally a little below the model profile. However most tests show little if any tendency for this zone to be eroded, the main effect is the development of a series of low bars and troughs. We may therefore conclude that the general trend of the equilibrium profile may be indicated by a parabola such as that given by the formula of Larras.

However such parabolas are not very satisfactory representations of surf zone profiles where bars occur. In this case a comparatively small error in the line drawn on double logarithmic paper may result in the volumes of the outer bar trough and crest relative to this line being greatly disproportionate. Consequently the use of such profiles for calculations of dune erosion based upon knowledge of an equilibrium profile must be considered with caution.

In fact the actual profile may be for practical purposes better schematised in another form with a series of straight lines or possibly curves and a horizontal line at each bar, so located that the bar and its trough are equally balanced about it.

5.14. Transport rates during profile development

5.14.1. Method of Calculation

The uniform coverage of the model basin in tests T17 and T26 by the ten
equally spaced profiles together with the comparatively large number of times
at which levellings were made (10 if the initial condition is included)
suggested that it might be profitable to calculate net sand transport rates
between the dune and the offshore profile. If it is assumed that no sand is
lost from the basin during the test which did in fact appear to be so from
observation and that the bulk density of the sand is the same at all points
in the profile and the sand dune, it is possible by application of the
principle of conservation of volume to calculate the net sand transport
rate in a seawards direction over the whole beach profile at a given point
as a function of time.

The procedure used for these calculations is shown schematically in figure
41. In fact it is not necessary to plot all the graphs shown in that figure.
The steps of the calculation were as follows:

1) Calculate the average profile from the 10 individual profiles made at each
   time.

2) Calculate the difference between each average profile and the initial
   profile, i.e. the amount of erosion and deposition at each point on the
   profile at a given time.

3) For each time starting at one end of the profile calculate the cumulative
   erosion at each point by adding algebraically the erosion and deposition
   volumes in each distance increment. This gives the total volume of sand
   which has moved offshore past each point at that time.

   In most cases it was found that this graph did not end on the zero line
   at the opposite end of the profile which it should have done if
   conservation of volume was indeed true. The reasons for this were either
   that the bulk density was different along the profile (see section
   5.65 for results of measurements of this quantity) or that the number
   of profiles was not sufficient to define the three dimensional effects
   of the surf zone. In general it was felt that the latter cause was the more
   significant, and the discrepancy was spread over the whole of the profile
   by shifting the datum line to close the diagram as shown in figure 41.

4) For appropriate values of x, the horizontal distance along the profile
(0.5 m up to 6 m and 1 m after 6 m), the total volume passing that point
was plotted as a function of time.

5) The net transport rate (volume per unit time) at a given point was then
determined as a function of time by calculating the slope of the total
volume curves. The averaging period adopted was half an hour for times
up to 2 hours and one hour after that, except near inflection points
where half hour increments were generally used.

6) The net transport rate was also plotted as a function of distance x at
a given time, the times chosen corresponding with those at which the
original profiles were made.

To avoid confusion and reduce the number of figures the net transport
rate at a given point as a function of time (see (5) above) is only
plotted at 1 m intervals up to 5 metres, and 2 metres thereafter.

5.142. Variation of net transport rate during test T26 (high dune)

The transport rate varies with time at all points in an alternating manner
with a series of peaks alternating with troughs of negligible offshore
transport or small landward transport when located offshore of the breaker
zone (figures 42 and 44). It is exceptionally large during the first half hour
of the test. These fluctuations in transport rate are directly related to
fluctuations in the sand supply caused by the intermittant collapse of the
dune face. It was generally observed in prototype that the front face of the
high dune was unstable and would collapse at intervals. This collapse was un-
doubtedly related to some extent to the erosion of the dune base by the wave
uprush as in tests with lower dunes but it appears that it is also a function
of time, i.e. the larger the partially eroded dune face stands the more likely
it is to collapse. This is shown in the plot of dune foot and water line
position against volume of sand eorded where the latter tends to increase with
time independently of either of the former (figures 24 and 25), The periodic
collapse of the dune face is reflected in differences in the rates of reces-
sion of the dune foot and the dune crest. Figure 47 shows quite clearly
three periods of rapid erosion followed by quite lengthy periods of no
recession.

The movement of the two positions is approximately 180° out of phase, i.e. when the dune crest is receding rapidly the dune foot is stationary and vice versa. Thus the uprush erodes the foot of the dune which then collapses, increasing the transport rate which reduces the wave run up distance due to the steeper beach slope and greater energy dissipation within the uprush. Once the dune collapse is completed the dune foot starts to receed again until the build up of the inner bar is such as to reduce the run up, at which time the dune base becomes stable again. The face of the dune is now at its steepest and thus it generally collapses at this time. Thus minimum transport occurs just before dune collapse when the dune foot position is temporarily stable while maximum transport occurs sometime after the collapse of the dune face. When we consider the variation of net transport rate along the profile at a given time (figure 45) we see that maximum transport occurs in the initial stages at the water line, i.e. at the end of the surf zone. Thus sand is deposited in the surf zone initially close to the shore but subsequently further out as can be seen from the gradual widening of the crest of the transport curve with increasing time as equilibrium is achieved in the inner portion of the surf zone. After $5\frac{1}{2}$ hours the net seaward transport is more or less constant within the surf zone, extending from the water line at about 1.8 metres to the breakpoint between 7 and 8 metres. In this situation the transport rate varies only with the recession of the sand dune, that is with the sand supply. This presumably means that bed load transport is at saturation level and suspended load fluctuates in response to the sand supply. The bottom profile is thus in general equilibrium for the conditions imposed upon it. The average bed profiles all show similar levels within the surf zone after $5\frac{1}{2}$ hours while sand accumulates offshore of the break-point to form the outer bar (section 5.13 and figure 37). Seaward of 12 m, i.e. at the foot of the outer bar the transport rate after the initial half hour is extremely small. Observations of characteristics of the initial breakpoint are generally consistent with the above behaviour in that up to about six hours the breakers have a spilling form at the initial breakpoint at 7.2 metres and develop a plunging roller further inshore at about 4.8 to 5 metres. After six hours plunging breakers predominate at the initial break point, which fact is consistent with the build up of the outer bar during the latter stages of the test.

5.143. Variation of net transport rate during test T17 (low dune)

In test T17 it is seen in contrast to test T26 that the initial peak
transport rate is generally lower and that it lasts for a shorter period of
time which is of course to be expected as the protential sand supply is much
smaller (figures 43 and 44). On the other hand the much greater rate of dune
recession means that the transport rate at the beginning of the test is still
substantial. The transport rate decreases very rapidly with time at most
points and after the initial peak at half an hour there seems to be no
systematic variation with time as there was in test T26. There is however
a noticable landward transport at the beginning of the test in the zone
seaward of 10 metres. This is presumably due to bed movement under the
influence of mass transport currents. Subsequently it is assumed that the
landward transport at the bottom is balanced by seaward transport in suspen-
sion as sand from the dune reaches and passes the outer bar. Transport
rates in this zone during most of the tests are negligible.
Considering figure 46 showing the transport rate along the profile at a given
time it will be noticed that after the first half hour maximum transport with-
in the surf zone is generally at some point seaward of the water line, i.e.
at about 3 or 4 metres in the vicinity of the outer bar. This is a consequence
of the fact that, because the sand supply is low, it is necessary for the dune
to recede a relatively large distance before a complete equilibrium profile
is developed. This means that the profile established initially in the
inner part of the surf zone is itself eroded later in the test as sand is
transported further seaward. This process commences as early as one hour after
the beginning of the test and continues right up to its end.

5.15. Summary

For the particular conditions of this series of tests the recession of a
sand dune when measured as the displacement of the storm surge water line
from its initial position is inversely proportional to the square of the dune
height measured relative to the storm surge water level and directly propor-
tional to the logarithm of the time.
The recession of the dune foot also varies inversely with the dune height,
the power of this relationship depending upon the reference point to which
the dune foot recession is referred.

The relationship of the dune foot recession with time is a power one which also depends upon the reference point for dune foot recession. The total volume of sand eroded from the dune and beach is directly proportional to the dune height and the 0.3 power of the time.

The centroid of the volume eroded above storm surge level at a given time is approximately independent of the dune height and its front slope, especially at equilibrium.

In general at a given time the higher the sand dune, the smaller the amount of dune recession but the greater the sand volume eroded.

In all cases deposition occurs rapidly initially on the inner bar but as time progresses sand is transferred to the outer bar. The final equilibrium profiles for different dune heights are basically the same except that they are displaced in position along the horizontal axis. Their general shape can be represented by a parabola similar to that given by the empirical formula of Larras.

The equilibrium position of the normal water line (N.A.P.) depends upon the height of the sand dune. For a high dune with relatively small dune foot recession, the normal water line may move seaward while with a low dune the opposite result may occur. At equilibrium the average slope of the dry beach between dune foot and storm surge water level is 1 in $5\frac{1}{2}$, the average slope between storm surge water level and normal water level (N.A.P.) is 1 in $13\frac{1}{2}$ and the average slope between normal water level (N.A.P.) and the outer bar trough is about 1 in 20.

The net seaward sand transport rates are initially high over most of the profile but decrease markedly after a short time. Thereafter the decrease in rate is comparatively slow until equilibrium is reached. Similarly transport rates decrease significantly seaward of the break point and may in fact become landward in direction offshore of the outer bar.

5.2. Influence of wave height and period upon erosion and profile development

5.21. Water line and dune foot recession

While it was not originally intended to investigate in detail the effect of variation of wave height and wave period upon the recession of the sand dune the results obtained do allow some conclusions to be made on this subject.

Firstly using data given in table 5.21-1 below from tests T0, T0', T4, T18, T19 and T20 for which the period was approximately constant (1.56 to 1.63) it is possible to see the effect of changes in wave height upon the recession of the water line and the dune foot.

TABLE 5.21-1

Dune recession as function of wave height
(metres)

	Test Number	Wave height H_o	Time - hours										
			$\frac{1}{2}$	1	2	$3\frac{1}{2}$	$5\frac{1}{2}$	8	11	$14\frac{1}{2}$	19	23	$26\frac{1}{2}$
Water line recession metres	T0	19.5 cm	0.19	0.30	0.27	0.41	0.50	0.68	0.80	0.83	0.84	-	-
	T0'	19.5	0.18	0.17	0.18	0.34	0.46	0.57	0.71	0.79	0.83	-	-
	T4	17.6	0.05	0.01	0.15	0.19	0.26	0.23	0.49	0.59	0.68	-	-
	T18	17.8	-	-	-	-	-	-	-	-	-	-	-
	T19	15.4	0.04	0.10	0.16	0.24	0.28	0.32	0.40	0.30	0.07	-	-
	T20	10.7	0.00	0.05	0.05	0.02	0.07	0.04	0.09	0.22	0.34	0.09	0.48
Dune foot recession metres	T0	19.5	0.59	0.72	0.84	0.92	1.02	1.09	1.14	1.21	1.23	-	-
	T0'	19.5	0.62	0.73	0.76	0.95	0.85	1.00	1.18	1.19	1.24	-	-
	T4	17.6	0.48	0.48	0.60	0.61	0.74	0.73	0.81	1.00	1.08	-	-
	T18	17.8	-	0.56	0.72	-	-	-	-	-	1.28	-	-
	T19	15.4	0.40	0.47	0.55	0.66	0.69	0.76	0.82	0.83	0.86	-	-
	T20	10.7	0.40	0.46	0.46	0.53	0.55	0.58	0.64	0.71	0.77	0.85	0.87

Plotting the data of the above table 5.21-1 as a function of time (figures 48 and 49) it is apparent that the recession of both the water line and the dune foot is greater when the wave height is greater, which results was indeed what was expected. However there are general inconsistencies in the data particularly with respect to the water line recession. This is particularly so for test T19 where the water line after reaching a maximum recession at 11 hours then moves seaward again until at 19 hours it is almost back at its initial position.

The exact reason for this is not clear but measurements of the wave height
during the test show unexplained variations in which the wave height also
reached a maximum about halfway during the test and then decreased again,
the variation of incident wave height after elimination of reflection being
about 20% of its mean value. For this reason and also because of the
irregularity of some of the other test results no attempt has been made
to relate the water line recession to the wave height.

Confining consideration to the recession of the dune foot we see from figure
50 that its relation to the wave height is not a simple one, but will depend
upon the reference point to which the dune foot recession is referred. No
simple relation was in fact found after several trial plots of this data.
A clearer picture of the effect of wave characteristics upon the rate of
dune recession is obtained when the effect of both wave period and wave
height upon the dune recession is considered. If we consider the following
five variables

$$x' \quad - \text{ dune foot recession}$$
$$H_o \quad - \text{ deepwater wave height}$$
$$T \quad - \text{ wave period}$$
$$t \quad - \text{ time}$$
$$g \quad - \text{ gravitational acceleration}$$

physical considerations indicate that

$$\frac{x'}{g\,T^2} = f\left(\frac{H_o}{g\,T^2}\,,\,\frac{t}{T}\right),$$

or since $\qquad L_o = \dfrac{g\,T^2}{2\,\pi}\qquad$ where L_o is the deepwater wave length

$$\frac{x'}{L_o} = f\left(\frac{H_o}{L_o}\,,\,\frac{t}{T}\right).$$

These three dimensionless parameters can be easily interpreted as follows:

$\dfrac{x'}{L_o}$ — a scale factor representing the known fact that model beaches are steeper than prototype ones (cf formula of Larras in section 2.3).

$\dfrac{H_o}{L_o}$ — the deepwater wave steepness.

$\dfrac{t}{T}$ — the number of waves.

Figure 51 using data from table 5.21-1 together with additional data from tests T22, T23 and T24 (see table 5.41-1), shows the parameter $\dfrac{x'}{T^2}$ plotted against $\dfrac{t}{T}$ for various tests (i.e. constant steepness $\dfrac{H_o}{T^2}$). It is apparent that for a given value of $\dfrac{t}{T}$ the parameter $\dfrac{x'}{T^2}$ increases with the wave steepness, while, except for relatively small values of $\dfrac{t}{T}$ and $\dfrac{H_o}{T^2}$, the lines of constant steepness $\dfrac{H_o}{T^2}$ have essentially the same shape, thus indicating a general functional relation between $\dfrac{x'}{T^2}$ and $\dfrac{t}{T}$ similar in form to that found in section 5.11 between x'' and t.

However the relation between $\dfrac{x'}{T^2}$ and $\dfrac{H_o}{T^2}$ for constant values of $\dfrac{t}{T}$ does not appear to be a simple one. Figure 52 obtained using values of $\dfrac{H_o}{T^2}$ and $\dfrac{x'}{T^2}$ read off the smoothed curves of figure 51 at given $\dfrac{t}{T}$, indicates that there is a discontinuity in this relationship when $\dfrac{H_o}{T^2}$ is approximately 7 cm/sec^2 ($\dfrac{H_o}{L_o}$ = 0.047). While the limitations in both the accuracy and range of the experimental data cause this to be viewed with suspicion, there is also qualitative evidence to suggest that this discontinuity represents a change in breaker conditions which are themselves, at least in the earlier stages of erosion, dependent to some extent on the initial profile. As explained in further detail in section 5.61 reflection from the beach is greater with the waves of low steepness and the tendency to dissipate the energy by a plunging breaker in the surf zone fairly close to the beach is also greater for these waves. Thus the relative length of the breaker zone is shorter for these waves as may be seen on figure 105. The significance of these points are more fully discussed in sections 5.61 and 5.63.

In general it can be concluded that the effect of changes of wave height and period upon the rate of dune foot recession can be expressed in terms of the parameters $\dfrac{x'}{L_o}$, $\dfrac{H_o}{L_o}$ and $\dfrac{t}{T}$, for a given sediment, water level, sand dune and initial profile.

However owing to changes in the character of the wave dissipation process
in the surf zone during the erosion of the sand dune and the development
of a new equilibrium condition it is difficult to derive definite functional
relationships between these parameters.

5.22. Sand volumes eroded

The determination of the influence of wave height and wave period upon
the volume of sand eroded is somewhat difficult as there is not a great
deal of data to work upon. The available data from the various flume
experiments are given in table 5.22-1 below.
To these have been added results from T14 (table 5.12-1) for the subsequent
analysis. This analysis has been confined to a consideration of the total
volume of sand eroded from the beach dune.

TABLE 5.22-1

Total sand volume eroded from beach and dune for different wave conditions
(metres^3/metre)

Test Number	Wave height H_o -cm	Wave period sec	Time-hours									
			0.5	1	2	3.5	5.5	8	11	14.5	19	26.5
TO	19.5	1.63	0.094	0.146	0.179	0.212	0.253	0.296	0.349	0.375	0.396	-
TO'	19.5	1.63	0.101	0.162	0.148	0.221	0.221	0.280	0.341	0.382	0.369	-
T4	17.6	1.63	0.065	0.081	0.111	0.117	0.187	0.191	0.250	0.324	0.359	-
T20	10.7	1.56	-	-	-	-	-	-	-	-	0.193	0.247
T22	9.8	1.04	-	-	-	-	-	-	0.113	-	0.124	-
T23	13.4	1.16	-	-	-	-	-	-	0.139	-	0.150	-
T24	18.2	1.29	0.055	0.087	0.114	0.141	0.166	0.187	0.217	0.233	0.251	-

Plotting the volume eroded with respect to time (figure 55b) yields some-
what similar shaped curves to those on figure 21 for various sand dunes.
The volume eroded is obviously larger for higher and longer waves. When
the possibilities of systemisation of the data by dimensionless representation
are considered, there appear to be two, reasonable alternatives. If it is
agreed that both the wave steepness $\frac{H}{L_o}$ or $\frac{H}{T^2}$ and the number of waves $\frac{t}{T}$ are

relevant parameters, which fact was indeed the case for the dune foot recession, then the dune erosion volume can be expressed by either of the following terms:

$$\frac{V}{H_o L_o} \quad \text{or} \quad \frac{V}{g H_o T^2} \qquad \text{and} \qquad \frac{V}{L_o^2} \quad \text{or} \quad \frac{V}{g^2 T^4}$$

where V is the volume eroded - in this case the total volume eroded from the beach and dune. When these parameters are plotted with respect to the parameter $\frac{t}{T}$ it is found that the data tend to be more clearly represented by $\frac{V}{T^4}$. For instance, in the plot of $\frac{V}{H_o T^2}$ (figure 53) it is not possible to detect a systematic effect of the wave steepness $\frac{H_o}{T^2}$, since while the steepness increases from right to left up to a value of 8.3 (test T14) and perhaps 10.1 (test T23), the results of test T24, where $\frac{H_o}{T^2}$ is greatest (11.1), fall almost exactly on the same line as T0 and T0' where $\frac{H_o}{T^2}$ is 7.4. On the other hand when $\frac{V}{T^4}$ is considered (figure 54) we find that all the data plot in curves of increasing steepness from bottom to top, that is except T22 which is clearly discordant in both representations and has therefore been neglected. The variation of $\frac{V}{T^4}$ with wave steepness is shown of figure 55_a where values have been read off the smoothed curves of figure 54 at constant $\frac{t}{T}$. The resulting curves are of considerable interest, in that they confirm the result obtained from the dune foot recession data (figure 52) indicating that the amount of dune erosion increases rather rapidly with wave steepness up to a certain value ($\frac{H_o}{T^2}$ = 8.0 cm/sec^2) after which there is a relatively much slower increase. A second interesting fact is that equilibrium is reached relatively more quickly with waves having a steepness of the same order of magnitude or a little less than this critical value. This is clearly shown on figure 54 where the lines of constant steepness for tests T0 and T14 are almost horizontal when $\frac{t}{T} \approx 4.5 \times 10^4$ while for test T24 (greater steepness) this does not occur until $\frac{t}{T} \approx 6. \times 10^4$. Test T20 (lower steepness) has not reached equilibrium at $\frac{t}{T} \approx 6 \times 10^4$. The reason for this difference is probably due to the fact that the initial profile is somewhat closer to the equilibrium profile for tests T0 and T14 than for the other tests. Some additional scale effect not represented by the parameters used may also be present due to a

relatively greater proportion of suspended load movement compared to bed
load movement in the tests with larger wave heights and periods, thus higher
velocities, etc. (i.e. T0,T14). The determination of a functional relation-
ship between the three parameters $\frac{V}{T^4}$, $\frac{H_o}{T^2}$, $\frac{t}{T}$ is thus very difficult, if
not impossible with the limited data available and therefore has not been
attempted in this case. Care should however be exercised in applying these
results, since the apparent decrease in relative erosion with waves of
higher steepness could also be due to the fact that these waves are smaller,
i.e. shorter period, while the range of period where the erosion volume
increases rather rapidly with steepness represents a condition where the
period is constant and the wave height is increasing. There is no certainty
that if this period (1.6 sec approximately) were maintained and the wave
height increased to give a steepness equal to that of test T24
($\frac{H_o}{T^2}$ = 11.1 cm/sec^2), the results would be consistent with the curves on
figure 55. It is of course quite possible that they would be since with
such a wave quite a considerable amount of energy would be dissipated in
breaking some distance offshore. In this case it is possible that the wave
height at the end of the surf zone and hence the wave run up which appears
to be very significant in dune erosion, reach a maximum value for this
particular initial profile at a certain wave steepness, thus limiting the
amount of erosion. This factor may also be the reason for the apparent
inconsistancy of the wave steepness lines on figure 53 ($\frac{V}{H_o T^2}$ versus $\frac{t}{T}$).
Finally it should be noted that the parameter $\frac{V}{T^4}$ or $\frac{V}{L^2}$ would seem to be
consistent with the dimensionless representation of beach profiles in terms
of $\frac{x}{L_o}$ and $\frac{y}{L_o}$ by Larras (reference 27) which is considered in sections 2.3,
5.13 and 5.23.

5.23. Profile changes and development of equilibrium profile

Since in most tests with wave heights and periods different to those used
in the dune height tests only a few profiles were measured, it is not
possible to say very much about profile development and how it is affected
by changes in the wave conditions. Reduction in the wave height without
changing the period obviously reduces the rate of dune erosion as the
results for test T20 given in section 5.20 show.

In this case many more waves are required before the equilibrium situation is obtained because of the much smaller transport rates which occur with lower energy waves. Consideration of the final profiles for the four tests T0, T4, T19 and T20 in which the period was approximately the same but the wave height was different does not give a great deal of information. Figure 56 shows that a reduction in deepwater wave height from 19.5 cm to 17.6 (tests T0 and T4) does not cause any significant change in the profile. On the other hand further reduction of the wave height to 15.4cm (tests T19) apparently has a large effect. The beach slope is flatter, being approximately 1 in 9.5 compared with 1 in 5 for the higher waves and there is a much more pronounced trough between the inner and outer bars. The crest of the latter is also shifted towards the shore. While the beach slope is flatter for test T19 the slope of the surf zone section of the profile is significantly greater. These differences are difficult to account for. The only significant hydraulic difference observed was that the waves did not break on the outer bar in test T19. However as mentioned in section 5.61 significant changes in incident wave height occurred during this test and these may have been related to the unusual profile developed. As no other profiles were measured earlier in the test no confirmation of this can be established. The fourth profile (T20) for H_o = 10.7 cm appears to be more consistent with a general slope within the surf zone of 1 in 17 which is the same as in tests T0 and T4. It shows relatively little change in the outer bar area although the tendency for the bar to form is still present. The inner bar is however much more prominent which is hardly surprising since the main break point occurs in this zone. When the profiles for the three tests with smaller wave periods are considered (figures 64, 65 and 66) it is seen that they represent typical profiles for a steep coast where the waves have relatively little effect upon the bottom seaward of the breakpoint. Indeed comparison with experimental results for the commencement of sand motion under wave action (reference 3) indicates that for test T22 no sand motion at all occurred in the offshore part of the profile. Basically the profile of tests T22 and T23 is concave upwards to a point somewhat seaward of the breakpoint, after which there is a relatively steep slope approximating the angle of repose of the sand under water.

A small bar may be present at the breakpoint, This type of profile is similar to those developed on the shores of inland reservoirs which have been investigated extensively in Russia (reference 25) and also in the United States (reference 48). Since the initial profile is relatively too steep these profiles are not suitable for comparison with actual beach profiles. Test T24 (figure 66) shows a somewhat different type of profile with bar at the main breakpoint together with smaller bars at the initial breakpoint (7 to 8 metres) and at the end of the surf zone (2.5 metres). The number of bars formed upon a profile may therefore be proportional to the wave steepness since this test had the greatest wave steepness ($\frac{H_o}{L_o} = 0.063$). No definite conclusions can be drawn concerning this matter.
An attempt was made to compare the equilibrium profiles obtained with the formula of Larras (reference 27). The agreement was fair but since it was obvious that a smooth parabola did not represent the shape or sand distribution within a barred profile very well it did not appear that this formula was satisfactory for estimating the equilibrium profile for dune erosion calculations.

5.24. Summary

Recession of the dune foot after a given time increases with both wave height and wave period. However it is difficult to establish the relevant functional relationship due to the fact that it is affected by the shape of the initial profile. The parameters $\frac{x'}{L_o}$, $\frac{H_o}{L_o}$ and $\frac{t}{T}$ appear to be relevant. The volume of sand eroded also increases with the wave height and wave period. The form of the equilibrium profile varies with changes in the wave characteristics and the outer bar becomes less important as the wave height and/or period are reduced. The number of bars on the profile may increase with increasing wave steepness.

5.3. Influence of changing water level upon erosion and profile development

5.31. Waterline and dune foot recession

The observations of waterline and dune foot recession for test T21 in which the water line alternated ± 2.5 cm about the storm surge level at half hour periods are given in table 5.31-1 below.

TABLE 5.31-1

Dune recession with changing water level (T21)
(metres)

	After low water					After high water			
Time hours	L.W.L. position	M.W.L. position	H.W.L. position	Dune foot position	Time hours	L.W.L. position	M.W.L. position	H.W.L. position	Dune foot position
0.5	-0.07	-	0.16	0.33	1.0	-0.25	-	0.18	0.68
1.5	-0.06	-	0.23	0.68	2.0	-0.22	-	0.29	0.74
2.5	-0.03	-	0.26	0.78	3.0	-0.11	-	0.31	0.84
3.5	0.01	-	0.30	0.83	4.0	-0.09	0.29	0.44	0.90
4.5	0.04	0.28	0.36	0.90	5.0	0.03	-	0.49	0.93
5.5	0.12	-	0.39	0.94	6.0	0.01	-	0.51	0.99
6.5	0.17	-	0.43	1.00	7.0	0.05	-	0.61	1.01
7.5	0.15	-	0.45	1.01	8.0	0.13	-	0.66	1.06
8.5	0.20	-	0.53	1.06	9.0	0.16	-	0.67	1.07
9.5	0.18	-	0.57	1.07	10.0	0.08	-	0.56	1.08
10.5	0.23	-	0.54	1.11	11.0	0.00	-	0.67	1.13
11.5	0.23	-	0.57	1.11	12.0	0.09	-	0.63	1.14
12.5	0.27	-	0.57	1.15	13.0	0.18	-	0.67	1.14
13.5	0.26	-	0.62	1.13	14.0	0.23	-	0.67	1.15
14.5	0.36	-	0.65	1.15	15.0	0.24	-	0.72	1.16
15.5	0.36	-	0.66	1.17	16.0	0.18	-	0.76	1.18
16.5	0.37	-	0.70	1.18	17.0	0.09	-	0.68	1.21
17.5	0.27	-	0.72	1.21	18.0	0.22	-	0.75	1.21
18.5	0.42	-	0.67	1.21	19.0	0.13	0.66	0.78	1.22
19.5	0.36	0.56	0.71	1.22	-	-	-	-	-

When these figures are plotted (figure 57) it a apparent that while the
dune foot position follows a relatively smooth logarithmic type curve with
respect to time, the recession of the water line is somewhat more
complicated.

Observation indicated that the recession of the dune foot and hence dune
erosion occurred only during high water periods. During the low water
periods the waves did not reach the dune foot but simply redistributed the
sand which had been eroded during the previous high water period.
This caused a change in the form of the beach which resulted in the high and
low water lines lying in different places after low water than after high
water conditions. The tendency is for the high and low water lines to be
closer after low water waves than after high water conditions. That is the
beach slope in the "intertidal" zone is steeper under low water conditions
which fact may be due to the fact that the residual wave height is smaller
under low water conditions. However an analysis of beach slopes in tests
with varying wave height (see section 5.63) does not encourage this
exploration. More likely is that the slope measured is that of a different
part of the beach profile which can be expected to be steeper near and
above the water level (see section 5.13). Comparing the dune recession
with that in the corresponding constant level test TO (figure 57) it is
seen that the dune foot recedes only slightly further at a given time in
the constant level test. This would seem to indicate that the effect of the
rise in water level which would be expected to increase the rate of dune
erosion is, in this case, compensated almost exactly by the fact that the
time which the waves are actually eroding the dune is reduced by half.
Comparing the water line position of the constant level test with that
of high water after waves at high water level we see that these two recede
by the same amount during the first half of the test. During the latter
half of the test the constant level test water line is somewhat further
landward. On the other hand the mean water line during the changing level
test is significantly further seaward than the water line of the constant
level test. Thus, for the particular conditions tested, dune erosion was
much the same for the constant and changing water level conditions but
the mean water line does not recede so far under changing level conditions.
The slope of the dry beach is therefore flatter when the water level is
changing.

5.32. Profile changes and development of equilibrium profile

During test T21 profiles were measured at 4 and $4\frac{1}{2}$ hours and at $_{\wedge}19\frac{1}{2}$ hours [19 and] in each case after a period of high water wave conditions followed by a period of low water conditions. These profiles are shown on figure 58 together with the profile for 19 hours from the comparable constant level test TO.

During the early stages of the test, i.e. 4 and $4\frac{1}{2}$ hours, the principal difference between the profiles after high and low water conditions is in the height and form of the inner bar located at about 4 metres. After high water waves this bar is high and steep and is in fact located at the initial breakpoint where the waves break in a strong plunging roller. After low water the bar is lowered by some 3 to 4 cms and its width extended. The depth of water of [over] the bar on the average profile is about a centimeter less than at high water which is consistent with the fact that the incident wave height is somewhat lower and the waves initially break in a spilling form further seaward at about 7 metres.

At the end of the test, i.e. 19 and $19\frac{1}{2}$ hours there is no significant difference between the high and low water profiles. The crest of the inner bar is at 4.4 metres and the outer bar has built up with its crest located between 8.5 to 9.0 metres. The initial breakpoint of the waves was at 8 metres or a little further seaward with both high and low water waves. The breaker form was however different, as high water waves initially broke as spilling breakers and low water waves as plunging breakers.

Comparing the final profiles with those of test TO (figure 58) it is seen that the amount of dune erosion is approximately the same although the mean water line has not receeeded as far as in the constant level tests (figure 57). The inner bar is higher in the changing level test than in the constant level test, while the outer bar has about the same height but is a little closer inshore. The amount of sand deposited offshore of the outer bar is not as large as in the constant level test. The difference in sand volume is stored in the vicinity of the inner bar. Thus with a changing water level under the particular conditions considered where the dune erosion is almost the same as with a constant level, a greater quantity of sand is deposited close to the shoreline in the inshore section of the surf zone. The comparative figure for the amount of sand eroded from the dune and deposited in the inner and outer bar areas are given in the following table 5.32-1.

TABLE 5.32-1

Comparison of erosion and deposition volumes for constant and changing
level at 19 hours (metres^3/metre)

Test number	Water level	Volume eroded from beach and dune	Volume deposited in inner bar zone	Volume deposited in outer bar zone
TO	constant	0.396	0.143	0.141
T21	changing	0.374	0.215	0.172 ?

When the changes in beach slope are considered it is found (table 5.32-2)
that the slope of the beach above mean storm surge level is generally steeper
after high water waves than low water waves. This is presumably due to the
tendency for the somewhat lower low water waves to move sand landward and
steepen the portion of the profile which is traversed by their uprush.
On the other hand the slope of the beach between the high and low water
lines becomes somewhat flatter after high water waves due to the opposite
tendency of the high water waves in flattening the profile slope immediately
below the high water line. The slope between the mean storm surge level
and normal water level however is not significantly different after high
or low water conditions and moreover at the end of the test has a value
of the same order of magnitude as in the constant tests (table 5.13-2).

TABLE 5.32-2

Beach and foreshore slopes during changing water level test - T21

Portion of profile	After H.W. 4 hours	After L.W. 4,5 hours	After H.W. 19 hours	After L.W. 19,5 hours
Between dune foot and high water-line	1 in 4	1 in 5.5	1 in 5.5	1 in 7.2
Between dune foot and mean water-line	1 in 4.5	1 in 5.5	1 in 5.5	1 in 7.5
Between high and low water-lines	1 in 9	1 in 7	1 in 10	1 in 8
Between storm surge level (M.W.L.) and Normal water-line	1 in 10.5	1 in 10.5	1 in 14	1 in 13.5

The position of the normal water line is substantially the same both after
high and low water waves as well as in the early stages and the end of the
test. In this case it is also identical with that of the final profile
of the constant level test TO (figure 58). However there is the possibility
that the breakpoint bar for high water waves on a steep offshore profile
such as exists in the early stages of the test may be above normal water
level which is in fact the case after 4 hours in test T21 (figure 58).
This will not necessarily be the case in general as conditions will vary
depending upon the relative increase in water level due to storm surge,
the tide range, and most of the other variables affecting dune erosion
and profile development.

5.33 Summary

The effect upon dune foot recession of the changing water level due to the
tide may in certain cases be relatively small since the increased erosion
potential of the higher water level at high tide is compensated by the
reduced duration of the high tide level in comparison with that for constant
level conditions.
At low tide the waves redistributed the sand eroded during high tide,
flattening the inner bar. This effect is more pronounced during the early
stages of dune erosion than at equilibrium.
The mean storm surge level does not recede as rapidly as with constant
level conditions, thus the slope of the dry beach is flatter at equilibrium
than for a constant level test.

5.4. Comparison of effects of wind and regular waves upon erosion and profile development

5.41. Water line and dune foot recession

The results of the three pairs of tests with regular and wind generated
waves are given in table 5.41-1 and are plotted on figures 59 and 60.
In comparing the data it should be noted that the dune foot position is
known extremely well for the regular wave tests, having been observed every
half hour during each the test.

On the other hand for the wind waves this was not possible and values are
only available at the times of levelling. As these values were estimated
from the profiles which were drawn from levels at 10 cm.spacing their
accuracy is not very great, which fact is evident from the figures, particu-
larly for test T6.

TABLE 5.41-1

Dune recession for wind waves and regular waves
(metres)

	Test Number	Wave height cm	Wave period sec	Time-hours								
				$\frac{1}{2}$	1	2	$3\frac{1}{2}$	$5\frac{1}{2}$	8	11	$14\frac{1}{2}$	19
Water-line recession metres	T7 w	6.7	1.00	0.16	0.18	0.20	0.24	0.27	0.28	0.37	0.34	0.31
	T22 r	6.6	1.04	0.07	0.11	0.15	0.21	0.25	0.25	0.31	0.35	0.35
	T6 w	9.4	1.11	0.14	0.13	0.27	0.21	0.36	0.40	0.32	0.35	0.35
	T23 r	8.9	1.16	0.08	0.15	0.16	0.20	0.22	0.30	0.32	0.40	0.43
	T8 w	11.2	1.29	0.04	0.05	0.12	0.21	0.19	0.23	0.40	0.57	0.56
	T24 r	10.9	1.29	0.16	0.13	0.20	0.29	0.27	0.33	0.43	0.49	0.50
Dune foot recession metres	T7 w	6.7	1.00	0.34	0.40	0.42	0.52	0.55	0.54	0.62	0.63	0.60
	T22 r	6.6	1.04	0.27	0.31	0.38	0.42	0.45	0.48	0.56	0.59	0.60
	T6 w	9.4	1.11	0.46	0.50	0.60	0.60	0.74	0.78	0.72	0.78	0.78
	T23 r	8.9	1.16	0.34	0.39	0.45	0.49	0.54	0.59	0.61	0.68	0.73
	T8 w	11.2	1.29	0.64	0.64	0.75	0.79	1.17	1.03	1.18	1.21	1.27
	T24 r	10.9	1.29	0.47	0.49	0.60	0.63	0.70	0.75	0.80	0.84	0.89

Firstly with regard to the recession of the water line this does not seem
to be consistently either greater or smaller than for regular waves. Tests
T7 and T6 indicate a somewhat greater recession at the beginning of the
test up to 11 to $14\frac{1}{2}$ hours after which the recession is less than for regular
waves. On the other hand T8 indicates exactly the opposite effect.

It is however evident, at least for tests T7 and T8, that there
is a definite similarity in the process of water line recession for both
regular and irregular waves. The changes in rate of recession in the
regular wave tests including the temporary slight seaward movement between
$3\frac{1}{2}$ and $5\frac{1}{2}$ hours in test T24, are clearly reflected in the wind wave tests.
Secondly, when the recession of the dune foot is considered, all tests
indicate a consistent general trend for the recession to be greater for
the wind waves. Tests T7 and T6 further show that while the dune recession
is greater for wind waves during the development of the erosion it tends
to the same value as for regular waves as equilibrium is approached. T8
however shows an opposite tendency, the reason for which is not particu-
larly clear. Several factors may have affected these latter results.
For instance test T8 had not reached complete equilibrium at 19 hours
although it appears unlikely that this is the cause of the discrepancy. Also
the sand dune was damaged just before $5\frac{1}{2}$ hours by falling timber dislodged
by the high wind velocity which is the reason for the greatly increased
dune foot recession at this time. Again it is doubtful whether this had
any permanent influence upon the greatly different dune foot positions at
the end of the test. Despite this inconsistency it is still generally true
that the development in time of the dune recession follows a similar pattern
to that of the regular wave tests, thus indicating a general similarity in
the erosion process and/or a common influence of the initial offshore
profile. An attempt has been made to express the dune foot recession for wind
waves in dimensionless terms similar to those used for the regular wave
tests (section 5.21). In this case the dune foot recession relative to the
original still water line is divided by the square of the average central
period of the wind wave spectrum which is approximately the same as the
average period determined from the pen recorder chart. The number of waves
$\frac{t}{T}$ was obtained in a similar way. The deepwater wave steepness parameter $\frac{H_o}{T^2}$
was calculated using the same value of T as above and the deepwater wave
height of the equivalent sine wave with the same value of H_{rms} as the wind
waves. The data are plotted on figure 51 and, while not completely consistent,
do give some clarification as to what actually happens. Firstly it can be
seen that the relative dune foot recession is approximately the same for
tests T6 and T7 and for the first 10 000 waves of T8 before the dune was
disturbed as mentioned above.

The relative dune erosion is however significantly greater during most of the remainder of test T8. It is evident however that this difference is not a function of wave steepness since T8 has a smaller steepness than T6. Secondly the relative dune recession is greater than that for the regular waves at all times including equilibrium. This apparent contradiction with the direct plots of dune recession on figures 59 and 60 is due to the fact that the periods of both T7 and T6 are somewhat less than those of tests T22 and T23. Firstly it is evident, although the scatter is rather great, that for a given wave spectrum as defined by the wave steepness paramenter the relative dune foot recession is related to the number of waves by a similar form of relationship as for regular waves. A point which should be borne in mind with respect to the apparent discrepancy of the results from test T8 is that this test was made at a high wind velocity (see figure 10). It is therefore quite possible that there are wind effects which influence the amount of dune recession. Firstly the bottom return current resulting from direct wind stress on the water surface may assist in the removal of sand seawards in such a way that the inshore bar does not form to the same extent as in the other tests with the result that the wave runup is correspondingly greater. Data given in section 5.43 would seem to give some support to the smoothing out of the bar while figure 104 certainly indicates that the relative wave run up is greater for this test. Secondly the wave run up may be increased by the direct action of the wind as the uprush moves up the beach. Finally and possible more significant than either of the preceeding factors, the high velocity wind is very moist from spray blown off the wave crest which fact probably results in the dune face having a higher moisture content than with the lower wind velocities. The extra weight of this increased water content of the sand will increase the rate of collapse of the dune face due to instability. The extra sand thus placed within the reach of the waves is carried away relatively rapidly and so the dune recedes further than it would have if it were dryer.

5.42. Sand volumes eroded

The sand volumes eroded from the beach and dune during wind wave tests T6, T7 and T8 are given in table 5.42-1 below.

Comparison with the equivalent data from regular wave tests T22, T23 and T24 is difficult since complete data are not available for tests T22 and T23. Further the analysis of the latter results in section 5.22 showed that test T22 was inconsistent with the other tests, the amount of erosion being relatively too large when expressed by either of the two suggested dimensionless parameters. Thus a direct comparison is difficult.

TABLE 5.42-1

Total sand volume eroded from beach and dune for wind wave tests
$$(\text{metres}^3/\text{metre})$$

Test Number	Wave height H_{rms} -cm	Wave period T-sec	Time-hours								
			0.5	1	2.0	3.5	5.5	8	11	14.5	19
T6	9.4	1.11	0.034	0.038	0.082	0.070	0.132	0.164	0.130	0.158	0.149
T7	6.7	1.00	0.049	0.061	0.054	0.085	0.092	0.110	0.148	0.133	0.123
T8	11.2	1.29	0.152	0.178	0.202	0.243	0.291	0.331	0.385	0.419	0.452

In terms of absolute values of sand volume eroded, wind wave tests T7 and T6 give results of the same order of magnitude as regular wave tests T22 and T23. On the other hand wind wave test T8 gives erosion volumes approximately twice those of regular wave test T24. When the sand volume is expressed in either of the dimensionless forms used in section 5.22, $\dfrac{V}{H_o T^2}$ or $\dfrac{V}{T^4}$,

it is evident that the relative erosion volumes are quite different from one another as well as in general being greater than for the equivalent regular wave tests (figures 61 and 62).
Consideration of the values of the equivalent deepwater wave steepness (see section 5.41 for definition) of the wind tests yields no systematic trend such as was found for regular waves. Indeed the differences in steepness are relatively small and it is unlikely that they would result in such large differences in relative erosion.

One possibility is of course the effect of the wind itself and the wind induced circulation within the surf zone. This factor has already been suggested as a possible explanation for differences in the relative rate of dune foot recession (section 5.41) but it is obviously not the only factor influencing the relative sand volume eroded since the curves are not displaced systematically with respect to wind velocity. The low velocity test T7 in fact lies between the two others on both graphs (figures 61 and 62). Another possible effect influencing the relative erosion volumes due to wind waves is the wave irregularity, i.e. the wave height distribution. For simplicity this has been expressed in terms of the ratio $\frac{H_{50}}{H_{15}}$ where H_{50} is the wave height which is exceeded by 50% of the waves and H_{15} is the wave height exceeded by 15% of the waves in a given sample. The values given in table 5.42-2 for the wind wave tests do not in themselves indicate any trend consistent with the experimental curves. However in the light of the analysis of erosion volumes for regular waves of different heights and periods (section 5.22) where the relative erosion volume $\frac{V}{T^4}$ increased with wave steepness $\frac{H_o}{T^2}$ for a given number of waves $\frac{t}{T}$ and the general increase in dune foot recession with wind waves as compared with regular waves (section 5.41) it seems reasonable that increases in one or other or both $\frac{H_o}{T^2}$ and $\frac{H_{50}}{H_{15}}$ should result in increased relative dune erosion. Further as discussed in section 5.41 an increase in relative dune erosion can well be expected due to direct wind effects.

The determination of the relative importance of the influence of wave steepness, wave irregularity and wind velocity upon dimensionless erosion volumes is difficult since the data available are insufficient. However considering the data in table 5.42-2 below we see that no effect due to wave steepness is apparent which is to be expected since regular wave tests showed comparatively little influence of wave steepness above a certain value in most cases (figure 54). On the other hand the more irregular waves of test T7 have a relatively greater erosion than the more regular waves of test T6. However when we consider test T8 it appears that the effects of wind velocity are more important than those of wave inregularity. The picture is however not very clear and it is quite probable that neither of the parameters $\frac{V}{H_o T^2}$ or $\frac{V}{T^4}$ are very suitable for expressing the erosion due to wind waves.

TABLE 5.42-2

Variation of wave steepness, wave irregularity and wind velocity with relative erosion volume for wind wave tests

Test number	Relative erosion volume $\frac{V}{T^4}$ at $\frac{t}{T} = 5\times10^4$	Wave steepness $\frac{H_o}{T^2}$	Wave irregularity $\frac{H_{50}}{H_{15}}$	Wind velocity metres/sec
T6	0.113	11.6	0.71	16.1
T7	0.126	9.9	0.76	11.6
T8	0.166	10.5	0.77	21.6

5.43. Profile changes and development of equilibrium profile

The final profiles for the three wind wave tests T7, T6 and T8 are given on figure 63 and compared with their equivalent regular wave profile on figure 64 to 66. The principle features of the wind wave profiles in comparison with the regular wave ones are rather difficult to deduce. However the following can be observed. Firstly, the beach slope is substantially the same for both wind and regular waves. This conclusion is based upon average values calculated from individual profiles. These are given in table 5.63-1 and show a slope of 1 to 5 or somewhat flatter in all cases. Since the dune foot rededes further with wind waves it is apparent that if the beach slope is unaffected, the dune foot must be higher with wind waves than with regular waves. This question is discussed further in section 5.63 on wave run-up. Secondly sand is moved further seaward with the wind waves and the profile slope offshore of the breakpoint is flatter than with regular waves. This is presumabely due to two factors. In the first case some of the individual waves are higher than the regular wave height and thus influence the bottom at greater depths. Since these waves will be the ones which break before the main break point they will tend to cause a seaward bottom current to compensate for the landward movement at the surface due to the breaking wave.

This current will presumably assist in moving sand further seaward.
The second factor is the seaward return current due to wind stress upon
the water surface which will likewise assist offshore sand transport.
Velocity measurements during these tests confirmed that such a seaward
drift was present (see section 5.64). Thirdly it is difficult to draw
any conclusions with respect to the position and formation of bars in
these tests from the average profiles shown. However comparison of individual
profiles indicated that bars were much less prominent in the wind wave
profiles than in the regular waves ones (figures 67 and 68). Both tests
T7 and T6 show a tendency for one bar to form at the main break point
as is the case for their corresponding regular wave tests T22 and T23.
On the other hand test T8 shows two distinct bars which is consistent
with the tendency to form several bars shown in test T24. Their location
is however out of phase with those of the latter test. Finally the general
slope of the wind wave profile within the surf zone is similar to that
of the corresponding regular wave profile, i.e. about 1 in 15 for tests
T7 and T6 and about 1 in 22 for test T8.

5.44. Transport rates during profile development

Comparison of the net seaward transport rates for tests T24 (regular waves)
and T8 (wind waves) indicates that there are both differences and
similarities between the two which is in general agreement with the results
for both dune foot and water line recession and the equilibrium profiles
(sections 5.41 and 5.43). Both tests show an initially high transport rate
over almost all the profile as was the case with tests T17 and T26
(section 5.14) although this peak rate is very much higher for the wind
wave test T8 (figures 69 and 70). Both tests also show a minimum in transport
rate at $1\frac{1}{2}$ hours or a little earlier between 2 and 5 metres, the reason
for which is not clear, although it may be due to the temporary build
up of the bar close inshore at about 3.5 metres (figures 74 and 76).
There is also a corresponding lull in dune recession about this time
(figure 60). Landward transport occurs offshore of 9 metres in test T24
and 7 metres in test T8 at about 3/4 hour due possibly to a temporary
reduction in reflection.

There is also a tendency at certain times for the transport to be land-
ward between the initial breakpoint at 7 to 7.5 metres and the main break-
point at 4 to 5 metres in both tests (figures 73 and 72) due presumably
to a predominance of bottom mass transport currents over the rather weak
spilling breakers. This effect is also evident offshore of 10 metres
during wind wave test T8.

Between 2 and $5\frac{1}{2}$ hours the crest of the main bar in regular wave test
T24 shifts from $3\frac{1}{2}$ to $4\frac{1}{2}$ metres (figures 74 and 75) while at the same
time the transport rate remains more or less constant across the surf zone
to the main breakpoint on this bar (figure 72). After the early stages
of the test maximum seaward transport generally occurs at the main break-
point with both wind and regular waves (figures 72 to 77), the seaward
moving sand then being deposited on the outer face of the bar extending
it in a seaward direction. Seaward transport at the initial breakpoint
for the regular waves is at all times quite small (figure 72). The
transport rates do not seem to shed any light upon the temporary pause
in water line recession for both wind and regular waves between $3\frac{1}{2}$ and
8 hours (figure 60) although this is probably associated with a build
up of the main bar with somewhat increased reflection. However the tendency
for the water line to move seaward again at the end of the wind wave test
(figure 60) while at the same time the dune foot is clearly receeding is
shown to be due to the inability of the waves to remove this new supply
of sand further seaward since the transport rate is a maximum between
these two points at this time (figure 73).

5.45. Summary

There is no consistent difference in the recession of the storm surge
water line for wind waves as compared with regular waves. The recession
of the dune foot is however consistently greater for wind waves with the
same energy and a central spectral period equal to that of the regular
waves. It is probable that dune erosion with wind waves is also a
function of the wave irregularity and the wind velocity. The beach slope
above storm surge water level is not significantly different for wind
waves but the height of the dune foot is higher than for regular waves.
The general profile slope within the surf zone is also much the same for
both types of wave. Regular waves however tend to show more pronounced bars
within the surf zone while wind waves transport sand further seaward offshore
of the breakpoint. Transport rates are generally greater for wind waves in
agreement with their greater dune erosion. Variations in the transport rates
are in many cases similar in tendency for wind and regular waves.

5.5. <u>Influence of Sand Size upon Erosion and Profile Development</u>

5.51 <u>Waterline and Dune foot recession</u>

It has been suggested that dune erosion might be greater if the size of
the sand were reduced since greater quantities of sand would be moved in
suspension and transported further offshore. The results of test T 25 in
which the median sand size was 0.15 mm. are given in table 5.51-1 below
and compared with those of test TO (where the median sand size was 0.22 mm.)
on the upper part of figure 78.

TABLE 5.51-1

Dune recession with fine sand-test T 25

(metres)

	Sand Size	Dune Height	Time-hours								
	mm.	cm	$\frac{1}{2}$	1	2	$3\frac{1}{2}$	$5\frac{1}{2}$	8	11	$14\frac{1}{2}$	1 9
Water Line Recession	0.15	40	0.13	0.21	0.27	0.42	0.50	0.58	0.64	0.61	0.51
Dune Foot Recession	"	40	0.49	0.60	0.74	0.81	0.92	0.99	1.09	1.16	1.17

It is immediately obvious that the dune recession is not increased with the
finer sand, indeed the opposite effect occurs and the dune foot does not
recede quite so far. The water line recession is much the same up to $5\frac{1}{2}$
hours after which the water line of the coarser sand test recedes rapidly
to an approximate equilibrium at 11 hours. In the case of the fine sand however
the water line recession reaches a maximum at 11 hours and then moves
seawards again. Reasons for this behaviour are suggested in section 5.53.
For the present it should be noted that the difference in water line
recession for the two different sand sizes between 8 and 11 hours is not
so marked if test TO' is considered instead of test TO (see table 5.21-1).

5.52 <u>Sand Volumes eroded</u>

Consideration of the total volumes of sand eroded from the beach and dune
for test T 25 (table 5.52-1) in comparison with those obtained for the

coarser sand test TO (table 5.22-1) indicates that these are substantially the same up to 11 hours. This would seem to imply that as the dune foot is slightly nearer the water line in test T 25 (fine sand) that either more sand is eroded from below the water level in this case or that the dune face has a somewhat flatter slope. After 11 hours the erosion volume remains sensibly constant for the fine sand which means that at the end of the test it is 10 to 15 % less than for the coarse sand. This appears to be largely due to the build out of the beach as indicated by the seaward movement of the water line. As discussed in section 5.54 this is apparently due to the transport of sand from the surf zone back to the beach.

TABLE 5.52-1

Total volume of sand eroded from beach and dune with fine sand T25

$$\text{(metres}^3\text{/metre)}$$

Sand Size mm.	Dune Height cm	Time—hours								
		$\frac{1}{2}$	1	2	$3\frac{1}{2}$	$5\frac{1}{2}$	8	11	$14\frac{1}{2}$	19
0.15	40	0.073	0.122	0.188	0.207	0.253	0.302	0.336	0.347	0.342

5.53 <u>Profile Changes and Development of Equilibrium Profile</u>

The various profiles obtained during test T 25 with fine sand are given on figures 79 to 87. In this case both the average and individual profiles at each time are shown. The full significance of the profiles and an explanation of their behaviour are given in section 5.61. For the moment it is sufficient to note that they show very clearly the build up of the inner bar in the surf zone between 3 and 4 metres in the early stages of the test together with its subsequent partial disappearance after $3\frac{1}{2}$ hours as sand is moved further seaward. Also very prominent is the build up of the outer bar at 8.5 metres which occurs between 8 and 11 hours during which time the inner bar becomes relatively insignificant. This corresponds to the development of full plunging breakers at this position with a consequent increase in the relative amount of energy

dissipated in the outer section of the surf zone. The residual waves
in the inner surf zone thus become smaller, dune erosion ceases
(figure 78) and the beach tends to move seaward again. Visual observations
of wave run up indicated that after 11 hours the waves did not reach the
dune foot. When we compare the equilibrium profiles for tests T 25
(0.15 mm. sand) and test TO (0.22 mm. sand) shown on figure 88, several
differences are evident, although the general overall trend of the
profiles is similar. The most obvious difference is that with the finer
sand the outer bar is much larger and its crest is located slightly closer
to the shore. Secondly the dry beach slope is much flatter with the
finer sand being 1 in 9.5 compared with 1 in 5.5 for the coarser sand.
Further with the fine sand this slope extends right down to the normal
water level while with the coarse sand there is a change in slope just
below storm surge bevel to a flatter slope of about 1 to 15. This
difference is of course associated with the build out of the beach during
the latter stages of test T25 (fine sand) which does not occur during
test TO. On the other hand the change in slope just below storm surge
water line which is evident in most other tests with the same wave
conditions also appears to be present during the earlier stages of the
fine sand test where the beach slope above the water line is of the
same order of magnitude as for the coarser sand, ie, on the average 1 in
5 or 1 in 5.5.

Seaward of the normal water line the general slopes with the two sands
are much the same. For instance the average slope between the normal water
line and the bar trough is of the order of 1 in 20 or 1 in 21 in both
cases although this slope is rather hard to define. On the seaward face
of the outer bar the average slope is 1 in 8.5 and this portion of the
profile lies at the same position in both tests. Further seaward there
are differences in the location of the minor bars which after consideration
of the profiles for the same wave conditions and sand sizes given on
figures 5 and 6 could well be due to differences rising from the different
test situations accentuated by differences in the initial profile as
actually built in the model.

5.54 Transport Rates during Profile Development

The net seaward sand transport rate during test T25 is shown on figure
89 as a function of time at a given point and on figure 90 as a function
of distance at times corresponding to the profile measurements. The curves
show a general similarity to those obtained for tests T17 and T26 (figures
42 to 46) as well as some significant differences. Firstly while the
initial high rate of sand transport is not as great, it is however
relatively wider, ie, the initial erosion is spread over a somewhat
larger period of time. Such a difference is not unexpected since the
sand dune heights are different as well as the sand sizes. At all points
there is sharp reduction in transport rate either at or before 2 hours.
At points offshore of the outer bar, ie, 11 metres and further, the
transport becomes landward for some time in the vicinity of three hours.
As explained further in section 5.61 this is related to a reduction in
wave reflection probably associated with a temporary disappearance of the
inner bar, which phenomenon reduced the sand supply passing the outer bar
and allowed the landward dominant mass transport currents to assert
themselves.

After 4 hours there is an increase in transport rate at most points between
4 and 11 metrs indicating increased sand movement between the inner and
outer bars (figure 89). The curves showing the transport along the
profile at $5\frac{1}{2}$ and 8 hours (figure 90) also clearly indicate that the
transport rate increases significantly from about $5\frac{1}{2}$ metres to 8 metres
after which it reduces again due to deposition resulting in the build up
of the outer bar (see section 5.53).

In the latter stages of the test small landward transports are found to
occur seaward of the outer bar for the same reason as given above for
this phenomenon at 3 hours and also at 2 metres which is the result of
the reduction of residual surf zone wave height due to the build up of
the outer bar (see section 5.53).

This latter reversal of transport direction being located seawards of the
actual water line shows that the build up of the beach during the last 8
hours of the test is caused by transport of sand back from the surf zone
and not by sand eroded from the sand dune.

5.55 Summary

The dune foot recession and the volume of sand eroded is not quite as great with the fine sand as with the coarser sand due to the seaward movement of the storm surge water line during the latter part of the test. The beach slope at equilibrium is flatter (1 in $9\frac{1}{2}$) with fine sand than with coarse sand (1 in $5\frac{1}{2}$).

The reason for the above behaviour appears to be associated with the greater mobility of the fine sand which results in the outer bar being much higher and dissipating more wave energy. This results in smaller wave heights at the shoreward end of the surf zone and a consequent retransport of sand landward causing the build out of the beach.

Dune erosion in this situation is definitely limited by build up of the break point bar.

5.6 Other Factors influencing Erosion and Profile Development

5.61 Wave reflection and bar development

During most tests made in the wind flume and the small basin incident wave heights and reflection coefficients were measured at half hourly intervals. From these measurements it immediately became evident that while the incident wave height remained sensibly constant during the tests* the reflection coefficient varied quite markedly in an apparently systematic manner. The general pattern of this variation was the same in each test with relatively low values to begin with, followed by a sharp increase in reflection to a value which very often exceeded 20% and sometimes reached 30%. The duration of these very high reflection coefficients varied from test to test but in all cases they eventually decreased again to a comparatively low value at the end of the test as equilibrium was approached. Indeed the attainment of a relatively constant low reflection coefficient appeared to be one of the criteria for reaching equilibrium conditions.

* Significant changes in incident wave height ($\pm$ 12%) occurred in test T19, the reasons for which are not known.

The variation in wave reflection is presumably to be explained in
terms of the processes occurring during the development of the
equilibrium situation. Since there are wide variations in the rates
of dune erosion etc, it is not surprising that there are wide variations
in reflection coefficient changes (figure 91). Changes in the reflection
coefficient thus indicate at best in some degree the interaction which
occurs between the waves and the bottom profile. This general question
will be discussed in terms of the results of test T25, the last test
made in the small outside flume, for which the greatest amount of
simultaneous information is avaible. The relevant data are presented
on figures 92 and 79 to 87.

At the commence of the test the waves initially commence to break (in
a spilling form) at 7.2 metres where the depth is about 30 cm. In this
position it is the wave steepness and the amount of reflection which
primarily influences the breaking. The major portion of the wave
energy is however maintained until the wave reaches the final steep
slope of the initial profile where the wave is transformed into a
shoreward moving bore which rapidly erodes the beach and dune causing
the very high initial transport rates. The sand eroded during this
period is deposited immediately seaward of the water line at the end
of the surf zone and is rapidly formed by the waves into a bar located
between 3 and 4 metres. This is what has been referred to previously
as the inner bar. The formation of this bar is accompanied by the
development of a roller or inner breaker of the plunging type.

The steep seaward face of this inner bar ($\tan \alpha = 0.25$, ie, 1 in 4),
augmented by its increase in height now results in an increasing
amount of wave energy being reflected (fig. 92 a), the initial value
of 5% being more than trebled just before 2 hours. At the same time
the initial breakpoint tends to move seaward particularly along the
centre line of the flume (profile 3) where the reflection measurements were
made. At this stage some new factor, possibly a rip current in the
centre of the flume, caused by a relative reduction of wave heights
in the surf zone which in turn results from the seawards shift of the
initial breakpoint, alters the form of the inner bar, particularly
in the centre of the flume, in such a way as to reduce the wave

reflection which falls to 7% at about 3 hours. The seaward slope of
the inner bar is now 1 in 15 (tan α = 0.067). A shoreward movement
of the initial breakpoint which is particularly marked at the centre
line of the flume now occurs (figure 92 b). Even more remarkable
is the distinct reversal of the direction of sand transport in the
offshore section of the profile at 11 metres and further seaward
(figure 89). Earlier the combination of high sand transport rates
together with high reflection had resulted in seaward sand transport
over the whole profile. Now the amount of sand in suspension seaward
of the outer bar region is significantly reduced and the landward
transport due to the bottom mass transport current predominates
and moves sand towards the outer bar region from further offshore.
This last process is all the more remarkable when it is remembered
that the sand transport rates are calculated from average values
over all five profiles while the large change in initial breakpoint
position occurs only on the centre profile.
This phase however does not last very long since the landward shift
of breakpoint on the centre line cancels out the conditions favourable
to the development of a rip current, if in fact one did occur, and
the inner bar tends to reform to some extent. Reflection now
increases again (at about 4 hours) and the initial breakpoint moves
seaward at all points across the flume. This is due to the build
up of the outer bar, which is apparent on the profiles measured at
$3\frac{1}{2}$ hours. While the direct evidence is lacking it is probable
that this was accelerated by the previously postulated rip current.
The initial breakpoint now stabilises at 7.8 metres or a little
further seaward at the centre line with breakers of the plunging
type predominating. The outer bar continues to build up steadily
in a seaward direction between $3\frac{1}{2}$ and 8 hours (figures 82 and 84).
There is comparatively little change in its height during this
period but conditions become increasingly favourable for the development
of plunging breakers on this bar. As a result more energy is dissipated
in this zone, reflection steadly diminishes and the inner bar tends
to disappear with the formation of a continuous surf zone.

Complete development of plunging breakers is achieved at 10 hours
when the initial breakpoint reaches its most seaward position at
8.2 metres and comparatively rapid build up of the outer bar follows
(figure 85). Net sand transport rates are now quite small in most
parts of the profile and landward sand movement is again evident from
11 metres seaward (figure 89). The reflection is now fairly constant
oscillating irregular between 5 and 8 %, ie, has the same order of
magnitude as at 3 hours when strong landward transport occurred. The
reason for the very great difference in magnitude of landward net
transport on these two occasions when the hydraulic conditions were
apparently similar may possibly be due to the fact that the initial
high seaward transport deposited a relatively large amount of material
in this zone which resulted in a significant change in profile from the
equilibrium condition. This was corrected fairly rapidly during the
hour or so of landward movement between 2 and 4 hours. Such an oversupply
was not present during the latter stages of the test and consequently
the landward transport is comparatively small.

A further important consequence of the development of the outer bar
and the increased energy dissipation in this zone is the cessation
of landward movement of the waterline which occurs at this time
(11 hours). An apparent equilibrium condition has been reached with a
profile that is essentially two dimensional. However the situation
is not completely stable as the dune foot continues to recede until
15 hours and the water line moves seaward again, due to transport of sand
both from the sand dune and from the inner part of the surf zone.
This can be seen from figure 89 where after 13 hours landward transport
occurs at 2 metres while seaward transport is occurring at 1 metre.
The waterline is roughly half way in between. Consideration of the
profiles (figure 86) shows that at $14\frac{1}{2}$ hours the outer bar is no longer
at right angles to the wave crests while observation in the model
indicated that the beach had been built seawards in the centre of the
flume by sand eroded from the dune at the sides. The exact reason
for this three dimensional development is not known although there
was obviously a tendency for a rip current to form in the centre of
the flume.

When we consider the reflection during tests TO,TO', T4 and T19

we find a somewhat different picture (figure 91). While it is difficult
to draw firm conclusions since the individual profiles were not
completely plotted for these tests it is apparent that the influence
of the inner bar was appreciable over a much longer part of these
tests. This presumably reflects the fact that the sand was somewhat
larger in these tests and was not transported so rapidly from the inner
bar to the outer bar. The outer bar is certainly smaller in test TO
(figure 88) than in test T25 where the wave height was the same. The
same factors apply to tests T4 and T19 together with the additional
one that since the wave height was lower, the proportion of wave
energy dissipated by a plunging roller in the 3 to 4 metre zone was
very much greater. Indeed in test T19 no breaking in spilling form occurred
in the outer bar area even though an outer bar was present. This was
also the situation in test T20.
The situation is again somewhat different when tests T22, T23 and T24
are considered (figures 93 and 94). In tests T22 and T23 the waves
break initially as plunging breakers and the break point moves seaward
as the bar presumably builds up between 3 and 4 metres[*]. Reflection
increases to a maximum in both cases somewhere in the vicinity of
7 hours and is accompanied by a temporary halt to the recession of both
the dune foot and the water line. The bar is presumably acting in
the same manner as the outer bar did in the latter stages of test T25
although in this case it appears that the reduction in wave height
inshore of the bar is due more to reflection of the wave rather than
its dissipation. This situation is however not a stable one as the bar
is apparently destroyed and/or sufficient sand is deposited seaward
of it to reduce the reflection. Consequently dune erosion recommences.
In test T22 this process is followed by the development of spilling
breakers with a relatively constant reflection of the order of 6% at
$9\frac{1}{2}$ hours followed by dune erosion stability at about 12 hours. On the
other hand test T23 shows an additional minimum and maximum of reflection
together with an associated temporary cessation of dune recession

[*] There are no profile measurements to substantiate this point.
Levellings were made only at 11 and 19 hours.

before the onset of spilling breakers. A somewhat similar situation
occurs in test T24 (data not shown) except that there is an initial
breakpoint with spilling breakers between 7 and $7\frac{1}{2}$ metres at all times
and a main breakpoint further inshore whose position shifts seaward
from $3\frac{1}{2}$ metres at the commencement of the test to 5.2 metres at its
end.

This process of interaction between breakers, reflection and bar
formation has also been described by Eagleson, Glenne and Dracup
(Reference 7). In their experience the equilibrium situation was always
associated with spilling breakers and small reflection. The above
observations are in agreement with this for tests T22, T23 and T24 but
not for test T25 where equilibrium is associated with plunging breakers
on the outer bar. Thus the statement of the above mentioned authors
that the process "appears to be independent of the incident wave and
initial slope" may have to be modified.

The sensitivity of the transport rate and direction offshore of the
breaker zone to changes in reflection has also been noted by Vincent
(reference 49) who has remarked that "the vertical distribution of
the transporting current appears to be highly sensitive to the
"purity of the waves".

Finally the question arises as to how relevant are changes in reflection
for a prototype situation where the slopes are of the order of five
times flatter. Obviously reflection will not be nearly so great and so
care must be taken in not attaching too much importance to this
phenomenon without first confirming its relevance in prototype which
will be extremely difficult. Perhaps the principal interest of these
results is that they indicate one of the possible scale effects which
must be accounted for in transferring the model results to the prototype.

5.62 Wave characteristics in the surf zone

5.6.2.1. Regular waves

It is generally known that the breaking of waves in shallow water is

affected by a number of factors (references 16, 20, 28, 33 and 37). These include the wave steepness $(\frac{H}{L})$, the relative wave height or breaker index $(\frac{H}{D})$, the bottom slope, wave reflection, currents such as rip currents, bottom roughness and backwash velocity.

In an equilibrium beach profile all these factors are delicately balanced so that there is no net sand transport in either direction at any point. Further the energy dissipation process within the surf zone determines the height of the final wave which causes the wave run up on the dry beach. The magnitude of this final run up determines both the ultimate limit of the dune recession at equilibrium as well as the actual recession at any given time during the development of equilibrium.

Following the completion of test T18 in the small outside basin some measurements of wave heights within the surf zone in an apparently equilibrium situation were made along three profiles. The actual wave heights and the bottom profiles at the time of measurements are shown on figures 95 to 97. Attempts were also made to determine the wave length from plots of the instantaneous water surface profile. However the effects of reflection and bottom topography variations were such that the results, while giving values of the same order of magnitude as 1st order theory with some increase in wave length in shallow water in general agreement with 3rd order theory, were not sufficiently consistent for practical use. Subsequent analysis was therefore made using wave lengths calculated from the usual 1st order linear theory. It can immediately be seen that for a given profile which includes the effects of bottom slope, reflection, backwash velocity, etc, to a greater or lesser degree, the principal factors are the two parameters defining the wave characteristics, the wave steepness $(\frac{H}{L})$ and the breaker index $(\frac{H}{D})$. A plot of the measured data in terms of these two parameters can therefore be expected to yield interesting results perhaps analogous to those published by Danel (reference 4) for waves upon a flat bottom. However since in this case we are dealing with the surf zone where the effects of the breaker index $(\frac{H}{D})$ are likely to predominate it appears better to replace the wave steepness $(\frac{H}{L})$ by the relative depth $(\frac{D}{L})$ or more conveniently its reciprocal $(\frac{L}{D})$ which

facilitates comparison with theoretical limiting curves proposed by Druet
(reference 6). Accordingly the wave heights along the three profiles
were plotted in terms of $\frac{H}{D}$ and $\frac{L}{D}$ (figures 98 and 99), taking values
at 0.5 metre intervals with 0.1 metre intervals when conditions changed
significantly. The results are interesting. As the wave travels from
the offshore section of the profile the relative wave height, $(\frac{H}{D})$
increases due to the sharp decrease in depth at the outer bar.
At profiles 1 and 3 where there is a definite bar at 9 metres, $\frac{H}{D}$ reaches
a maximum of about 0.65 after which it reduces sharply as the wave
crosses the through landward of the bar. Unfortunately the exact point
of breaking was not observed at the time of the measurements but
observations a few hours earlier when the profiles had apparently
reached equilibrium showed that the breakpoint was located somewhat
further landward at about 8.3 metres. After crossing the trough
where $\frac{H}{D}$ is comparatively low, ie 0.3 to 0.4, which is the same order
of magnitude as offshore of the outer bar, the value of $\frac{H}{D}$ again
increases to a maximum in the vicinity of 5 m. This time there are
differences between the two profiles. At profile 1 the second
breakpoint is located right on the inner bar and $\frac{H}{D}$ has a maximum
value of 0.9. At profile 3 the bar is located somewhat further inshore
and it appears that breaking is initiated by reflection from the inner
bar. $\frac{H}{D}$ is only slightly higher than at the outer bar, ie 0,68, and
it appears that the de struction of wave energy has not been nearly
so complete, which fact appears to be confirmed by a third smaller
bar further inshore outside the limits of wave height measurements. In
the case of profile 5 where there is no outer bar, the picture is
rather different. The relative wave height $\frac{H}{D}$ increases steadily from
a value of 0.4 on the offshore section of the profile up to 0.9
at 7 metres where breaking occurs and an appreciable portion of the
energy is dissipated. Thereafter $\frac{H}{D}$ remains comparatively constant
between 0.5 to 0.6 as the wave travels over a fairly smooth curved bottom.
 However the wave height varies quite a lot apparently due to reflection from
the beach and the small bar at the end of the surf zone.
On each of the figures 98 and 99 for the three profiles are shown the
theoretical limiting curves for a level bottom proposed by Druet
(reference 6). These are shown for zero, 10% and 100% reflection and

refer to values of $\frac{H}{D}$ calculated using the incident wave height. Thus
to compare the present measurements which are calculated from actual
wave heights including reflection we must multiply the theoretical
values of $\frac{H}{D}$ by 1 + R/100 where R is the reflection coefficient expressed
as a percentage. A rough comparison of $\frac{H}{D}$ values at both breakpoints
on profile 3 and the first breakpoint on profile 1 indicates the model
measurements are somewhat low even when the measured reflection of 6 to 7 %
is taken into account. However the difference is not serious since the
theoretical curves make no allowance for bottom slope etc. The higher
values of $\frac{H}{D}$ observed at the inner breakpoint on profile 1 and the main
breakpoint on profile 5 are consistent with theoretical reflections
between 10 and 50 %. These are somewhat high when compared with experimental
reflection coefficients for similar slopes and wave conditions
(e.g. those of Greslou and Mahe for smooth slopes-reference 12) and
the effects of bottom slope which include backwash effects are undoubtedly
important as has been shown by various inivestigators (references 16
and
to 20). Thus it may be concluded in agreement with Horikawa and Kuo
(reference 16) that the theoretical limiting condition for a solitary
wave on a level bottom H = 0.78 D does not express the wave height
within the surf zone. Thus should it be desired to use the theoretical
calculation of wave run up of Le Méhauté (reference 29) which is
based upon this condition, for the estimation of dune recession due to
wave runup in various situations, it will be necessary to reconsider
the assumed breaking conditions. Another factor which may be relevant
in surf zone dynamics is the variation in mean water level which occurs
due to second order effects as a wave is propagated into shallow water.
Attention has been drawn to this phenomenon by Longuet-Higgins and
Stewart (reference 31) who have discussed it in terms of " radiation
stresses " and Lundgren (reference 32) who uses the terms " wave thrust
and energy level ".
Basically what occurs is that as the waves travel shoreward there is a
change in momentum due to the relative increase in kinetic energy
compared with potential energy (the two are equal in deep water).
In the absence of energy dissipation the force

due to this change in momentum or the wave thrust is balanced by a change in hydrostatic pressure, i.e. in water depth. Since the momentum increases in a landward direction, the difference in the wave thrust exerted on a given fluid section is seaward in direction which means that the balancing hydrostatic pressure can only be produced by a fall in mean water level as the waves approach the shore. From energy considerations (Bernoulli equation) it is possible to derive an expression for the wave energy level Y_E referred to the bottom which is analogous to the specific energy of open channel flow. This expression is (reference 32)

$$Y_E = D + \frac{H^2}{16D} \frac{2D'}{\sinh 2D'} \qquad (5.621\ a)$$

where $D' = \frac{2 \pi D}{L}$

In deep water

$$Y_E = D \qquad (5.621\ b)$$

and in swallow water

$$Y_E = D + \frac{H^2}{16D} \qquad (5.621\ o)$$

Now if the energy level remains constant, i.e. there is no dissipation, and if it is assumed to be equal to the still water depth in deep water, the change in mean water level h as the wave travels into shoaling water is given by the equation

$$h = - (Y_E - D) \qquad (5.621\ d)$$

where h is positive upwards from the deepwater still water level. Whence

$$h = - \frac{H^2}{16D} \frac{2D'}{\sinh 2D'} \qquad (5.621\ e)$$

In the surf zone we have

$$h = - Y_E + D + h_L = - \frac{H^2_M}{16D} \frac{2D'}{\sinh 2D'} \qquad (5.621\ f)$$

where h_L is the change in energy level due to surf zone dissipation and H_M is the actual measured wave height.

The value of h_L can be estimated by calculating the theoretical water level
change when the deepwater wave height, modified by shoaling effects, H_1 is
inserted in equation 5.621 e and the resulting value of h compared with
that from equation 5.621 f. These two values have been **calculated for each**
of the three profiles for which wave height data were available within
the surf zone and plotted on figures 95 to 97. In each case it is seen
that there is very little energy dissipation on the outer bar face where
the wave height must obviously obey the usual shoaling conditions. This
situation occurs right up to the initial breakpoint, where the mean water
level reaches its lowest point. In profiles 1 and 3 both the theoretical
and "actual" mean water levels rise again after passing the outer bar.
The theoretical level however does not rise as much as the actual level,
thus indicating that there has been some energy dissipation. However this
dissipation may not be as great as it first appears since, if any of the
energy is reflected seawards at the bar, this will accentuate the water
level rise by decreasing the momentum change still further. For profile
3 this effect has been calculated assuming that all the 7% reflection occurs
at this bar using the formula of Longuet-Higgins (reference 30) which is
identical in form with that of Lundgren quoted above. The result (figure
96) which amounts to assuming a discrete energy loss or wave height reduction
at the bar crest indicates that for this particular profile relatively
little energy is lost in the vicinity of the outer bar. On the other hand
considerable energy losses are indicated over the inner bars and at the
main breakpoint on profile 5. Of course such calculations are highly suspect
since once the waves break conditions are changed and the basic theory
upon which the change in mean level is based no longer applies. There are
however some interesting tendencies. Firstly it will be noted that in each
case the mean level in the outer bar trough and also landward of the inner
breakpoints is substantially the same as the model offshore still water
level which is about 2 mm lower than it would have been if the model
extended to deep water conditions. Secondly there is a gradient of mean
water level directed downwards on either side of a bar crest or breakpoint.
These gradients are in the opposite direction to the bottom slopes of the
bar. Thus we have at the bar a situation somewhat analogous to that which
occurs at a weir or other submerged construction within an open channel.

If the waves do not break upon the bar we have a situation similar to a
submerged weir where the flow passes with an increase in kinetic energy
but with comparatively little energy loss. This appears to be the case
for the outer bar of profile 3. On the other hand if the wave breaks forming
a wave of translation or bore, as is evidently the case for the inner
bars of profiles 1 and 3 and possibly in a more gradual manner for the
mean breakpoint of profile 5, then we have a situation some what akin to
the conditions occurring at a control weir where the flow passes through
critical depth. For in this situation if the water particle velocity
exceeds that of the wave form itself, which is what is generally assumed
to occur at breaking, then no reflected wave can be propagated seaward
past the breaker zone and the breakpoint bar indeed becomes a control
point[*]. The significance of this with respect to the formation of equilibrium
profiles is not at this stage completely clear since there are no
measurements of wave heights within the surf zone for profiles which are
very much different from the equilibrium condition. However it is suggested
that these would show a very large change in water level at the inner
surf zone plunge point with considerable energy dissipation and a sharp
rise in water level on the landward side due to the change in momentum
force both on account of energy dissipation and reflection from the seaward
face of the bar. Under these conditions the mean water level on the land-
ward side of the bar would be greater than that on its seaward side and
there would be a strong tendency for this water to force its way seaward
along the bottom, since the surface layers would be predominately landward moving
due to the breaking process, either in the form of rip currents or as an
undertow which would accelerate seaward transport.[**]

[*] This can only be true for a relatively complete break such as presumably
occurs with plunging breakers. Where partial breaking (spilling breakers?)
occurs the control is not complete and reflected waves travel offshore
from the surf zone as the discussion in section 5.61 indicates.

[**]Measurements by Galvin and Eagleson (reference 10) of mean water level
landward of the breakers in a fixed bed model with a plane beach definitely
indicate that the water level rises in this zone. Such an increase in
level is the basis of the wave current or lateral expansion current of
Irribarren (reference 19) which occurs in the lee of breakwaters and head-
lands (also Gourlay reference 11).

5.62.2 Wind Waves

From wave height measurements made during wind wave tests T6, T7 and T8 it has been possible to derive some information concerning the **interrelation between wave height, wave period and water depth for wind waves.**

At the offshore position H2 (figure 10 b) the values of To, T mean, Hmax, H_{15}, H_{50}, Hrms and $\frac{H50}{H15}$ as well as depth D which is virtually constant, were averaged over the full length of each test. In most cases there is very little trend in the values over the test period although there is some small evidence that the change in reflection point with dune erosion together with possible changes in the reflection coefficient has affected the magnitudes of the wave heights. This certainly appears to be the case in T8 where the general average value of the wave heights differs by about 10% between the beginning and end of the test (figure 100). At the inshore position H1, the same method of averaging values over the whole test was used in tests T7 and T6 where the water depth does not change significantly at this point.

In above way 5 points were obtained, each point being the result of averaging approximately 38 individual measurements.

At point H1 in T8 a different method was used since the water depth varies significantly during the test from 29 to 18 cm approx (figure 101). In this case a mean line was drawn through the measured points indicating the general trend with time. The wave heights and corresponding depths were then read from these mean lines at two hourly intervals. Thus a further 10 points were obtained, each point representing an average of 3 to 4 individual measurements. For each of the 15 wave height points so obtained, the wave length was calculated using the average period from the wave recordings, T_{mean}. As in every case no discernible trends with time at a given point were found where values of T_{mean} were used. Then for each wave height (Hmax, H_{15}, H_{50}, Hrms) using the appropriate wave length, the dimensionless ratios $\frac{D}{L}$, $\frac{L}{D}$, $\frac{H}{D}$ and $\frac{H}{L}$ were calculated. The data are plotted on figure 102 in two different graphs. In the upper one H/D is plotted as a function of L/D while on the lower H/L is plotted as a function of D/L.

The first presentation emphasises the shallow water conditions which are
mainly dependent upon H/D while the second emphasises the deep water
situation which is mainly dependent upon H/L. In both cases it is evident
that for each wave height (ie Hmax, etc.) both the shallow water parameter
$\frac{H}{D}$ and the deep water one $\frac{H}{L}$ tend to a constant value depending upon the
L/D or D/L. In shallow water $\frac{L}{D} > 7$ or D/L < 0.15), the relative wave height
H/D tends to the values given in table 5.62.2-1 below. There is however
some scatter or rather a trend in the points due to reflection, similar
to that obtained with regular waves during dune erosion (section 4.22
and figure 8).

TABLE 5.62.2-1

Wave height-water depth ratios for wind waves in shallow water

Wave height	$\frac{H}{D}$
$H_{max_{500}}$	0.75
H_{15}	0.52
H_{50}	0.41
H_{rms}	0.25

The value of H/D for Hmax approaches 0.78, the theoretical value for
a solitary wave on a level bottom. Individual values of Hmax give
somewhat higher values of H/D which are none the less reasonable
when the effects of both refelection and bottom slope upon the limiting
wave height are considered. For deep water (normally D/L > 0.5 although
in this case 0.3 seems to be sufficient) the limiting wave steepness values
are given in table 5.62.2-2. Thus it can be seen that the limiting steepness
for the maximum wave height approaches the theoretical value of 0.143
for waves in deep water.

TABLE 5.62.2-2

Wave steepness ratios for wind waves in deep water

Wave Height	$\dfrac{H}{L}$
$H_{max_{500}}$	0.135
H_{15}	0.094
H_{50}	0.067
H_{rms}	0.047

Individual maximum values, not shown on the figure, agree more
closely with this limit and may even be somewhat higher, either due to
reflection or to the fact that the wave length of the particular wave con-
cerned is greater than the average value.

Another significant fact which is revealed in figure 102 particularly
in the graph of H/L versus D/L is that the value of the limiting steepness
in deep water is affected by the wave height distribution or wave
height variability. Values of H_{50}/H_{15} indicated on the graph show that
the limiting wave steepness is lower when the waves become more irregular.
The difference is not very great for the average maximum wave height and
presumably no such difference exists when actual maximum waves of limiting
steepness are considered. It is however quite appreciable for H_{50} where
a 5 or 6% difference in H_{50}/H_{15} results in rather more than twice this var-
iation in the limiting steepness. It is obvious that this perfectly
reasonable result is not without significance when comparisons are made be-
tween model and prototype situations and **the values given in table**
5.62.2-2 above which are true for $\dfrac{H_{50}}{H_{15}}$ = 0.72 should be interpreted
with care.

For instance data given by Wiegel (reference 50) indicate that when
the significant wave height H1/3 ($\approx H_{13}$) and the mean deep water wave
length are used to define the steepness, the latter has a value of the
order of $\dfrac{1}{11.4}$ or 0.088, ie somewhat lower than the limiting value of
0.094 given above for H_{15}. This indicates that the model waves are somewhat
more regular than prototype which is in fact the case.

A similar situation is found when the shallow water limiting values are compared with values obtained from the Dutch coast (reference 46). In this case $H1/3 \approx 0.38$ D represents the general trend of the limiting relative wave height in shallow water. This is appreciably different from the value $H_{15} = 0.52$ D given in table 5.62.2-1. Again differences in wave height distribution are no doubt a contributing cause to the discrepancy since in the model $\frac{H_{50}}{H_{15}}$ was equal to about 0.80 or a little

greater in shallow water. A point which should not be overlooked is the method which is used to analyse the wave recordings. Different methods will give different results and it is probably that the model data presented above are affected by the method of analysis. In this case a partly subjective method was used in which very small waves were ignored (see section 3.22). This will obviously tend to give higher values of H_{15} and H_{50} and so the limiting ratios $\frac{H}{D}$ and $\frac{H}{L}$ will be higher than if all waves are counted. It is probable that some of the difference between the model and prototype data of reference 46 can be accounted for in this way. It is evident that there are significant changes in wind waves as they propagate over a shoaling bottom. Energy is dissipated in such a way that the limiting maximum wave height is approximately the same as that for monochromatic waves (see upper graph of figure 102). Further the waves tend to become more regular as is shown by the increase in $\frac{H_{50}}{H_{15}}$ as D/L decreases (lower graph of figure 102.

Some further light is shown on these changes when we compare the wave spectra measured simultaneously at the offshore and inshore measuring points. A typical such comparison is given on figure 103. Several facts are immediately obvious. For instance the spectral peak, ie, the frequency with maximum energy, shifts towards the lower frequencies (higher periods) in shallow water. Thus the average wave period of the waves increases to some extent. This point was verified by separate analysis of the wave recordings. This shift in central period appears to be due to the fact that a relatively greater proportion of energy is dissipated on the high frequency side of the spectral peak than on the low frequency side.

The shallow water spectrum also shows a tendency for the low
frequencies to be amplified possibly due to mass oscillations within
the surf zone. Further a second spectral peak is generally present
with a central period of half that of the main peak (cf. spectra for
regular waves figure 7). While the energy associated with this peak
is only relatively small compared with total energy (4 to 14 %) it
is evident that this second harmonic results from the distortion of
the wave in shallow water which causes energy to be transferred from
the main spectral periods to higher harmonics. Finally it can be seen
that for the example given on figure 103, test T6 a considerable portion
of the wave energy (of the order of 50%) is dissipated over the
outer section of the beach profile before the main plunge point is
reached, indeed in the zone where virtually no change occurred in the
beach profile (figure 65).

5.63 Wave Run-up Height, Beach Slope and Breaker Distance

As had been indicated in earlier sections the erosion of a sand
dune depends to a great extent on the amount of wave run-up. This in
turn depends primarily upon the wave height at the end of the surf
zone and the beach slope. The former quantity in turn depends upon the
energy dissipation process which occurs in the surf zone, an indication
of which can be obtained by the distance over which the energy is
dissipated or the breaker distance. The beach slope on the other hand
depends upon both the wave height and the size of the beach material.
In most cases observation in the model indicated that the limit of
wave run-up occurred at the dune foot, so the position and elevation
of this point were used for calculating both the run-up distance and
hence the slope of the dry beach above storm surge level. While there
was obviously some variation in run-up during the tests, the variation
was not very great and it was not possible to correlate it with other
factors, so average values were calculated for each test from all
individual profiles. Similarly the variations in beach slope at different
times during a test were not significant when compared with the
variations between different profiles at a given time.

Occasionally, i.e. test T19, where the actual runup distance was observed
to be greatly different from the dune foot position, the former has
been used to calculate the runup height and beach slope. The data are
given in table 5.63-1 below. Since the average beach slope is of the
same order of magnitude in most tests the relative runup R/H_o has been
plotted as a function of the wave steepness $\frac{H_o}{L_o}$ (figure 104). Also shown
on this graph are curves derived from figure 3-3 of reference 47 for
smooth impermeable slopes fronted by a 1 on 10 bottom slope, the change
in slope occurring at the water level (i.e. $\frac{D}{H_o}$ = 0). This condition is
fairly close to the model profile situation. The model relative runup
values are obviously lower than the fixed slope results which is not
surprising since the presence of bars offshore will cause greater energy
dissipation in the surf zone and hence a smaller residual wave height
and smaller runup.

TABLE 5.63-1

Wave runup height and beach slope

Test Number	Number of observations	Wave-height H_o—cm	Wave period T — sec	Runup height R — cm	Beach slope
TO	5 x 9	19.5	1.63	8.5	1 in 5.1
TO'	9	19.5	1.63	8.8	5.4
T4	9	17.6	1.63	8.2	5.3
T19	1	15.4	1.56	5.5	9.7
T20	2	10.7	1.56	6.5	5.8
T22	2	9.8	1.04	4.2	5.9
T23	2	13.4	1.16	4.9	5.2
T24	9	18.2	1.29	6.4	5.6
T7	9	9.9	1.00	5.3	4.8
T6	9	14.3	1.11	7.7	5.0
T8	8	17.3	1.29	11.2	5.8

Note: For wind wave tests H_o is the deepwater wave height of the sine
wave with the same H_{rms} as in the test.

This result is consistent with experimental results of other investigators both concerning model sand beaches (reference 45) and the effect of a berm upon wave run up (reference 15). The presence of sand in suspension in the uprush will also presumably increase the energy dissipation and hence reduce the run up. As expected figure 104 shows that the runup is relatively greater with wind generated waves although the beach slope does not appear to change greatly. In this case the relative runup value obtained from the beach profiles represents the runup of that particular wave height which determines the dune erosion. Unfortunately the runup heights for the wind wave tests are not very accurate but a comparison between the relative runup heights of the wind generated and regular waves and the wave height distributions for the wind wave tests indicates that the significant wave for dune erosion may well be the same or very close to the significant wave $H_{1/3}$ or H_{13} used to represent prototype wind waves for engineering purposes. This is shown in table 5.63-2 below where the ratio of the relative runup for wind and regular waves is compared with the ratio of H_{15}, which closely approximates the significant wave height, and the equivalent sine wave height $\frac{H_{rms}}{0.707}$. The agreement is very good in the case of tests T6 and T23 and while the other two pairs of tests do not agree so well this could partly be due to experimental error. For instance the value of $\frac{R}{H_o}$ for test T22 is apparently too high compared with the other regular wave data. If it is reduced to 0.38 to be consistent with the other points on figure 104 then the relative runup ratio for test T7 and T22 becomes 1.42 which agrees well the wave height ratio of 1.47 in table 5.63-2. In the case of test T8 it is difficult to offer an explanation apart from those already suggested in earlier sections for its apparent discordance with the other tests (see sections 5.41 and 5.42).

As mentioned above the breaker distance, defined here as the distance from the initial breakpoint to the final runup position, is an indication of the way in which the wave energy is dissipated within the surf zone. It could be expected that at equilibrium this factor would be related in some systematic manner to the wave and profile characteristics as has been found to be the case for the equilibrium profile itself (section 5.23) and the wave runup.

TABLE 5.63-2

Comparison of relative runup for wind and regular waves with wave height distribution

Test Number	$\frac{R}{H_o}$	$\left(\frac{R}{H_o}\right)_w \Big/ \left(\frac{R}{H_o}\right)_R$	$0.707\ H_{15}\big/H_{rms}$ Inshore H_1	Offshore H_2	Average
T7	0.54	1.26	1.52	1.42	1.47
T22	0.43	-	-	-	-
T6	0.54	1.47	1.54	1.43	1.48
T23	0.37	-	-	-	-
T8	0.65	1.85	1.50	1.33	1.42
T24	0.35	-	-	-	-

Consideration of the parameters which influence wave breaking suggested that either of the parameters $\frac{X_b}{T^2}$* or $\frac{X_b}{D_b}$ might vary in a systematic manner with the wave steepness $\frac{H_o}{T^2}$.

Figure 105a shows that the dimensionless breaker distance in terms of the wave length effectively separates the data into two zones, one where the break point lies on the initial inshore slope and the other for waves breaking on the outer bar. In tests such as T4 and T24 where an inner and an outer break point were observed the resultant points lie on the appropriate portion of the graph. When the dimensionless breaker distance in terms of the breaker depth (figure 105b), which is in effect a measure of the overall profile slope between breakpoint and the beach, is considered, it is found that the points tend to be grouped along straight lines in accordance with the different periods with the exception of test T22 which was also inconsistent with regard to wave runup. Thus we see that for a given wave steepness $\frac{H_o}{T^2}$ the relative breaker distance $\frac{X_b}{D_b}$ increases as the period increases, i.e. the profile becomes flatter. Further it can be shown that this decrease is approximately proportional to T^2 and hence to the deepwater wave length L_o, which fact is consistent with the empirical formula of Larras (reference 27).

* X_b is the breaker distance and D_b the breaker depth.

5.64. Orbital velocities within the surf zone

After the completion of test T18 in the small outside basin some experiments were made to determine the feasibility of using a miniature current meter (micrimolen) to measure orbital and drift velocities of waves within the surf zone. Relatively little definite information is available on this subject which is essential for a clear understanding of the processes which occur during the development of beach profiles. Some field measurements have been made of velocities within breaking waves by Miller and Zeigler (reference 34) or offshore of the break point (reference 18) and this question has been studied in the laboratory (references 14, 20, 28, 33 and 35). Measurements of drift velocities (i.e. mass transport) made in a horizontal channel confirm that bottom motion in non breaking waves is landward (reference 38 and 42). The only measurements known of the net movement near the bottom within the surf zone are those of Longinov reported by Zenkovitch (reference 52 *). These indicate landward transport at the bottom up to the breakpoint and seaward transport at the bottom between the break point and the beach. The measurements obtained in the outside model have enabled a comparison to be made between the maximum orbital velocities at the crest and trough of the wave at various depth^{c}and different points along the beach profile. The measurements are shown on figure 106 where it can be seen that significant changes occur. Initially seaward of the break point the maximum orbital velocity in the landward direction (wave crest) is somewhat greater than that in the seaward direction (wave trough), both however are of the same order of magnitude as that calculated from 1st order theory and both are greater near the surface than at the bottom. As the waves move shoreward the landward velocity distribution distorts with the surface velocities increasing and the bottom velocities decreasing. The order of magnitude of the mean maximum orbital velocity remains much the same, i.e. about 40 cm/sec. The seaward velocities however reduce in magnitude and become almost uniform with depth in the outer surf zone (6 to 7 metres) with an average velocity of about 20 cm/sec.

* Other measurements are referred to by Ingle (reference 17) but it was not possible to obtain the original reference describing them.

Further inshore (4 and 3 metres) the seaward (trough) velocities tend to
increase towards the bottom and both landward and seaward maximum orbital
velocities are approximately equal, being somewhat greater than 30 cm/sec.
No analysis has yet been made of the net drift velocity at various points
within a vertical along the beach profile but it is evident that since
the waves are distorted in shallow water with the crests occurring for less
than half a wave period and the troughs for more than half a period,
the landward velocities will act for a shorter period of time than the
seaward ones. While nothing is known at present of how these times differed
for the measurements shown on figure 106, it is obvious that at the points
close inshore where the maximum velocities are equal close to the bottom,
the net movement must be seaward at the bottom and landward at the surface
in agreement with Longinov's field measurements (reference 52). This means
that, either this section of the profile was not in equilibrium at the
time of the measurements, or that the more turbulent breaking wave crest
transports relatively more sand landward in suspension in the upper portion
of the vertical than is returned seaward by the less turbulent backwash
whose motion predominates at the bottom. Field observations by
Fukushima and Mizoguchi (reference 9) appear to confirm the fact that suspended
sand concentrations close inshore are at least of the same order of magnitude/near
as those near the bottom.   — (the surface)

Attempts were also made to measure orbital velocities during the wind wave
tests T6 to T8. The miniature current meter was located next to the
inshore wave height meter (figure 10) and measurements were made at several
points in a vertical immediately before each profile levelling simultaneously
with wave spectra and wave height distribution measurements. At each level
the velocities were recorded for 15 to 20 waves with a simultaneous record
of wave height. At the same time the total number of velocity pulses in
either direction together with the duration of the measurement were recorded.
The relative durations of landward and seaward motion were obtained from
the velocity recordings and so it was possible in principle to determine
whether landward or shoreward velocities predominated at a given point.
In practice it was found impossible to obtain useful results from these
measurements because the length of the recordings at a given position was

too short and the results were affected by the presence of the seiche
or similar oscillation with a period of the same order of magnitude as
the length of recording. The effects of this oscillation were at times
very significant particularly during periods of relatively low waves when
the horizontal velocities due to it were very often greater than the orbital
velocities of the wind waves, Thus correlation between orbital velocities
and wave heights was difficult and in some cases impossible while correla-
tion between orbital velocities and wave periods was at all times
impossible. An example of the better results is shown on figure 107 from
test T6 just before the end of the first half hour of the test. In the upper
graph of the figure it is seen that the maximum orbital velocities of
individual waves are generally proportional to the height of the corresponding
wave crest above still water level or to the depth of the corresponding
wave trough below still water level. This is in agreement in principle
with 1st order theory for regular waves where the orbital velocity is
proportional to the wave height as the following expression indicates:

$$u_{max} = \frac{H\,\pi}{T} \quad \frac{\cosh \frac{2\,\pi}{L}\,(D + z)}{\sinh \frac{2\,\pi\,D}{L}}$$

where u_{max} is the maximum horizontal orbital velocity at a point during
the passage of a wave,

z   is the distance from the water surface, taken as a positive
upwards.

Measurements of the slope of the lines in the upper graph of figure 107
and similar figures for other depths not shown give the magnitude of
$\frac{u_{max}}{H}$ which, ignoring the effect of period which could not be established,
is a function of $\frac{D}{L}$ and the position z at which the measurement was made.
The lower graph of figure 107 shows the relative magnitudes of $\frac{u_{max}}{H}$ at
various depths within wind waves in a situation where some waves are breaking
in a spilling form offshore of the main plunge point. There is an obvious
asymmetry in the functional relationship between $\frac{u_{max}}{H}$ and $\frac{D}{L}$ at a given
point similar to the asymmetry of orbital velocities for regular waves
within the surf zone.

Also shown on the same graph is the average horizontal velocity in each direction. While the measurements are not complete there is obviously reason to conclude that in this situation the bottom velocities were predominantly seaward. This was presumably due both to the effect of the breaking wave crests and the return flow caused by wind stress. The measurement point, it should be noted, was offshore of the main plunge point.

5.65. Sediment density and grain size distribution variations

In a number of tests sand samples were taken from the surface of the model at the end of the test at equilibrium. From these samples grain size analyses and bulk densities were determined at one or sometimes half metre intervals along certain profiles. For the present discussion results from tests T17, T25 and T8 only are considered. Firstly considering the bulk density of the sand, most data are available for test T17. On figure 108 are shown three lines representing the variation of the bulk density with distance along three separate profiles. There are apparently no significant trends except for the fact that the density is lower at the landward end of the profile, i.e. zero distance. There the density is of the order of 1400 kg/m^3 while elsewhere an average value of 1600 kg/m^3 is found. Evidently the wave action consolidates the bottom material to some extent. A similar trend is found in wind wave test T8 (figure 112). This result of course supplies one possible reason for the discrepancies between the volume of sand eroded from the sand dune and the amount deposited. On this account it is to be expected that the amounts of sand deposited should be about 15% less than those eroded from the sand dune. Examination of these quantities for various tests showed that this was not in fact the case. Indeed in many cases the amounts deposited were greater than those eroded. Thus it appears that the influence of nonuniformity due to three dimensional effect is more important than any change in bulk density of the sand. It is also possible that the decreased density in the uneroded sand dune applies only near the surface. On the other hand when the variation of sand size along the profile is considered, there are significant differences. On figure 108 are plotted the median sand sizes d_{50} for test T17 along three separate profiles while grading curves for selected points on one of them are shown on figure 109.

There are obviously significant differences from the average value of 0.22 mm for the original sand. The sand size increases by almost 50% to about 0.30 mm or more between the one and two metre points which are just seaward of the water line at the end of the surf zone. It was in this vicinity that maximum sand transport generally occurred (figure 46), i.e. where deposition of the sand eroded from the dune commenced. The sand size then steadly reduces through the surf zone out to a point a metre or so seaward of the initial breakpoint, that is on the seaward face of the outer bar. At this point the median size is about 0.18 mm or a little finer. Thereafter it increases again until at 16 metres it is 0.22 mm, that is, the original average value. Similar behaviour is shown in test T25 with the finer sand (average value of d_{50} for original sand 0.15 mm) only in this case both the absolute and relative increases in size at the end of the surf zone were greater (figure 110 and 111). This was due to a large extent to the presence of shell and pieces of stone or peat which were present in the original sand in comparatively small amounts but which all tended to move to this point within the model. A similar decrease below original size is also evident at 10 metres on the seaward face of the outer bar as in test T17. The explanation for these differences in sand size is presumably to be found in the relative importance of bed and suspended load movement within the surf zone. Firstly the large pieces of shell, etc. in test T25 are probably picked up and transported shoreward as bed load or even partly in suspension by the turbulent breakers. However except in the backwash on the dry beach where gravity assists, the seaward velocities are not strong enough to counteract this motion. Consequently these particles accumulate at the end of the surf zone just below the water line. Secondly when we consider the sand itself, the finer particles will have smaller fall velocities and hence larger values of the parameter $\frac{H_o}{Tw}$ (see section 3.31).

They will of course then be more readily moved in suspension out through the surf zone. Consequently the deposits on the outer bar consist of a relatively greater proportion of the finer material while those in the inner part of the surf zone are coarser. Evidently the seaward transport ceases at the foot of the outer bar, offshore of which the material has substantially the original grain-size. This last condition is of course consistent with the landward net transport observed in the latter part of the various

tests as equilibrium is approached (figures 45, 73 and 90). The fine sand
deposited in this zone during the early stages of the test is presumably
largely returned to the outer bar. The same general trend for median
diameter is evident for wind wave test T8 (figure 112) as occurs in tests
T17 and T25. Here however the size variations are not as great and the
maximum size occurs further seaward on the two surf zone bars (see figure
68). A direct comparison with the regular wave tests is not possible since
comparable data are not available for test T24, but it appears that the
irregularity of the waves in the inner surf zone prevents the sand being
sorted to a great degree. Coarse particles do not accumulate near the water
line but at a point somewhat further out since some of the waves have a
relatively greater capacity for transport in suspension than do the average
wave conditions. This effect is also assisted by the bottom return current
due to wind stress.

Comparison of the above results with those of other investigators reveals
important discrepancies. For instance tests on profile development by the
U.S. Bureau of Reclamation (reference 48) indicated that the bulk density
of the deposited sand was less than that of the uneroded beach. In this case
the sand size was greater than in the present tests (0.57 mm compared with
0.22 or 0.15 mm) while considerable effort was made to pack the sand of
the initial profile at maximum density. This latter fact probably accounts
for the discrepancy. However these tests also show sand size variations
almost exactly the opposite to the present ones in that the sand in the
surf zone is finer than the original material while the seamost deposits
are coarser. The reason for this difference is not clear but appears to be
associated with the fact that the waves were both smaller and flatter while
the sand size was larger. Sufficient data were not available at the time
of writing to check the point but it is probable that bed load movement
was more significant in the U.S.B.R. tests.

Finally it should be noted that certain field investigators find that the
coarsest material lies at the break point (e.g. Ingle pages 93 to 100
of reference 17). The results of the present tests do not agree with this,
but it is difficult to compare them since the particular prototype condition
referred to was more related to swell conditions (H_o = 1.2 metres and
T = 11 seconds) than to the storm conditions reproduced in the model.

5.66. Summary

Wave reflection varies greatly during the development of the equilibrium
profile but tends to a relatively low value as equilibrium is reached. This
effect is apparently related to changes in the inner surf zone bar. An
increase in reflection shifts the initial breakpoint seawards and vice
versa (at least for spilling breakers) while large reflections may reverse
the net sand transport direction offshore of the outer breakpoint bar.
Temporary stability of dune recession may occur due to the build up of
a bar and the consequent reflection of significant amounts of wave energy
from it. When H/D is plotted as a function of L/D for regular waves travelling
into the surf zone it is found that H/D has a maximum at each break point,
followed by a minimum. This effect is more pronounced for bar profiles
(plunging breakers) than for smooth profiles (spilling breakers).
Calculations of mean water level variations within the surf zone using
Lundgren's wave thrust and energy level concepts indicate a tendency for
the water level to have a minimum at a break point. It appears also that
the general water level within the surf zone between bars at equilibrium
may be the same as that offshore of the main outer bar. It is possible that
such variations in water level can be considered analogous to those in steady
non uniform open channel flow and that a fully developed plunging breaker
at a bar represents a control point analogous to critical depth flow over
a weir.

The maximum heights of wind waves in shoaling water are of the same order
as the theoretical limiting curves where $H = 0.143$ L in deep water and
$H = 0.78$ D in shallow water. Other heights within the wave height distri-
bution (e.g. H_{15}, H_{50} and H_{rms}) also approach similar but lower constant
limiting values in deep and shallow water. The magnitudes of the latter li-
miting values depend upon the wave height distribution, i.e. the amount
of wave irregularity. Thus the model results give somewhat higher limiting
values of the significant wave height in both deep and shallow water than
has been found in prototype which is consistent with their greater
regularity. Further the period of wind waves tends to increase in shallow
water.

The relative wave runup $\frac{R}{H_o}$ at a given wave steepness $\frac{H_o}{L_o}$ is less than for
a similar smooth slope due primarily to increased energy dissipation within
the surf zone. The relative wave runup is however greater for wind generated
waves than for regular waves with the same energy and period.

Further comparison of the relative runup for wind waves with that for regular waves indicates that either the significant wave height $H_{1/3}$ or H_{15} may well be the effective one for dune erosion. Orbital velocity measurements for regular waves within the surf zone at approximate equilibrium appear to indicate a tendency for bottom velocities to be predominately seaward thus giving support to the idea that equilibrium within this zone on a sand beach depends basically upon a net zero circulation of sand rather than zero sand transport.

Velocity measurements within wind waves were rather unreliable but indicate that maximum crest and through orbital velocities were generally proportional to the height or depth relative to mean water level and further that seaward velocities predominate near the bottom offshore of the mean break point, at least on certain occasions.

The bulk density of the sand on the underwater profile is somewhat greater than that of the uneroded sand dune.

The median sand size at equilibrium varies along the profile, being a maximum at the landward end of the surf zone just seaward of the water line and a minimum at the outer break point bar.

REFERENCES

1. Bascom, W. — <u>Waves and beaches</u>. Anchor books, Doubleday and Co, New York 1964, pp 267.

2. Bijker, E.W. — <u>Some considerations about scales for coastal models with movable bed.</u> Delft Hydraulics Laboratory Publication no 50, 1967.

3. Bonnefille, R. and Pernecker, L. — <u>Le début d'entraînement des sédiments sous l'action de la houle.</u> Bul. C.R.E.C. no 15, March 1966, pp 27-32.

4. Danel, P. — <u>On the limiting clapotis</u>. Symp. on gravity waves. U.S.N.B.S. circular 521, 1952. pp 35 to 38.

5. Diephuis, J.G.H.R. — <u>Scale effect of the breaking of waves</u>. Procs 6th coastal engineering conference, Florida, Dec. 1957, Part 1, pp 194-201.

6. Druet, C. — <u>Nomographic chart for determination of the Monochromatic wave type in the region of foundation of a designed hydrotechnical structure.</u> 21st Int. Nav. Congress, Stockholm 1965, Section II-1, pp 183-201.

7. Eagleson, P.S., Glenne B. and Dracup, J.A. — <u>Equilibrium characteristics of sand beaches</u>. Procs A.S.C.E. Vol 89, No HY I, Jan. 1963, pp 35-58.

8. Edelman, T. — <u>Vormveranderingen aan zandige kusten</u> Part II "Het dwarsprofiel en het materiaaltransport haaks op de kust". Studierapport W.W.K. 67-3, Rijkswaterstaat, Directie waterhuishouding en Waterbeweging, afd. Kustonderzoek, 1967.

9. Fukushima, H. and Mizoguchi, Y — <u>Field investigation of suspended littoral Drift</u>. Coastal engineering in Japan. Vol 1, 1958, pp 131-134.

10. Galvin, C.J. and Eagleson, P.S. — <u>Experimental study of longshore currents on a plane beach</u>. M.I.T., Hydrodynamics Lab. Rep. No. 63, May 1964. 88 pp.

11. Gourlay, M.R.   - Wave generated currents - Some observations made in fixed bed hydraulic models. Univ. of Qld Dept of civ. enging. bul. No 7, Nov. 1965.

12. Greslou, L. and Mahe, Y - Etude du coefficient de réflexion d'une houle sur un obstacle constitué par un plan incliné Procs 5th coastal engineering conference, Grenoble, Sept 1954, pp 68-84.

13. Groot, T.   - Nota duinprofielen 1965 - Studie betreffende het dimensioneren van een kunstmatige duin; voorlopige resultaten. Rijkswaterstaat Directie Zeeland-Studiedienst Vlissingen, nota 65.2, Nov, 1965.

14. Hamada, T.   - Breakers and beach erosions. Port and Harbour Technical Research Institute, Ministry of transportation, Japan. Ref. Doc. No 1, 1963 (Reprint of earlier Publication Dec. 1951).

15. Herbich, J.B., Sorensen, R.M. and Willenbrock, J.H. - Effect of berm on Wave runup on Composite Beaches. Procs A.S.C.E. Vol 89, No. W.W. 2, May 1963.

16. Horikawa, K and Kuo, C.T. - A study on wave transformation inside surf zone. Coastal Engineering in Japan. Vol. 9, 1966, pp 69-81.

17. Ingle, J.C.   - The movement of beach sand-development in sedimentology 5. Elsevier, Amsterdam, 1966, 220 pp.

18. Inman D.L. and Nasu, N - Orbital velocity associated with wave action near the breaker zone. U.S. Army beach erosion board, tech. memo. No.79, March 1956.

19. Irribarren Cavannilles, R - Corrientes y transportes de arena originados por el oleaje. Revièta de Obras Publicas, May-June 1947. French translation in Annales des Ponts et Chaussées. Jan-Feb. 1949.

20. Iversen, H.W.   - Laboratory Study of Breakers. Symp. on Gravity Waves. U.S.N.B.S. Circular 521, 1952, pp 9-32.

21. Iwagaki and Noda,   - Laboratory Study of Scale Effects in Two-
                              Dimensional Beach Processes. Procs 8th Coastal
                              Engineering Conference, Mexico City, Nov. 1962,
                              pp. 194-210.

22. Iwagaki Y and Sawaragi, T - Experimental Study on the Equilibrium Slopes
                              of Beaches and Sand Movement by Breakers.
                              Coastal Engineering in Japan. Vol. 1 1958,
                              pp 75-84.

23. Kemp, P.   - The Relationship between Wave Action and Beach
                              Profile Characteristics. Procs 7th Coastal
                              Engineering Conference, The Hague, 1960, Vol 1.
                              pp 262-277.

24. King C.A.M.   - Beaches and Coasts. Arnold, London, 1959, 403 pp.

25. Kondrajev, N.E.   - Forecasting Shore Transformations at Large
                              Reservoirs. Procs 10th I.A.H.R. Congress, London,
                              1963, Vol. 1, pp 139-146.

26. Larras, J.   - Débit solide charrié par une houle perpendiculaire à
                              la rive sur un fond horizontal de granulats.
                              C.R. Acad. Sc. Paris, Vol. 263, Series A, 3 Oct.
                              1966, pp 474-476.

27. Larras, J.   - Les profils d'équilibre des fonds de sable sous
                              la mer. Ann. des Ponts et Chaussées Vol. 129,
                              No 4, 1959, pp 391-404.

28. Larras, J.   - Recherches expérimentales sur le déferlement des
                              lames. Ann. des Ponts et Chaussées Vol. 122,
                              No 1, Jan-Feb. 1952, pp 525-542.

29. Le Méhauté, B.   - On Non-Saturated Breakers and the Wave Runup.
                              Procs 8th Coastal Engineering Conference, Mexico
                              City, Nov. 1962, pp 77-92.

30. Longuet-Higgins, M.S. - On the Wave-induced Difference in Mean Sea Level
                              between the Two Sides of a submerged Breakwater.
                              Jour. Mar. Res. Vol.25. No 2, 1967, pp 148-153.

31. Longuet-Higgins, M.S. and Stewart, R.W. - Radiation Stresses in Water
                              Waves: a Physical Discussion, with applications.
                              Deep-Sea Res. Vol. 11, 1964. pp 529-562.

32. Lundgren, H.   – Wave Thrust and Wave Energy Level. Procs. 10th I.A.H.R. Congress, London. Vol. 1 1963. pp 147-151.

33. Mason, M.A.   – Some Observations of Breaking Waves. Symp. on Gravity Waves U.S.N.B.S. Circular 521, 1952, pp 215-220.

34. Miller, R.L. and Zeigler, J.M. – The Internal Velocity Field in Breaking Waves. Procs 9th Coastal Engineering Conference, Lisbon, June 1964, pp 103-122.

35. Morrison, J.R. and Crooke, R.C. – The Mechanics of Deep Water, Shallow Water, and Breaking Waves. U.S. Army Beach Erosion Board, Tech, Memo. No 40, March, 1953.

36. Multer, R.H. and Galvin, C.J. – Secondary Waves: Periodic Waves of Nonpermanent Form. Paper 073 of the 48th Annual Meeting of A.G.U., 1967. Abstract in Trans. Am. Geoph. Union Vol. 48. No 1. March 1967, p 139.

37. Nakamura, M.,Shraishi, H and Sasaki, Y. – Wave Decay due to Breaking. Procs 10th Coastal Engineering Conference, Tokyo, Vol 1, Sept 1966, pp 234-253.

38. Onoszko, J.   – Dynamika profilu brzegy piaszczystego pod wplywem dzialonia fal o kierunku prostopadlym do linii brzegowej w swietle badan laboratoryjnych (Profile dynamics of a sand shore under the influence of wave action having a perpendicular direction to the shoreline in view of Laboratory Investigations). Instytut Budownictwa Wodnego, Rozprawy Hydrotechniczne, Zeszyt 17, Warsaw 1965, pp 71-158. In Polish with English summary.

39. Popov, I.J.   – Experimental Research in Formation by Waves of Stable Profiles of Upstream Faces of Earth Dams and Reservoir Shores. Procs 7th Coastal Engineering Conference, The Hague, 1960, Vol 1. pp 282-293.

40. Priest, M.S.   – Effects of Change in Wave Height and Change in Wave Period upon Beach Profiles. Procs 8th I.A.H.R. Congress, Montreal 1959. Volume IV.

41. Rouse, H. (Editor)   – Engineering Hydraulics. Wiley, New York, 1950, 1039 pp.

42. Russell, R.C.H. and Osorio, J.D.C. - An Experimental Investigation of Drift Profiles in a Closed Channel. Procs 6th Coastal Engineering Conference, Florida, 1957, pp 171-193.

43. Saville, T.   - Scale Effects in Two Dimensional Beach Studies Procs 7th I.A.H.R. Congress, Lisbon, Vol.1 Paper A3, 1957.

44. Sawaragi, T and Kawasaki, Y - Experimental Studies on Behaviour of Scouring at the Toe of Seadikes by Waves. Disaster Prevention Research Institute, Annual No 4, 1961 (Japanese text with English summary).

45. Shinohara, K.,Tsubaki, T. and Saito, T.- Laboratory Investigation of the Equilibrium Profiles of a Sandy Beach. Reports of Research Institute for Applied Mechanics, Kyushu University, Vol IX, No 34, 1961.

46. Svasek, J.N.   - Kustveranderingen veroorzaakt door zeegolven. Unpublished report, Rijkswaterstaat Deltadienst 1967.

47. United States Coastal Enging Res. Centre. - Shore Protection, Planning and Design. U.S. Army Coastal Enging Res. Centre., Tech. Rep. No 4, Third edition, June 1966.

48. United States Bureau of Reclamation - Laboratory Study to Determine the Equilibrium Beach Profile for Figarden Reservoir-Central Valley Project, California. U.S. Bureau of Reclamation, Hydraulic Branch Rep. Hyd. 475, July 27, 1962.

49. Vincent, G.E.   - Contribution to the study of Sediment Transport on a Horizontal Bed due to Wave Action. Procs 6th Coastal Engineering Conference, Florida, 1958, pp 326-355.

50. Wiegel, R.L.   - Wind Waves and Swell. Procs 7th Coastal Engineering Conference, The Hague, 1960. pp 1-40.

51. Yalin, S.   - A Model Shingle Beach with Permeability and Drag Forces Reproduced. Procs 10th I.A.H.R. Congress London, Sept 1963. Vol 1, pp 169-175.

52. Zenkovitch, V.P.   - Processes of Coastal Development. Oliver and Boyd, Edingburgh and London, 1967.

53. Anonymous   - De stormen van november en december 1965. Deltawerken, number 39, February 1967, pp 454-465.

VOORLOPIG

WATERLOOPKUNDIG LABORATORIUM

RAPPORT No: M935/M936

Beach and dune erosion tests I
(additional chapters 6 and 7)

AUTEUR: M.R. Gourlay – R. Reinalda.
DATUM: July 1969.
CODE No:

6. Application of results to the design of artificial sand dunes

6.1. Estimation of maximum dune erosion

For a coastline formed of sand the maximum possible dune erosion for a given storm surge level may be estimated from a knowledge of the equilibrium profile for the waves associated with that particular storm surge level and the initial profile existing before the surge occurred. Maximum dune erosion is then determined by moving the initial and final profiles relative to one another until the eroded and deposited volumes are equal (figure 113).

In principle this process is very simple, but in practice its application presents serious difficulties. Firstly, during a storm surge the most serious conditions last only for a short time, and it can not be expected that an equilibrium profile, associated with these conditions, will occur. Secondly, the process described above assumes that no sand is removed from the offshore zone by currents running parallel to the coast. The removal of sand by such currents or any other mechanism can be expected to result in increased erosion as has been shown in a further series of tests to be described in a separate report. Thirdly, in the model large variations occur from profile to profile along the beach due to three-dimensional effects such as rip-currents, and these phenomena may also happen in the prototype. Consequently an exact balance between dune erosion and offshore deposition can never be expected along any given profile.

An application based upon this principle, but using simplified profile shapes has been described by Edelman (reference 8). In this paper the influence of both dune height and storm surge level upon the dune erosion has been investigated, together with the effect of complete removal of the eroded sand from the surf zone.

6.2. The concept of an effective storm surge level

The model tests clearly indicate in all cases that the position of the dune foot is determined by the run-up distance of the waves attacking the dune. The dune foot-elevation must therefore be above the water level at a

height equal to the run-up height. Prototype observations are, however,
in consistent disagreement with this behaviour when dune foot elevations
are compared with the maximum storm surge level. For instance in November-
December 1965, the dune foot elevation along the coast of Goeree was
generally 2.8 m, while the maximum storm surge level measured nearly at
Ouddorp was 3.35 m (reference 53). Similar behaviour was observed for the
1953 surge (reference 13). In the vast majority of cases the dune foot,
where it is clearly defined, lies below maximum surge level. This may be
due to one or more of the following causes. '

(i)   The local storm surge level may have been different to that at the
      nearest tide gauge. This is a possibility particularly where the
      gauge is located inside an estuary.

(ii) The dune face was unstable and collapsed after the storm surge peak
      subsided, thus giving a false indication of the dune foot position.

(iii) The final dune foot height was determined by storm conditions which
      occurred during the falling stages of the storm surge. For this to be
      the case the waves and storm surge must have been of such a magnitude
      and have lasted for a sufficiently long time, for the dry beach formed
      at maximum surge level to be completely eroded.

Now the results of test T21 with alternating water levels suggest that
the effect of the normal tidal fluctuations superimposed upon the storm surge
itself, i.e. the change in mean water level, may not be very significant.
Thus as far as dune erosion is concerned the comparatively short duration of
the maximum surge levels may not be so significant in determining the amount
of dune recession during a given storm surge. It appears useful then to
define what might be called an effective surge level for a given storm surge.

For the consideration of dune or shoreline recession we assume that no
erosion occurs during periods of normal weather when the mean sea level is
constant. The effective storm surge level may then be defined as the storm
surge level which, if it occurs for the same duration as the actual storm
surge, gives the same amount of dune erosion.

Before we can determine the effective storm surge level from this
definition it is necessary to consider the relation between the storm surge

level and the storm waves. It is obvious that it is not the storm surge,
i.e. change in mean water level, which causes dune erosion, but the wave
action which accompanies it. The test results where the wave characteristics
were varied for a given storm surge level (section 5.2) indicate that

$$x' = L_o \ f \ (H_o/L_o \ , \ t/T)$$

where x' is the dune foot recession.

Now for storm conditions H_o/L_o will be sensibly constant at maximum
steepness, while the size of the waves, represented above by L_o, will
increase with the wind velocity. The wave height H_o will thus also increase
with the wind velocity and it is reasonable to expect that the storm surge
level will do so too. Indeed the observations made during the Nov.-Dec.
1965 surges show clearly that both the storm surge level and wave height
increased simultaneously with the wind velocity. Further analysis also
indicated that the wave height in shallow water increased directly with the
water depth (reference 6). Consequently, we assume in the following
discussion that the influence of wave action is directly related to the
storm surge level and so need not be explicitly considered.

The determination of the effective storm surge level in accordance
with the above definition is thus dependent upon a knowledge of the amount
of dune erosion which results from a given storm surge level (y), during a
given time (t).

Unfortunately, the present tests did not investigate the effect of
various storm surge levels upon the amount of dune erosion. However, as was
mentioned earlier, Edelman (reference 8) has estimated the effect of varying
storm surge levels upon the equilibrium dune erosion using a simplified
profile shape. Figure 3 of this reference indicates that a linear relation
between dune foot recession and storm surge level is a fairly reasonable
assumption in the absence of other information. In figure 114 the relation-
ship between the dune erosion (V) and time (t) is shown diagrammatically
for various storm surge levels (y).

The storm surge level which determines the final position of the dune
foot can be estimated for a given storm surge. For example, we consider an
arbitrary storm surge with a step hydrograph as shown on figure 114.
Assuming that the V-t relationships for each y are independent of one another
we can determine the amount of erosion which is caused by each surge level
in the manner shown on the figure. The last surge level which contributes
to the erosion will then be the storm surge level which determines the final
position of the dune foot. However, as long as the erosion-storm surge level-
time relationships for prototype conditions are unknown, the determination
of the effective storm surge level for a given storm is impossible.

The principle application of the effective storm surge level concept
lies in its ability to enable a comparison between various storm surges to
be made and their relative dune erosion potentials to be assessed. The
analysis of prototype observations can then be made upon a more consistent
and logical basis, which takes account of the duration of the surge, the
shape of the storm surge hydrograph and does not include the physical in-
consistency of a surge level which lies above the dune foot elevation as
is the case when the maximum surge level is used as a basis for comparison.

6.3. Time scale for the dune erosion

Up to now nothing has been said about the time scale for the dune
erosion in the model, although it is felt that this is a very important factor
for the evaluation of the model results. The greater part of the tests was
extended over such a time that the changes in the profile became small,
which should mean that more or less an equilibrium situation was reached.
In the first series of tests with varying dune heights such a situation was
attained after about 19 hours.

Since the vertical scale of the model was assumed to be 1 in 25, the
time scale for the waves was 1 in 5. Consequently for the wave motion 19
hours in the model correspond with 95 hours or 4 days in the prototype.
However, experience has taught that the time scale for the hydraulic phenomena
may deviate strongly from the time scale for the morphological phenomena, in

this sense that the latter occur relatively fast.

In his report "The Influence of Dune Height on Dune Erosion", Mr. W.T. Bakker has tried to calculate the time scale for the dune erosion, and although the prototype data are very scarce, he arrives at a time scale of 1 in 300 or even more. Also in another model in the laboratory De Voorst which has the same geometrical scales and in which waves attack the coast obliquely, a time scale for the longshore transport of the same order of magnitude has been found. This should mean that the dune erosion in the prototype during a storm surge of three days is reproduced in the model in a period of roughly a quarter of an hour, or perhaps even less.

The model results show that in this period the rate of dune erosion is great, and that an equilibrium situation is not nearly reached. Thus the determination of the dune erosion during a storm surge with the use of equilibrium profiles, as set out in 6.1, gives too unfavourable results.

Further it seems likely that the cause of the fact, that the dune foot elevation in the prototype after a storm surge lies below the maximum water level during that surge, must be ascribed to the circumstance that a well-defined dune foot can not be formed in the short period of maximum water level, when large amounts of sand are eroded from the dune. Only during the lower water stages after the maximum storm surge level a well-defined dune foot can be formed, when the actual dune erosion has stopped.

7. Summary of results and conclusions

7.1. Dune erosion and shoreline recession

(a) The recession of a sand dune at a given time when measured by either
the change in position of the storm surge water line or the dune foot
position, increases both as the height of the sand dune decreases and as
the initial slope of the dune face becomes flatter.

(b) In general at a given time the higher the sand dune, the smaller the
amount of dune recession, but the greater the total volume of sand
eroded from the beach and dune.

(c) Dune erosion is very rapid in the early stages of a constant level storm
surge. For the tests with various dune heights, the total volume of sand
eroded above storm surge level can be approximated by the relation

$$V = 0.9 \frac{D_1}{D} \left\{ 1 - e^{-0.26 \sqrt{\frac{D}{D_1}} \, t} \right\} \qquad \text{(see figure 115)}$$

in which: V = volume of sand in m^3/m',

$\quad\quad\quad\quad D_1$ = dune height above storm surge level,

$\quad\quad\quad\quad D$ = vertical distance between the dune crest and the depth
till where the sand is deposited,

$\quad\quad\quad\quad t$ = time in hours.

(d) Dune erosion at a given time, as measured for example by the dune foot
recession x', increases with both wave height and period. The parameters
$\frac{x'}{L_o}$, $\frac{H_o}{L_o}$ and $\frac{t}{T}$ appear to be relevant, $x' = L_o \, f \, (H_o/L_o \, , \, t/T)$.
Thus for a given storm surge level, a given initial profile and a given
bed material, dune recession increases with the absolute size of the
waves (L_o), the wave steepness (H_o/L_o) and the number of waves (t/T).

(e) Dune foot recession at a given time is greater for wind waves with the
same energy (or H_{rms}) and a central spectral period equal to that of the
regular waves. The dry beach slope and storm surge water line recession

are however much the same, consequently the dune foot height is greater for wind waves.

(f) Dune erosion does not necessarily increase when the beach and dune material is made finer and thus relatively more mobile, since the increased offshore transport rate in suspension through the surf zone results in a more rapid build up of the outer bar and a consequent great energy dissipation at this point.

(g) The amount of dune erosion caused by a given storm is thus dependent upon the following factors:
  (i)   the size and geometry of the sand dune;
  (ii) the hydraulic effects of the storm, such as storm surge levels and their duration together with the accompanying wave conditions;
  (iii) the preceding weather conditions which determine the initial beach and offshore profile;
  (iv) the size of the beach sand.

7.2. Beach and surf zone profiles

(a) In the model the elevation of the dune foot is above storm surge level since the position of the dune foot is determined by the run-up of the breakers at the landward end of the surf zone. In the prototype the elevation of the dune foot is usually below maximum storm surge level, which may be due to the relatively short duration of the storm surge.

(b) The final beach and surf zone profile is independent of the sand dune geometry and depends only upon the wave and sediment characteristics. The slope of the dry beach is distinctly steeper than the slope of the underwater surf zone profile.

(c) The general final profile slope within the surf zone is much the same for both wind and regular waves. Regular waves, however, tend to show more pronounced bars within the surf zone, while wind waves transport sand further seaward offshore of the main breakpoint.

(d) Similar discontinuities and variations in the corresponding curves for dune erosion and transport rates under regular and wind waves indicate general similarity of the erosion processes. This is probably to be interpreted as evidence of the effect of the common initial profile.

(e) A reduction in sand size results in a final profile with a more pronounced break-point bar and a dry beach with a flatter slope.

7.3. Surf zone processes

(a) Sand transport rates are initially extremely high but decrease significantly after a relatively short time. The transport rate decreases significantly seaward of the breakpoint and generally becomes landward in this zone when the wave reflection from the beach is small.

(b) Wave reflection varies greatly during the development of the beach profile, but tends to a relatively low value as equilibrium is approached. Large reflections caused by a build-up of the inner surf zone bar, result in increased offshore sand transport both seaward and landward of the initial breakpoint, while at the same time decreased dune erosion occurs. The position of the initial breakpoint shifts seaward with increased reflection when spilling breakers occur, but appears relatively stable with plunging breakers.

(c) It is probable that the wave set-up, or rise in mean water level in the surf zone is only significant when the surf zone profile is a non-equilibrium one. It is suggested that in the equilibrium profile the wave energy is dissipated in such a way that wave set-up is negligible except near the still water line. Moreover the mean water level is locally depressed over each breakpoint bar at which there is either a significant change in transport capacity of the waves or a change in direction of net sediment movement.

(d) Orbital velocity measurements for regular waves within the surf zone at approximate equilibrium appear to indicate a tendency for bottom velocities to be predominantly seaward, this giving support to the idea

that equilibrium within this zone on a sand beach depends basically upon a net zero circulation of sand rather than zero sand transport. Such a concept is consistent with a predominance of suspended sand movement.

(e) Since suspended load movement is of primary importance in the movement of sand in the surf zone during storm surge conditions any attempt to reproduce these conditions in a model should be based essentially upon similarity of suspended sediment transport processes within the surf zone. In this regard it is considered that the parameter $H/T.w$ (in which H = wave height, T = wave period, w = fall velocity of the sediment particles) is very important, particularly when rates of erosion and profile development are being studied.

(f) The median sand size at equilibrium varies along the profile, being a maximum at the landward end of the surf zone just seaward of the water line and a minimum at the outer breakpoint bar.

7.4. Artificial sand dune design

(a) If a sufficiently wide dune reservation is permissible, it will be more economical in terms of sand volumes eroded to have a relatively low dune. A high dune will, however, reduce the magnitude of dune recession at the expense of greater sand loss.

(b) If sand is removed from the surf zone by any means, then increased erosion can be expected. However, it is believed that in practice the loss of sand from the surf zone will be small compared to the supply of sand from the dune during a storm surge.

(c) It is believed that during a storm surge no equilibrium profile will develop, which is associated with the hydraulic conditions at maximum or nearly maximum water level during that surge. Therefore the dune erosion cannot be determined with the use of equilibrium profiles.

(d) The analysis of prototype data can be made more consistent and logical by the use of the effective storm surge concept which takes into account the duration of the surge and the shape of the storm surge hydrograph. For the use of the effective storm surge however, the relation between the dune erosion, the storm surge level with associated wave action, and the time should be known.

7.5. Recommendations for further work

(a) The relationship between storm surge level, dune erosion and time has not been properly investigated up till now. A series of tests in which all independent variables other than the storm surge level with associated waves are kept constant would be therefore of great assistance. For this, however, sufficient information from prototype sources concerning the relation between surge level and wave characteristics should be available.

(b) An investigation into the time scale for the dune erosion in the model is of utmost importance, which can be done by carrying out tests on different scales. In this respect also the relevance of the parameter $H/T.w$ should be investigated using models with different bed materials.

(c) The various ideas and conclusions associated with the effective storm surge concept should be tested by:
  (i) checking the validity of the concept in laboratory test in which the storm surge level and wave characteristics are varied in a realistic manner;
  (ii) re-analysing prototype data wherever possible to see whether more consistent relationships can be obtained between observed dune recession, the dune characteristics and the storm surge conditions.

(d) From the point of view of basic research towards an understanding of the surf zone processes which occur during beach erosion and profile adjustment, it will be necessary to pay a great deal more attention to

the hydraulics of the surf zone.

Detailed measurements of wave heights, velocities, wave set-up, break-points and wave run-up as well as sand movement are all required.

STORM SURGE WATER LEVEL

NORMAL WATER LEVEL (N.A.P.)
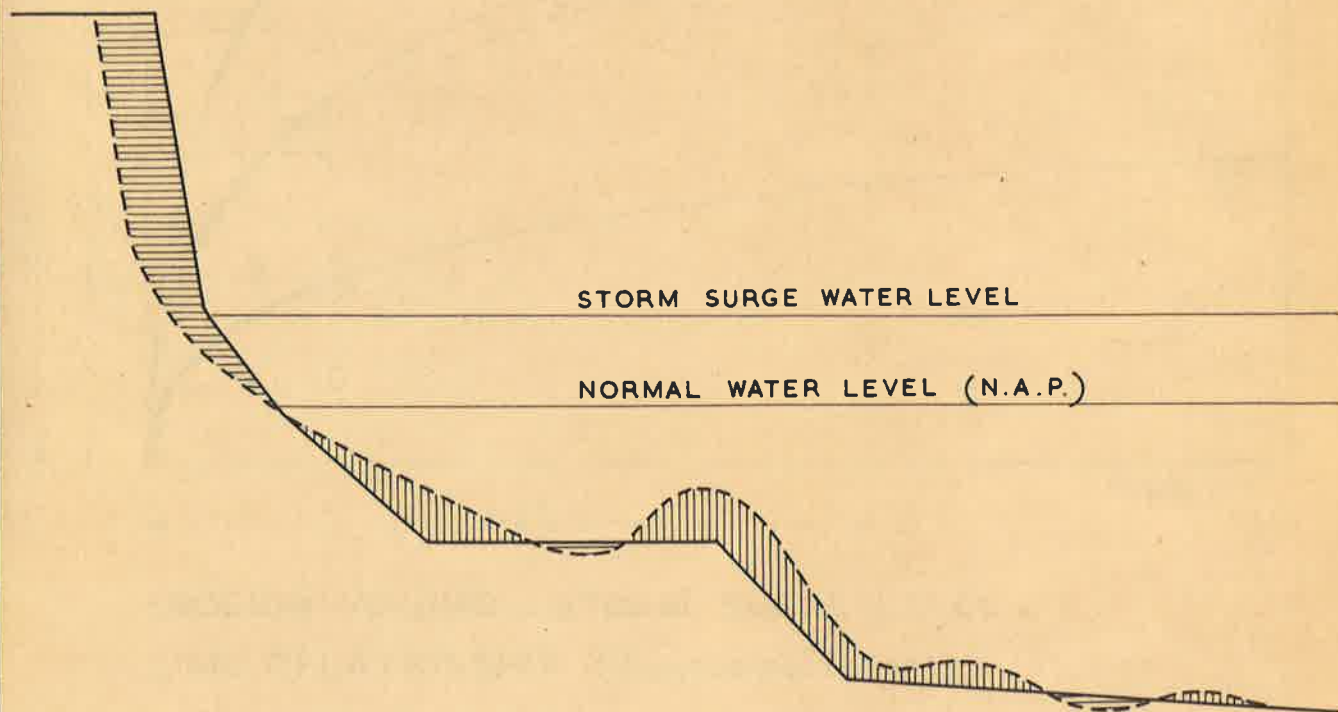
INITIAL PROFILE
FINAL PROFILE
EROSION
DEPOSITION

FOR MAXIMUM EROSION AT A GIVEN STORM SURGE LEVEL THE
TOTAL EROSION MUST EQUAL THE TOTAL DEPOSITON.

DETERMINATION OF AVERAGE MAXIMUM DUNE
RECESSION FROM INITIAL AND FINAL PROFILES

WATERLOOPKUNDIG LABORATORIUM | M.935/M.936 | FIG. 113
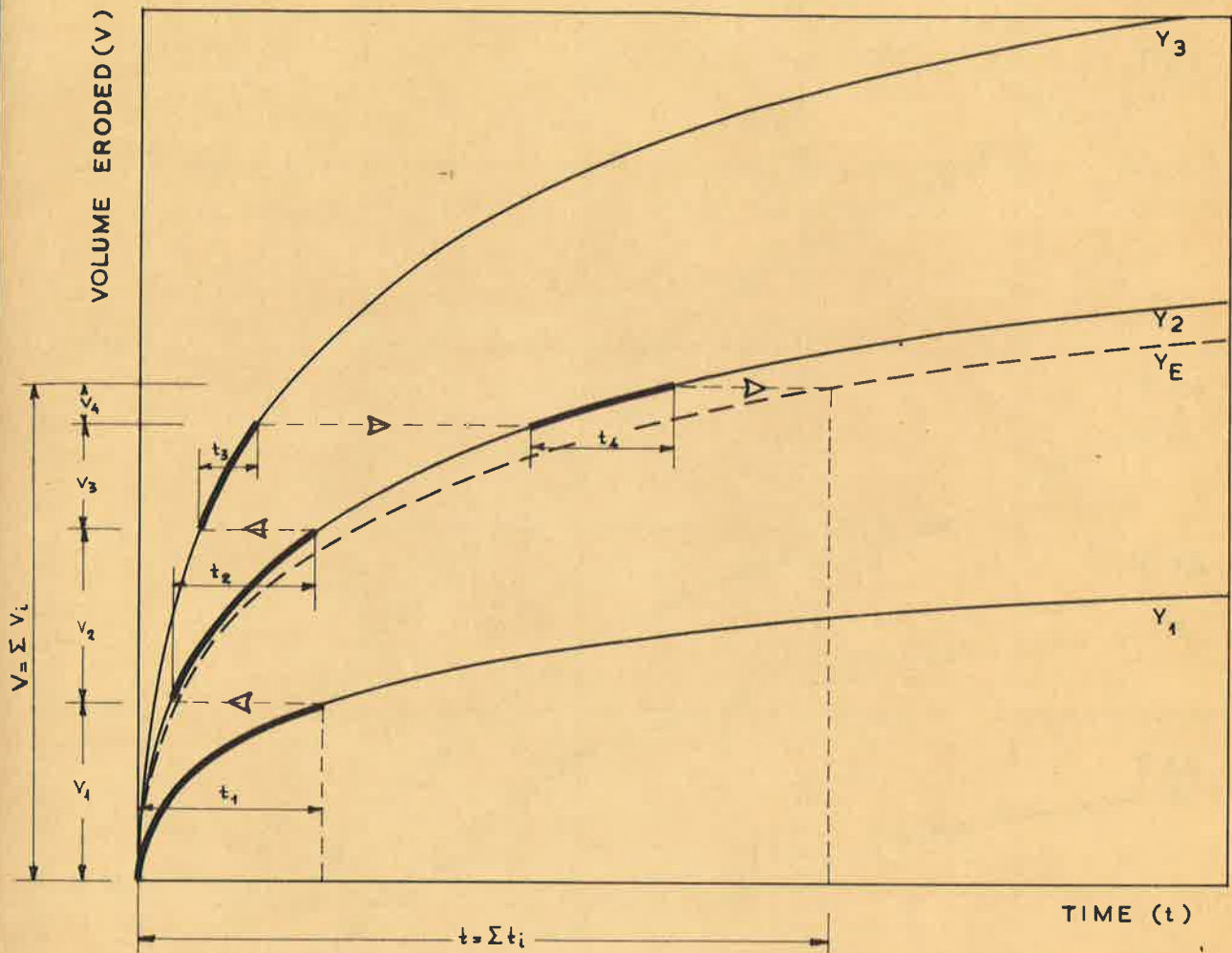
EROSION VOLUME — STORM SURGE LEVEL —
TIME RELATIONSHIP (diagrammatic only)
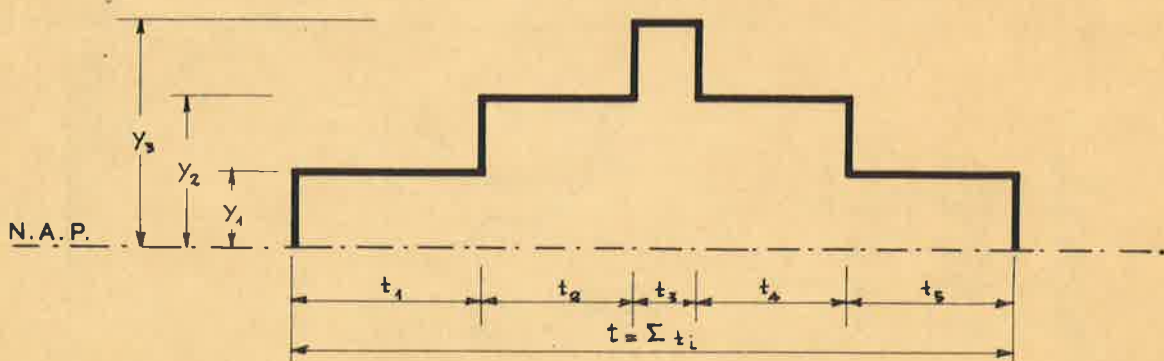
SIMPLIFIED STORM SURGE HYDROGRAPH

DETERMINATION OF EFFECTIVE		
STORM SURGE LEVEL		
WATERLOOPKUNDIG LABORATORIUM	M.935 / M.936	FIG. 114

ERODED VOLUME ABOVE STORM SURGE LEVEL IN m^3/m^1

TIME IN HOURS

T 26

T 14

T 15

T 16

T 17

$$V = 0.9 \ \frac{D_1}{D} \left\{ 1 - e^{-0.26 \sqrt{\frac{D}{D_1}} \ t} \right\}$$

T 26	$D_1/D =$	$8/13$
T 14	$D_1/D =$	$4/9$
T 15	$D_1/D =$	$3/8$
T 16	$D_1/D =$	$2/7$
T 17	$D_1/D =$	$1/6$
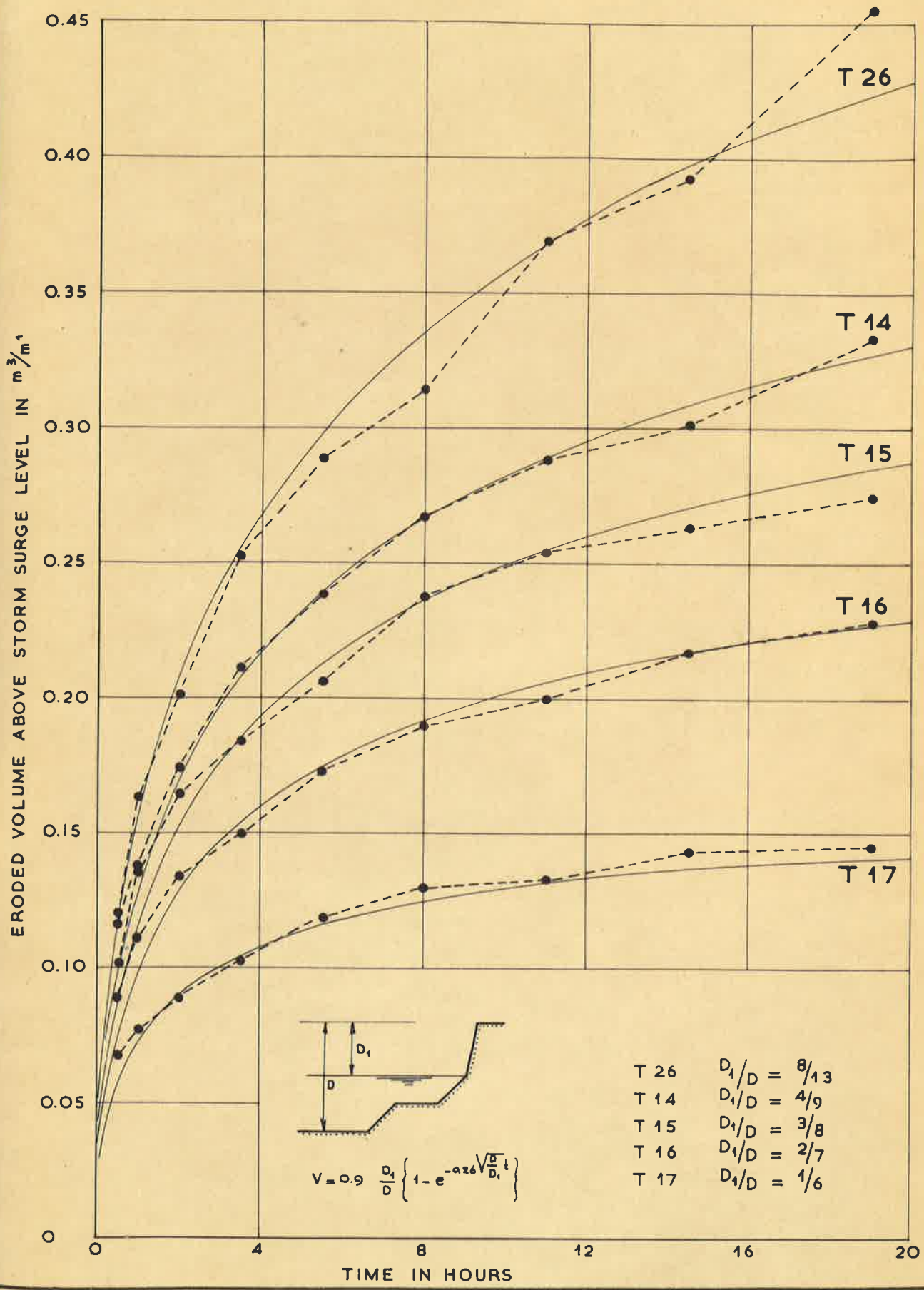
DUNE EROSION AS FUNCTION
OF DUNE HEIGHT AND TIME

WATERLOOPKUNDIG LABORATORIUM

M.935/M.936

FIG. 115

WATERLOOPKUNDIG LABORATORIUM

RAPPORT No: M 935/M 936

BEACH AND DUNE EROSION TESTS I

FIGURES

AUTEUR: M.R. Gourlay

DATUM: May 1968

CODE No:

Side Walls
(Hardboard and timber)

Sand Dune

Wave Filter

Large Basin

Wave Machines

Measure Bridge

20 m.

15.65 m.

Dividing Wall

Small Basin (Flume)

4.35 m.

0m   5 m   10 m   15 m   20m
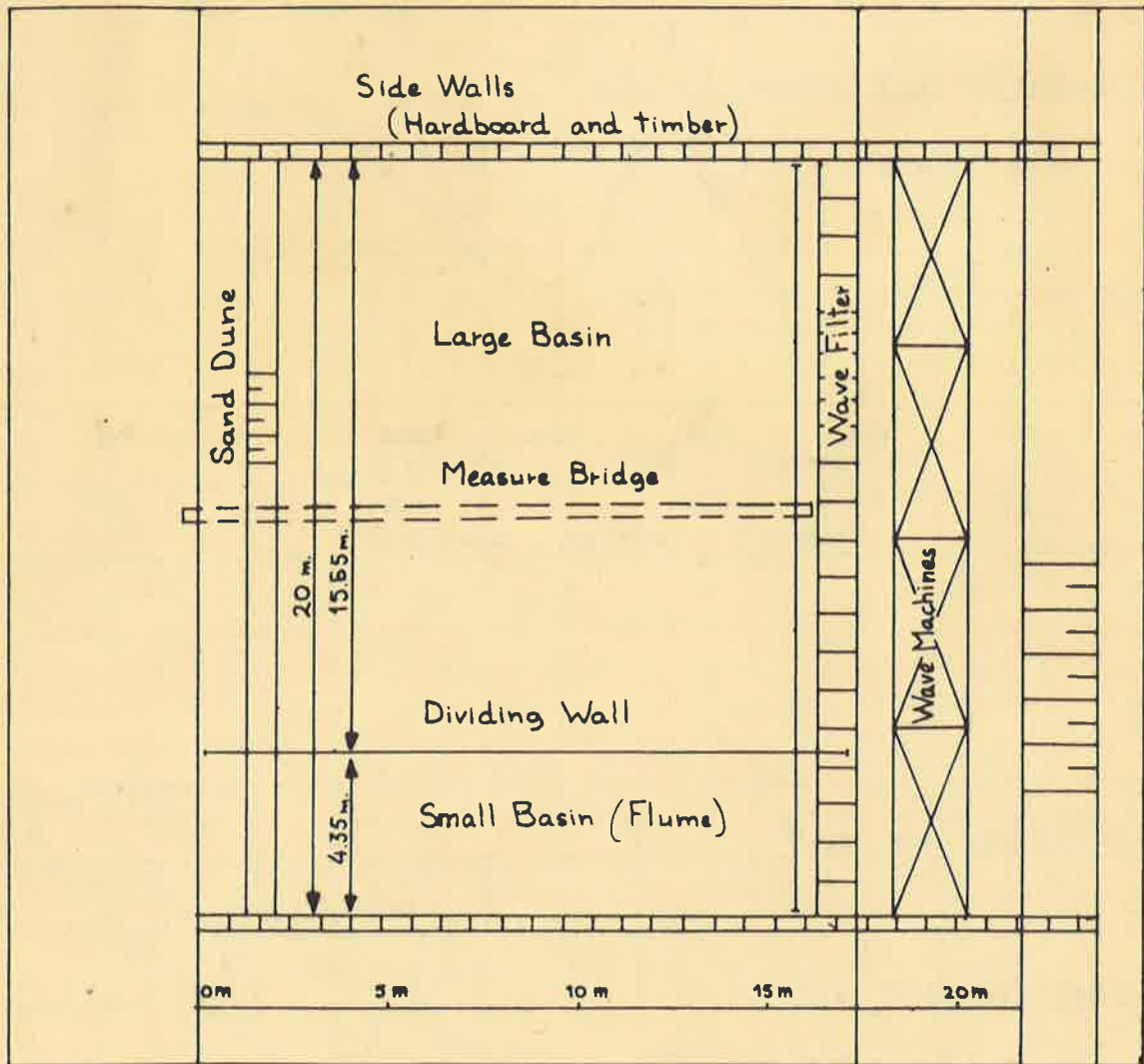
GENERAL LAYOUT OF OUTSIDE MODEL

Schaal 1 : 200

WATERLOOPKUNDIG LABORATORIUM   M 936   1

Mean Sea Level (N.A.P.)

Profile Z.H. 75/1965

Model Initial Profile

M.H.W.+0.74

M.L.W.-0.86

Elevation - metres (prototype)

Elevation - cms (model)

Distance - metres (prototype.)

Distance - metres (model)

Mean Sea Level (N.A.P.)

Profile Z.H. 80/1965

Model Initial Profile

M.H.W.+0.74

M.L.W.-0.83

Elevation - metres (prototype)

Elevation - cms (model)

Distance - metres (prototype)

Distance - metres (model)
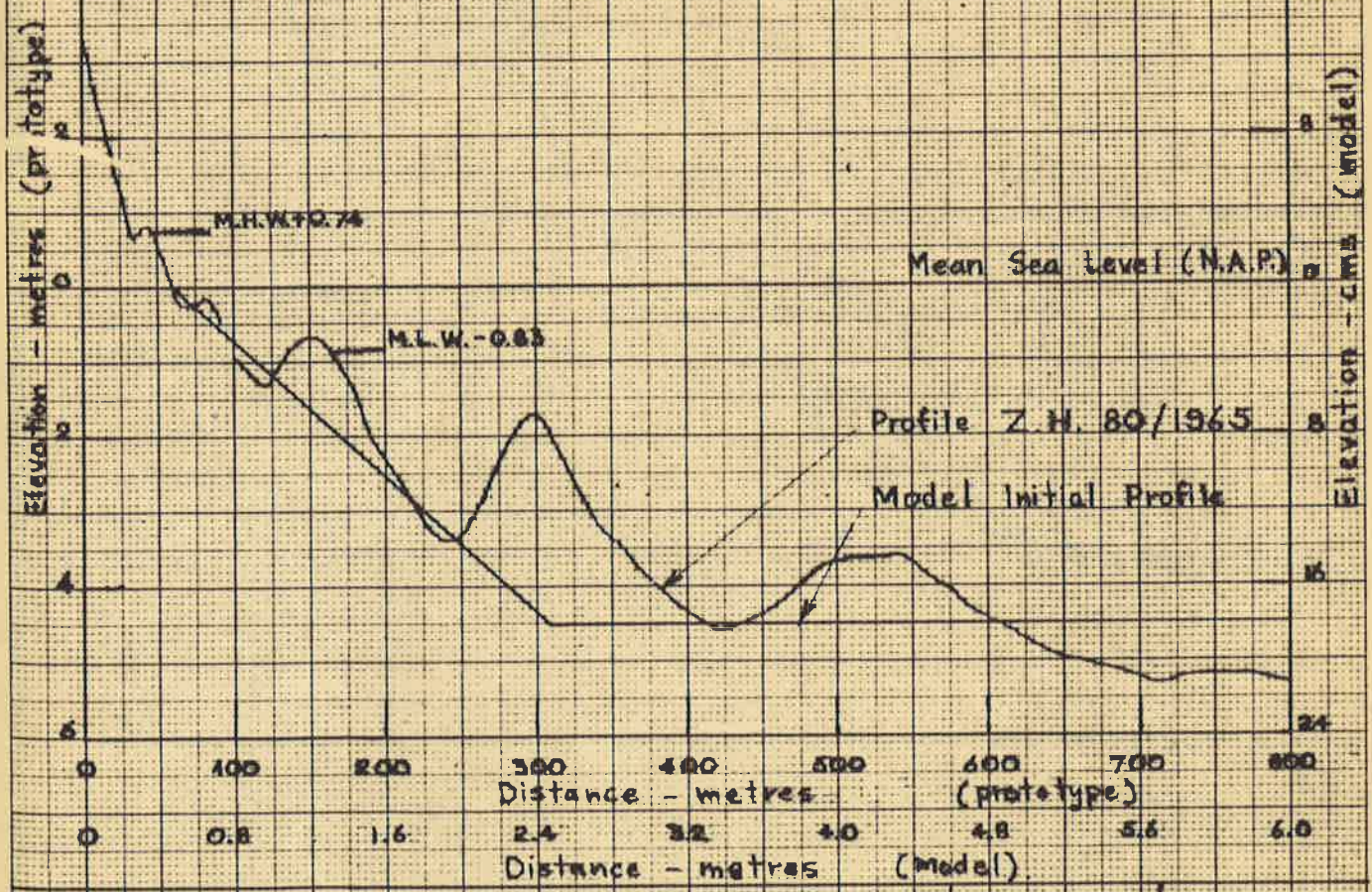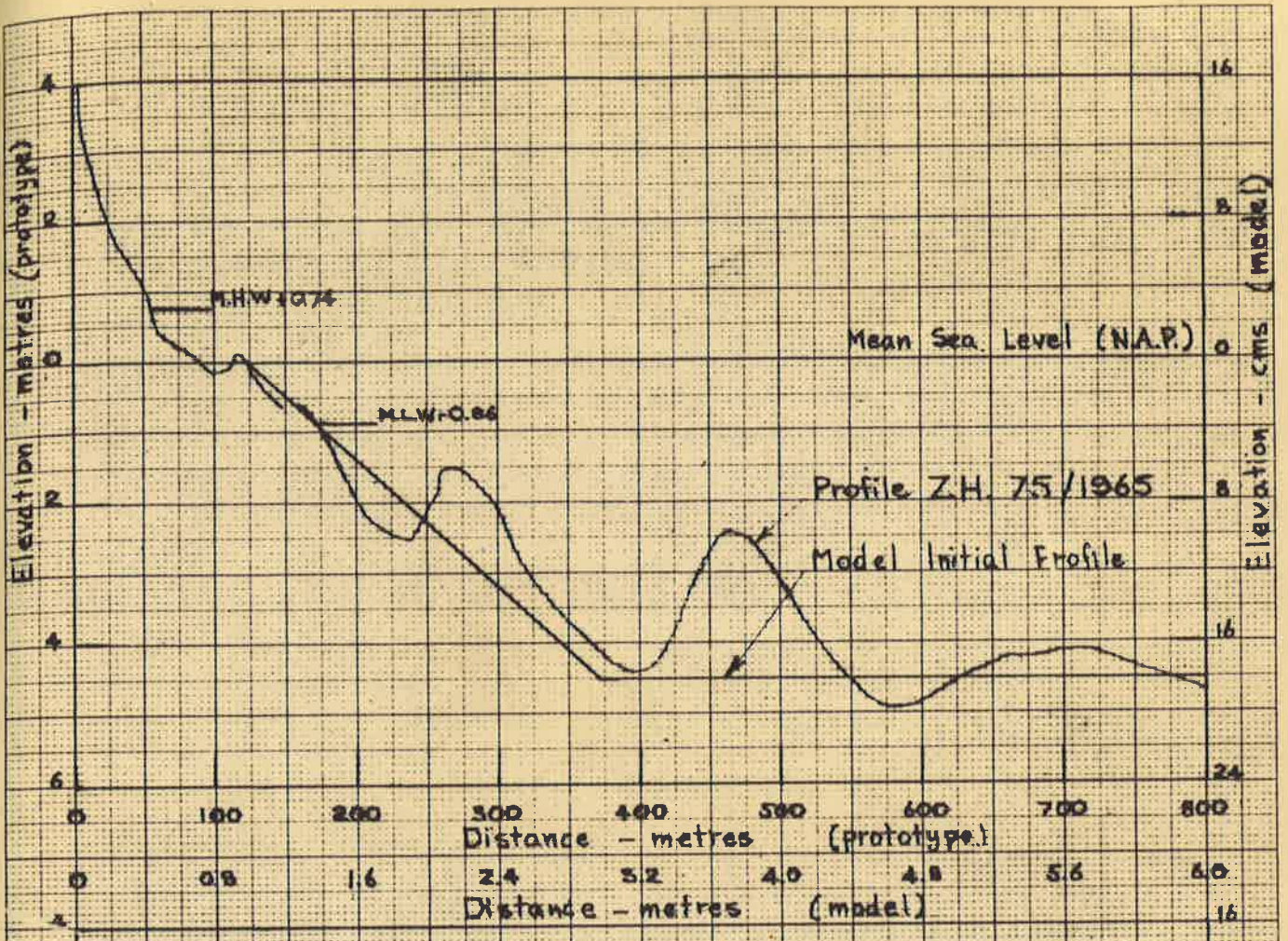
COMPARISON OF PROTOTYPE BEACH
PROFILES WITH MODEL INITIAL
PROFILE

2

Legend (top right):
- Original Profile
- Equilibrium Profile - 12½ Hours
- Adopted Initial Profile
- Actual Initial Profile T14
- Initial Profile after 2 Hours T14

Storm Surge Water Level

Normal Water Level (N.A.P.)

Height – cm

Depth – cm

Distance – metres
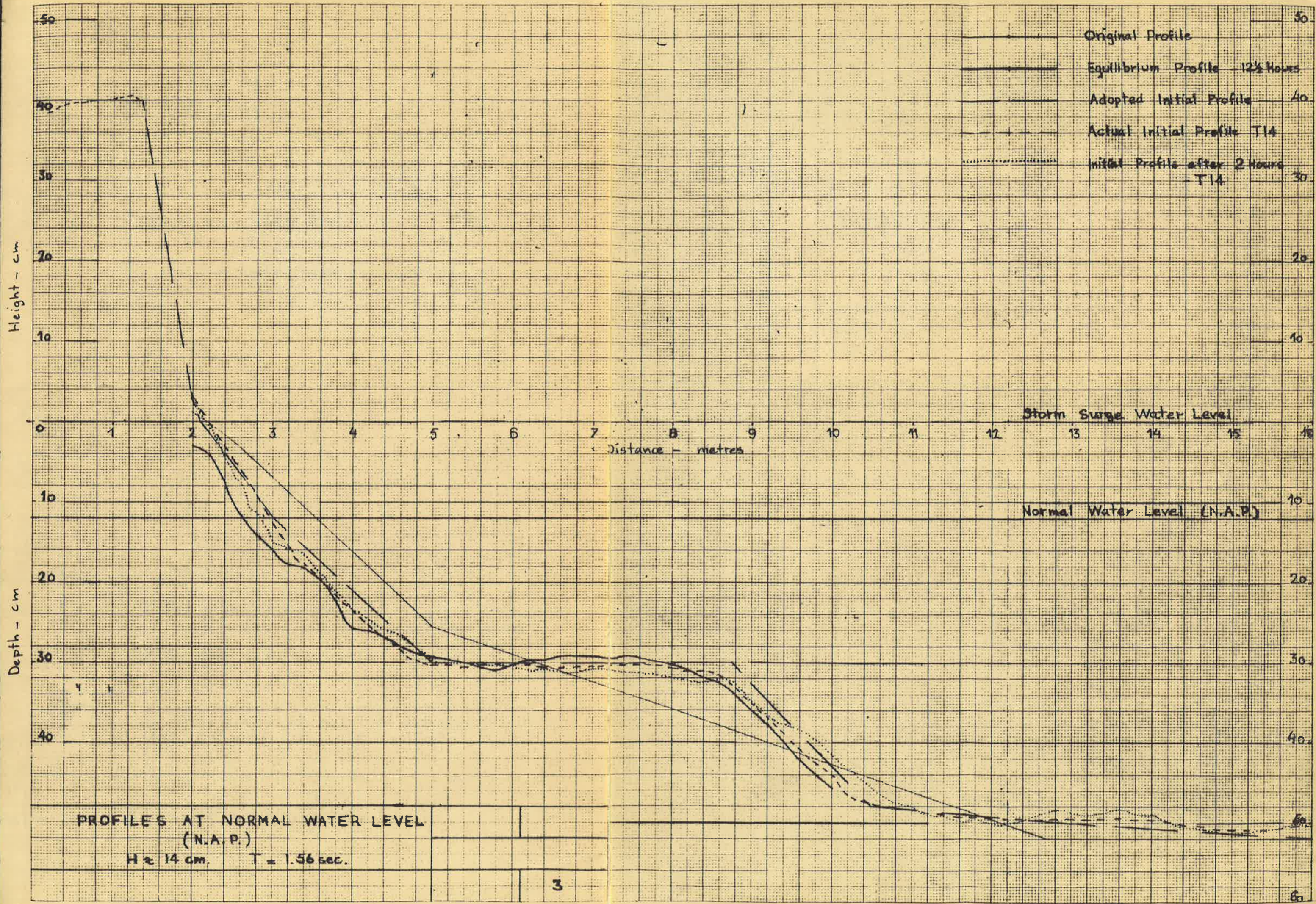
PROFILES AT NORMAL WATER LEVEL
(N.A.P.)
H = 14 cm.   T = 1.56 sec.

3

Dune Height - cm

40

T13

20

T11

T12

0

Storm surge water level

1.4   1.2   1.0   0.8   0.6   0.4   0.2   0.0

Distance from initial water line — metres

Dune Height - cm

80   T26

60

40   T14

T15

20   T16

T17

0   Storm surge water level

1.4   1.2   1.0   0.8   0.6   0.4   0.2   0.0

Distance from initial water line — metres
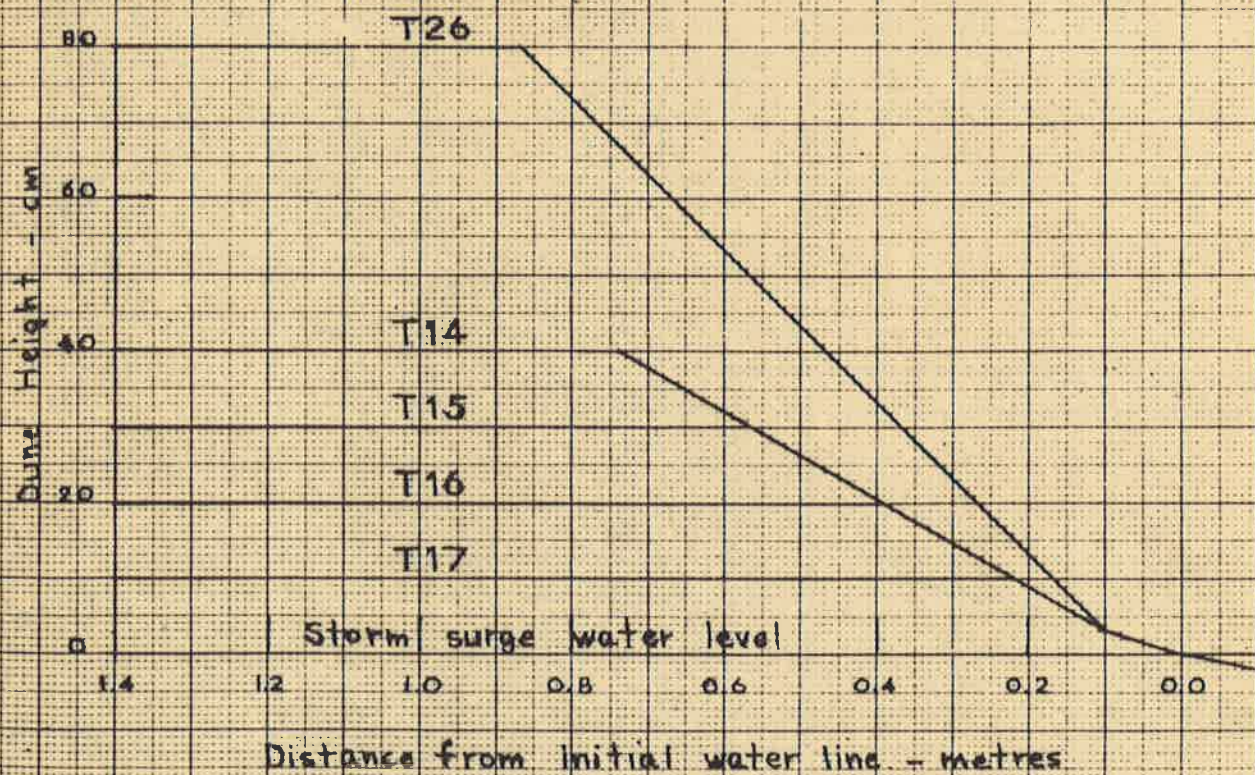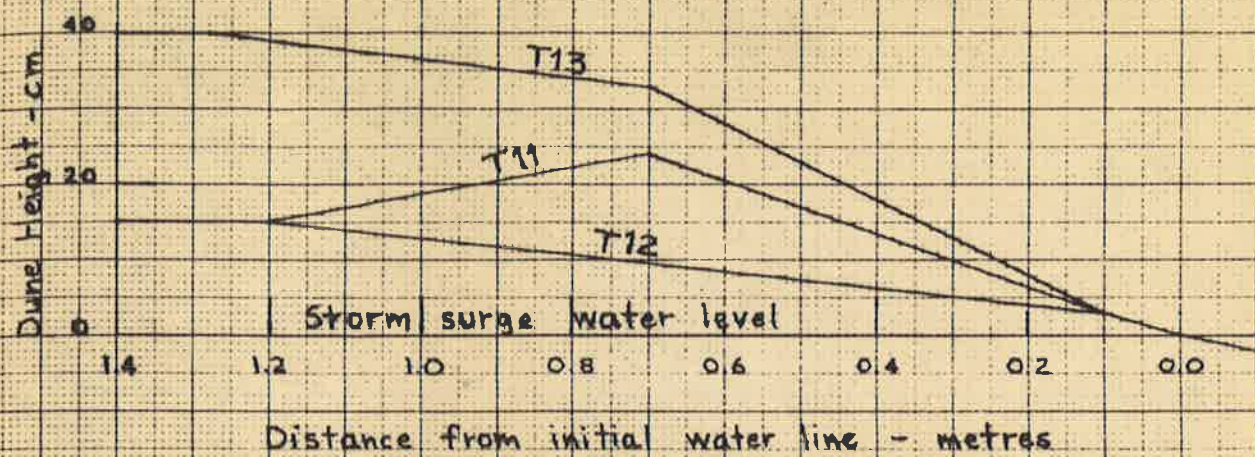
Note

The sand dune profile of test T14 was used in all
tests in both the wind flume and small outside basin

SAND DUNE PROFILES FOR VARIOUS
TESTS.

4
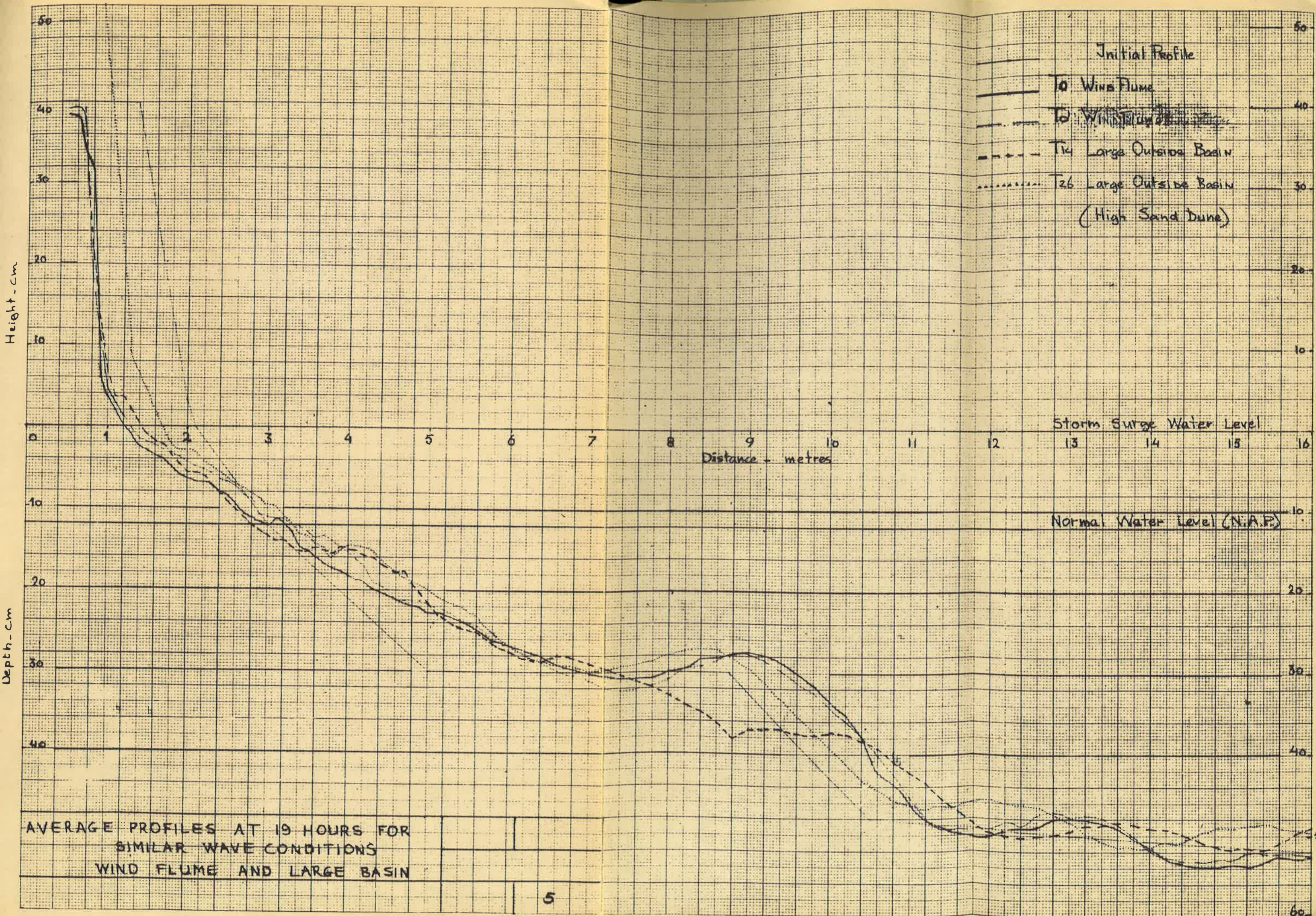
Initial Profile

To Wind Flume

To Wind Flume ....

T14 Large Outside Basin

T26 Large Outside Basin

(High Sand Dune)

Storm Surge Water Level

Normal Water Level (N.A.P.)

Height - cm

Depth - cm

Distance - metres

AVERAGE PROFILES AT 19 HOURS FOR
SIMILAR WAVE CONDITIONS
WIND FLUME AND LARGE BASIN

5

Height - cm.

Depth - cm.

Distance - metres
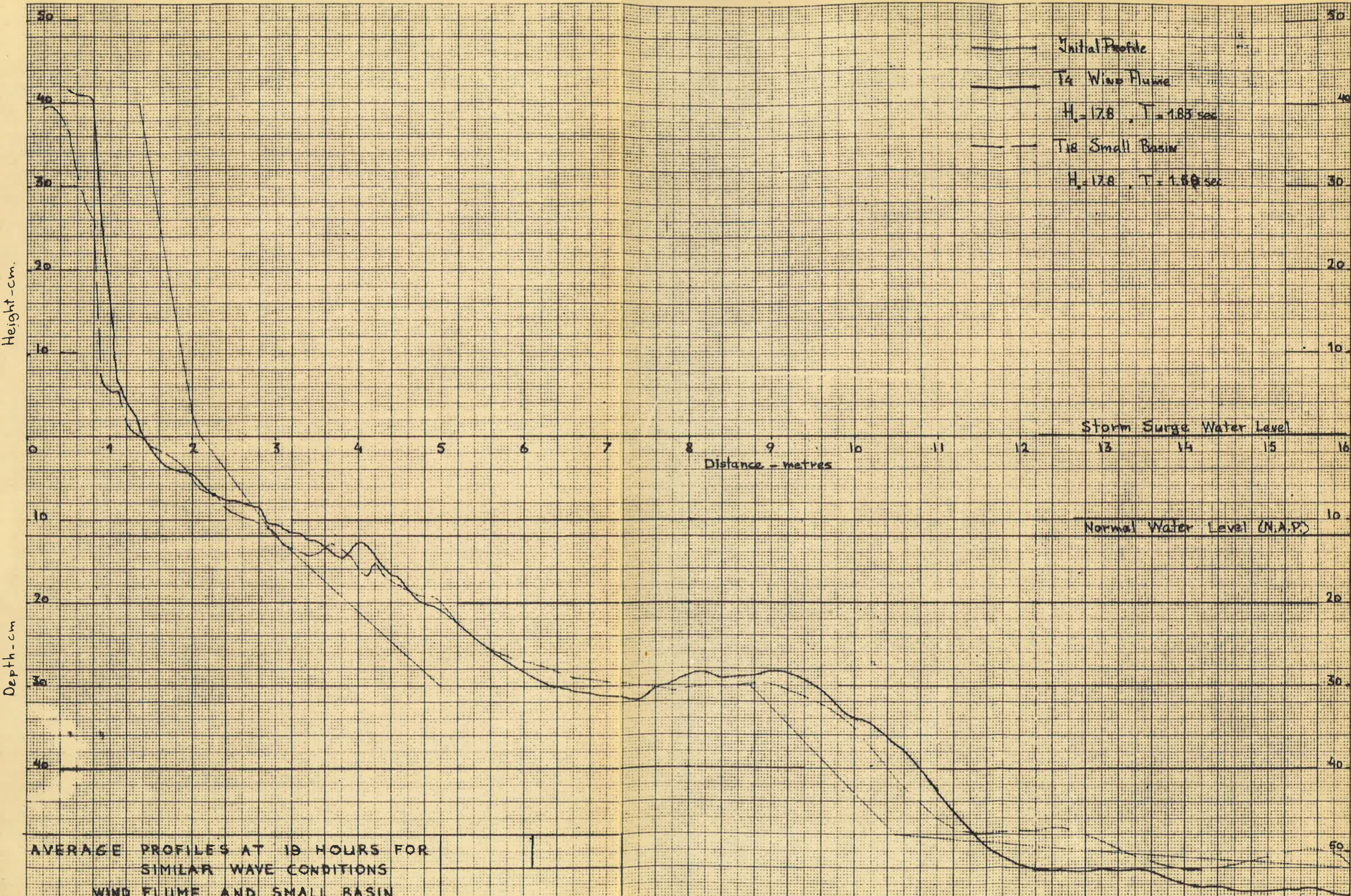
Initial Profile

T4 Wind Flume
H₀ = 17.8 . T = 1.85 sec

T18 Small Basin
H₀ = 17.8 . T = 1.80 sec

Storm Surge Water Level

Normal Water Level (N.A.P.)

AVERAGE PROFILES AT 19 HOURS FOR
SIMILAR WAVE CONDITIONS
WIND FLUME AND SMALL BASIN

6
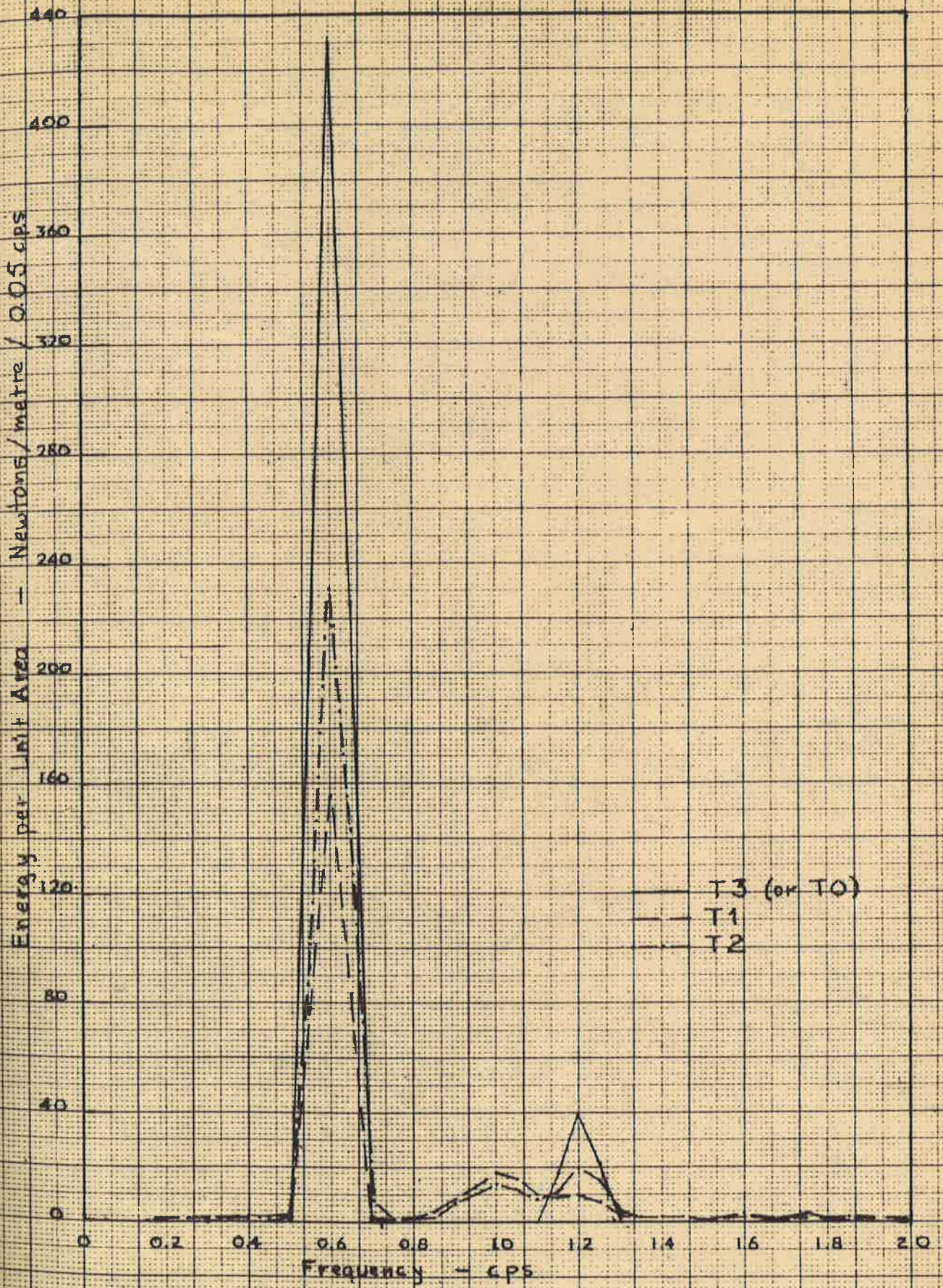
WAVE SPECTRA FOR TESTS
T3, T1 AND T2.

7
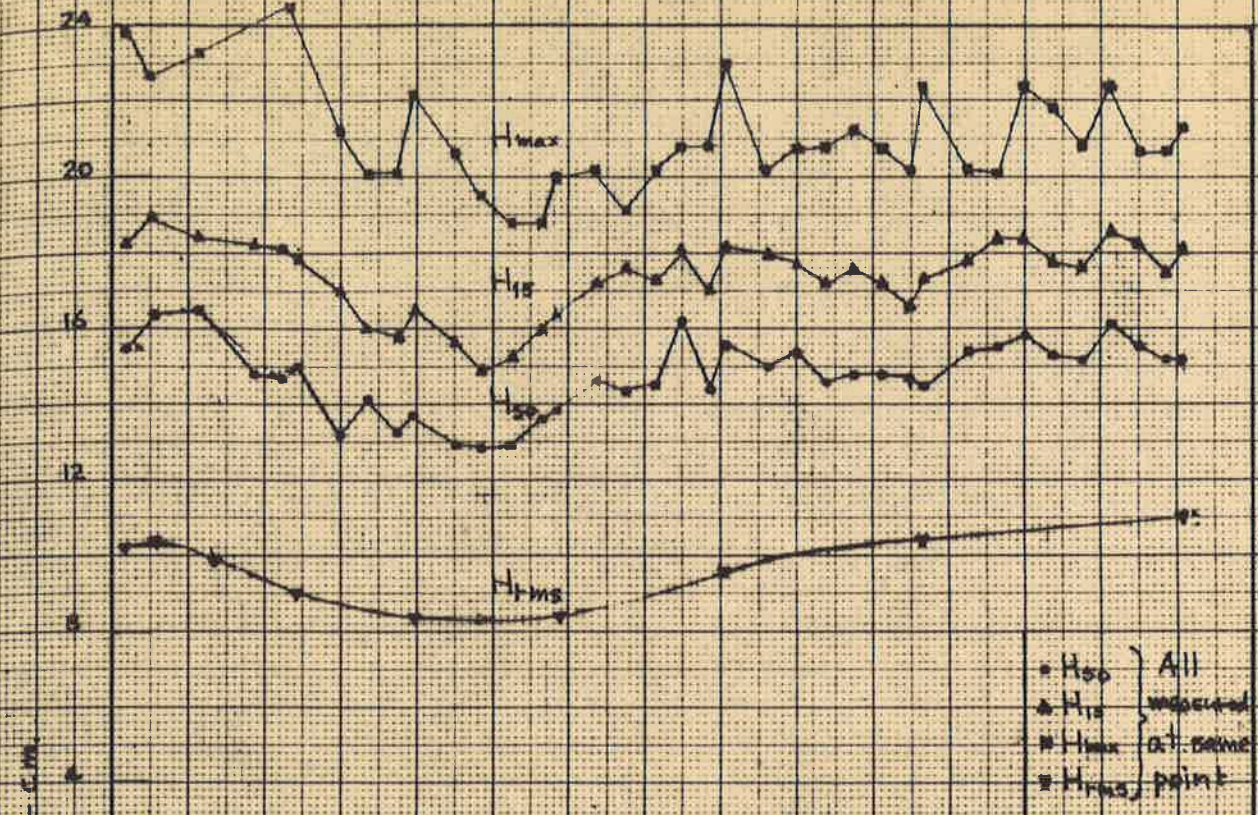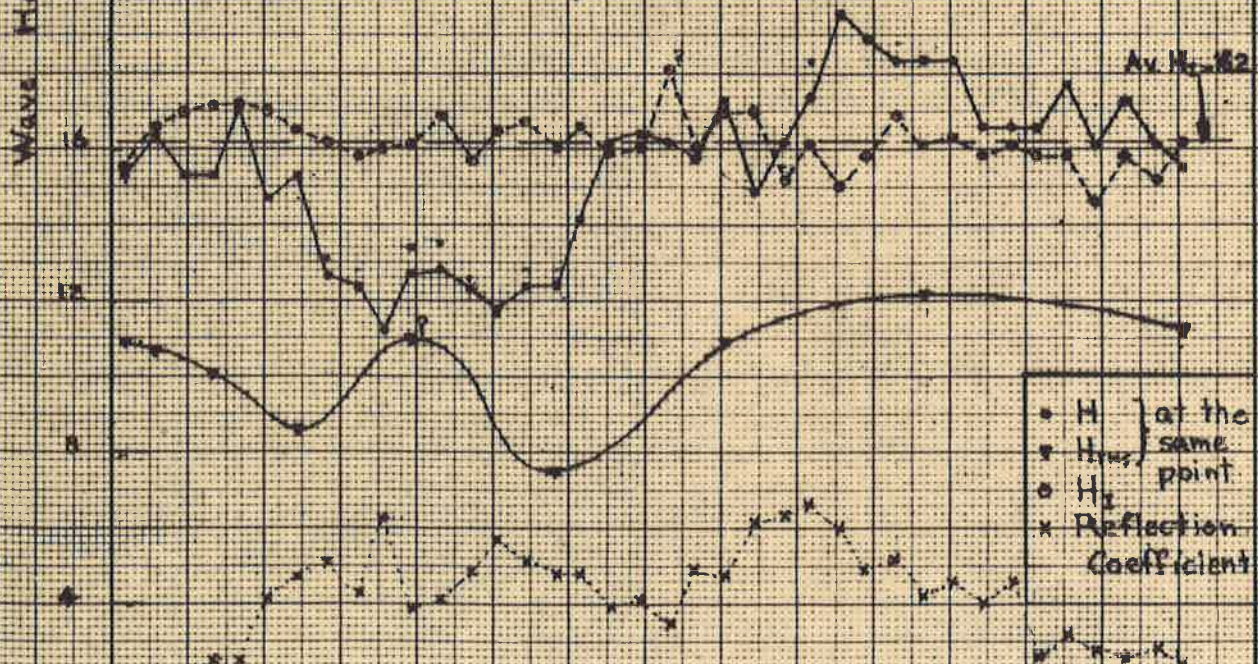
EFFECT OF WAVE REFLECTION ON WAVE HEIGHT MEASUREMENTS OF REGULAR AND IRREGULAR WAVES

8
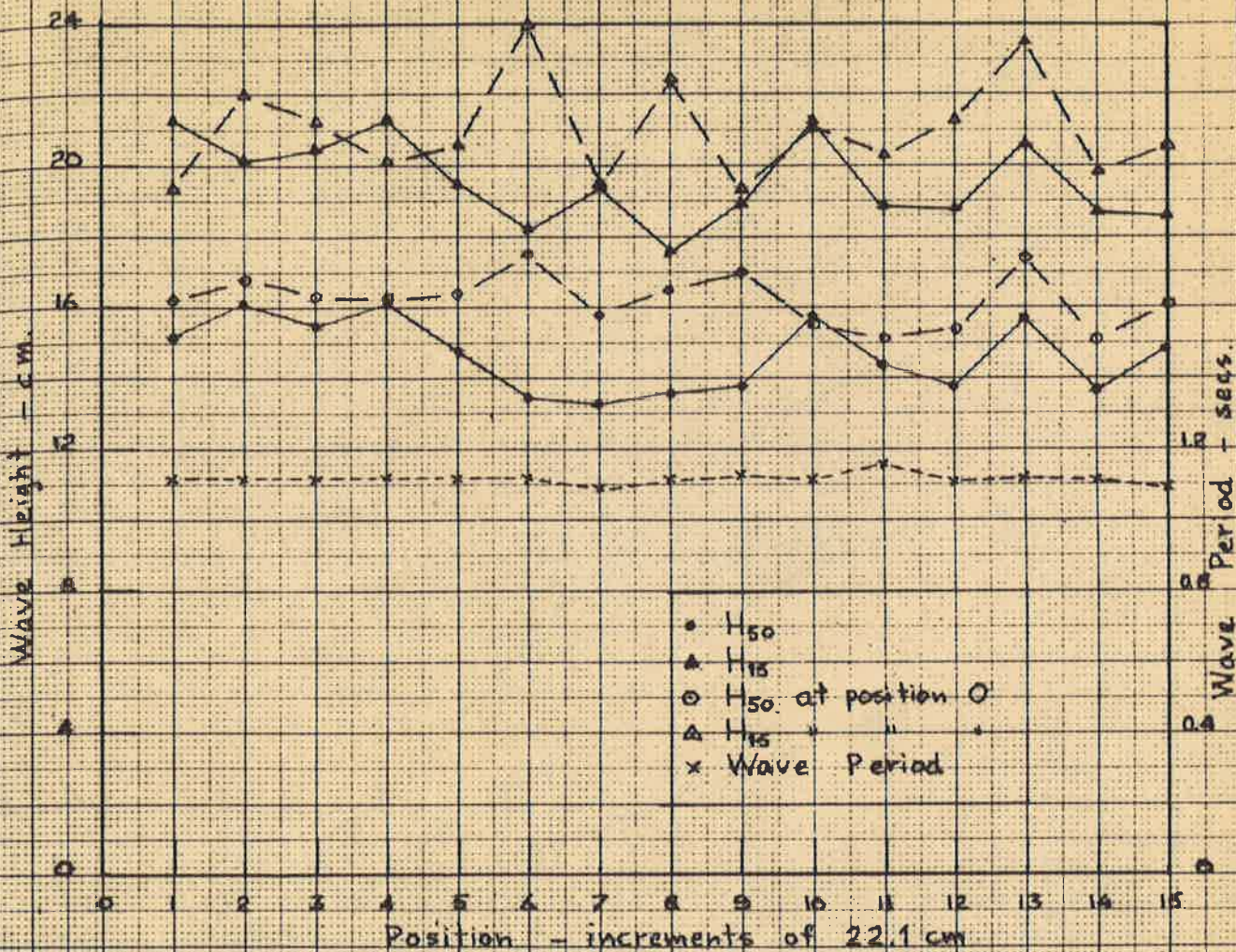
(a) Effect of Measurement Position upon Wind Wave Height.

Legend:
- H_{50}
- H_{15}
- H_{50} at position O'
- H_{15} " "
- × Wave Period

Position – increments of 22.1 cm

$H_{rms} = 0.707 H$

- ▲ T3
- ● T4
- ✶ J24
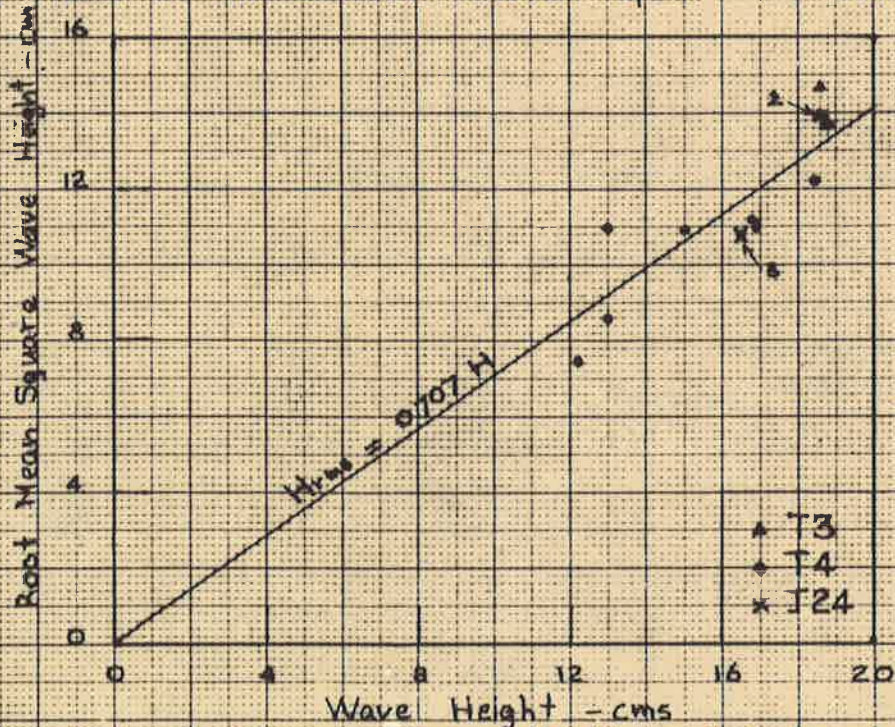
(b) Relation between Measured Wave Height and Root Mean Square Height for Regular Waves

EFFECT OF MEASUREMENT POSITION ON WIND
WAVE HEIGHT AND RELATIONSHIP BETWEEN
H and H$_{rms}$ FOR REGULAR WAVES

9
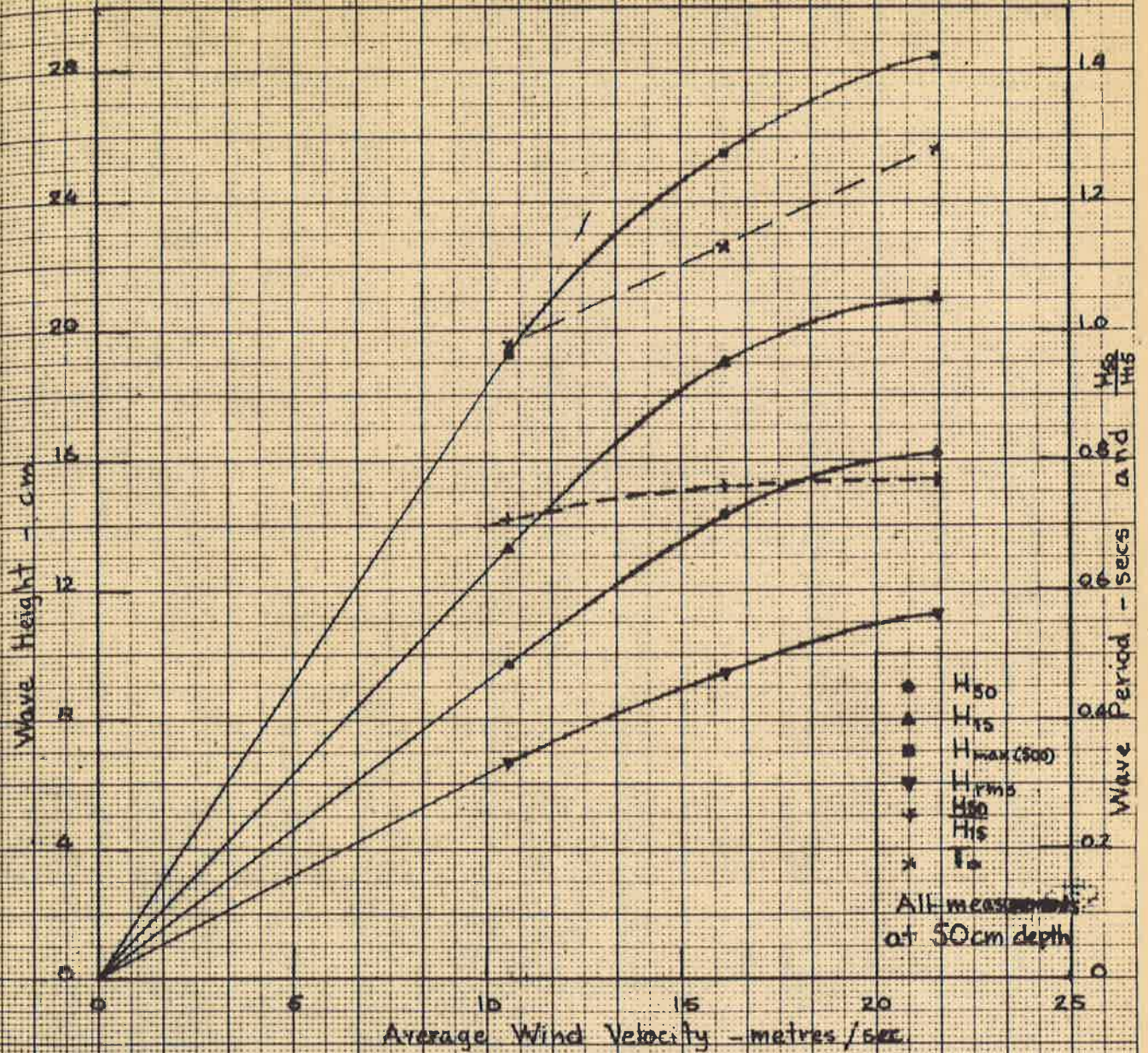
(a) Wave Characteristics for Wind Wave Tests
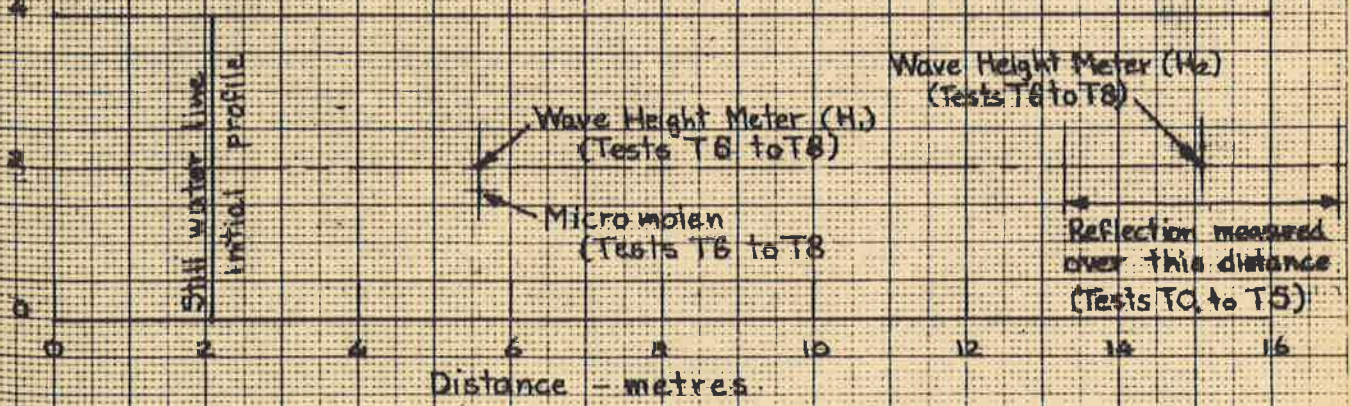
(b) Wave Measurement Positions

WAVE CHARACTERISTICS WIND WAVE TESTS
AND
WAVE MEASUREMENT POSITIONS

10
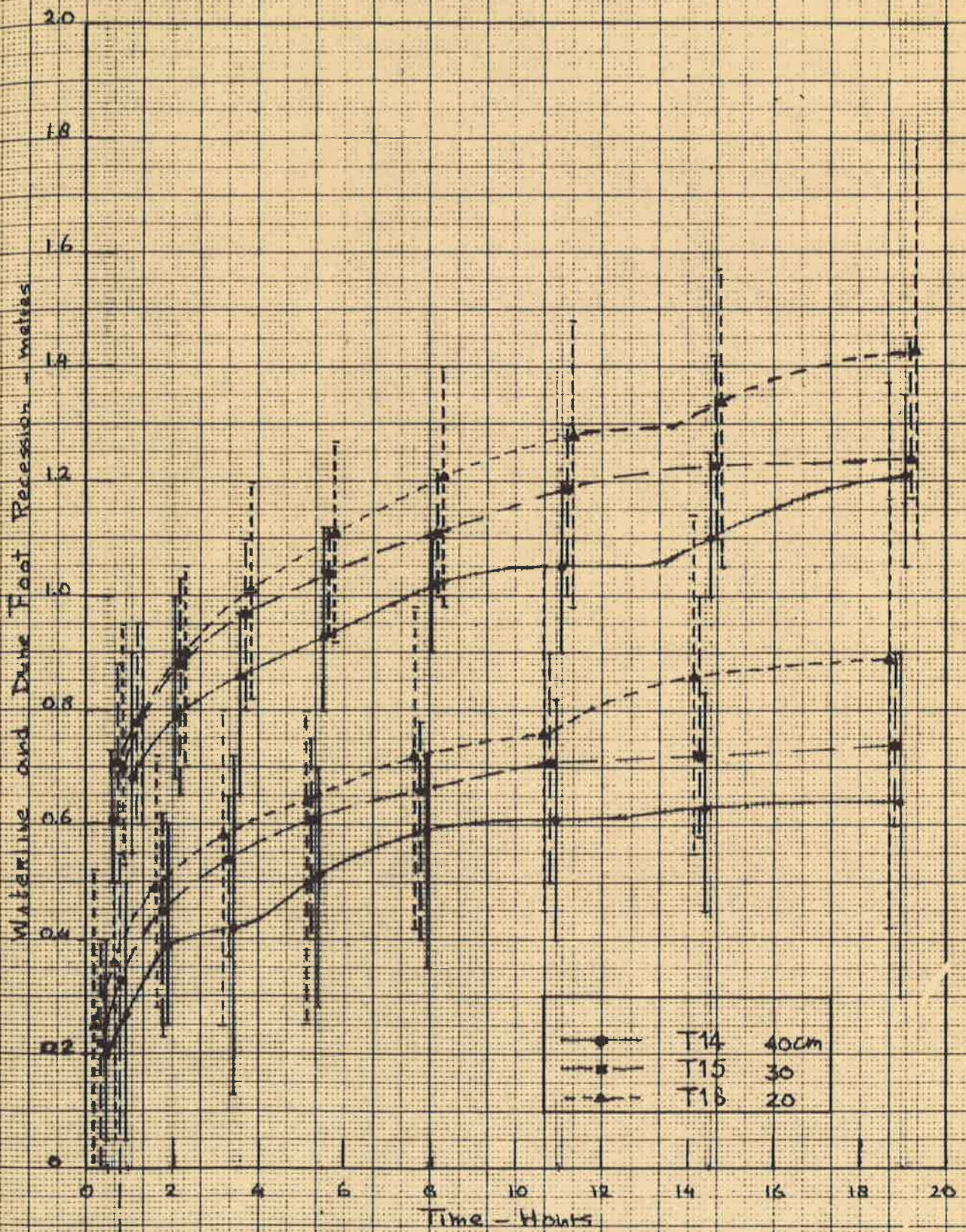
VARIATION OF WATERLINE AND DUNE
FOOT POSITIONS — TESTS T14, T15 and T16
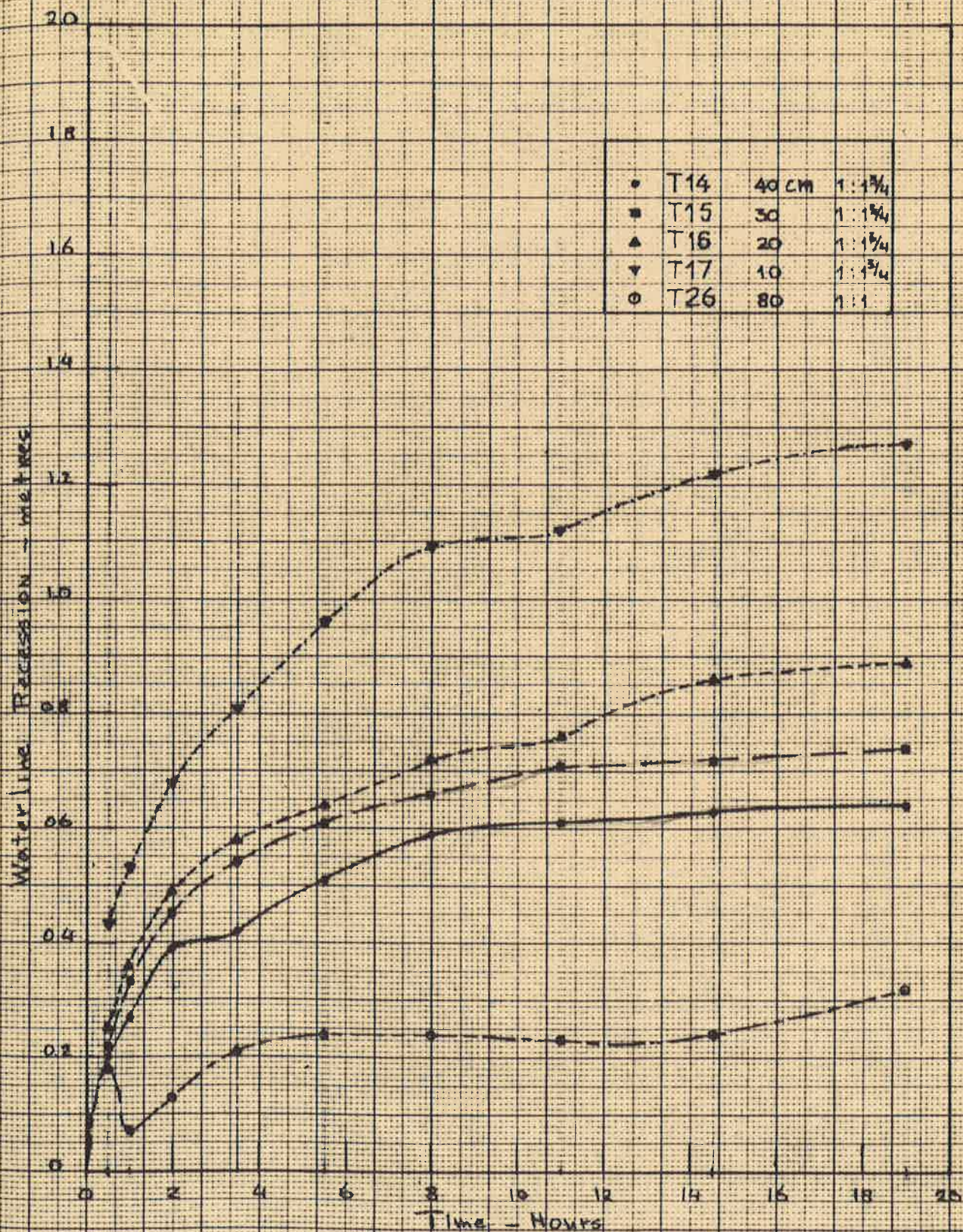
11

RECESSION OF WATERLINE FOR
VARIOUS DUNE HEIGHTS
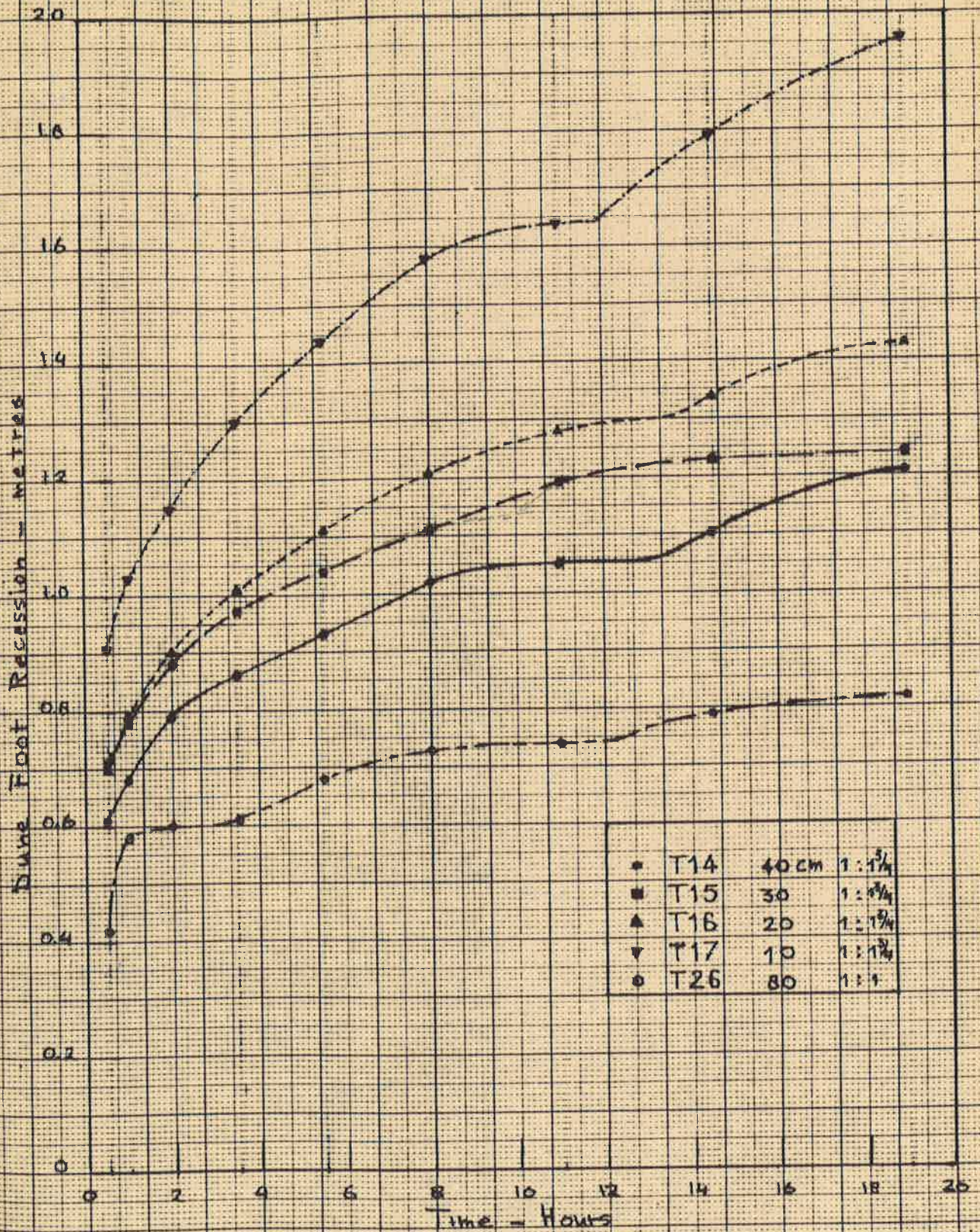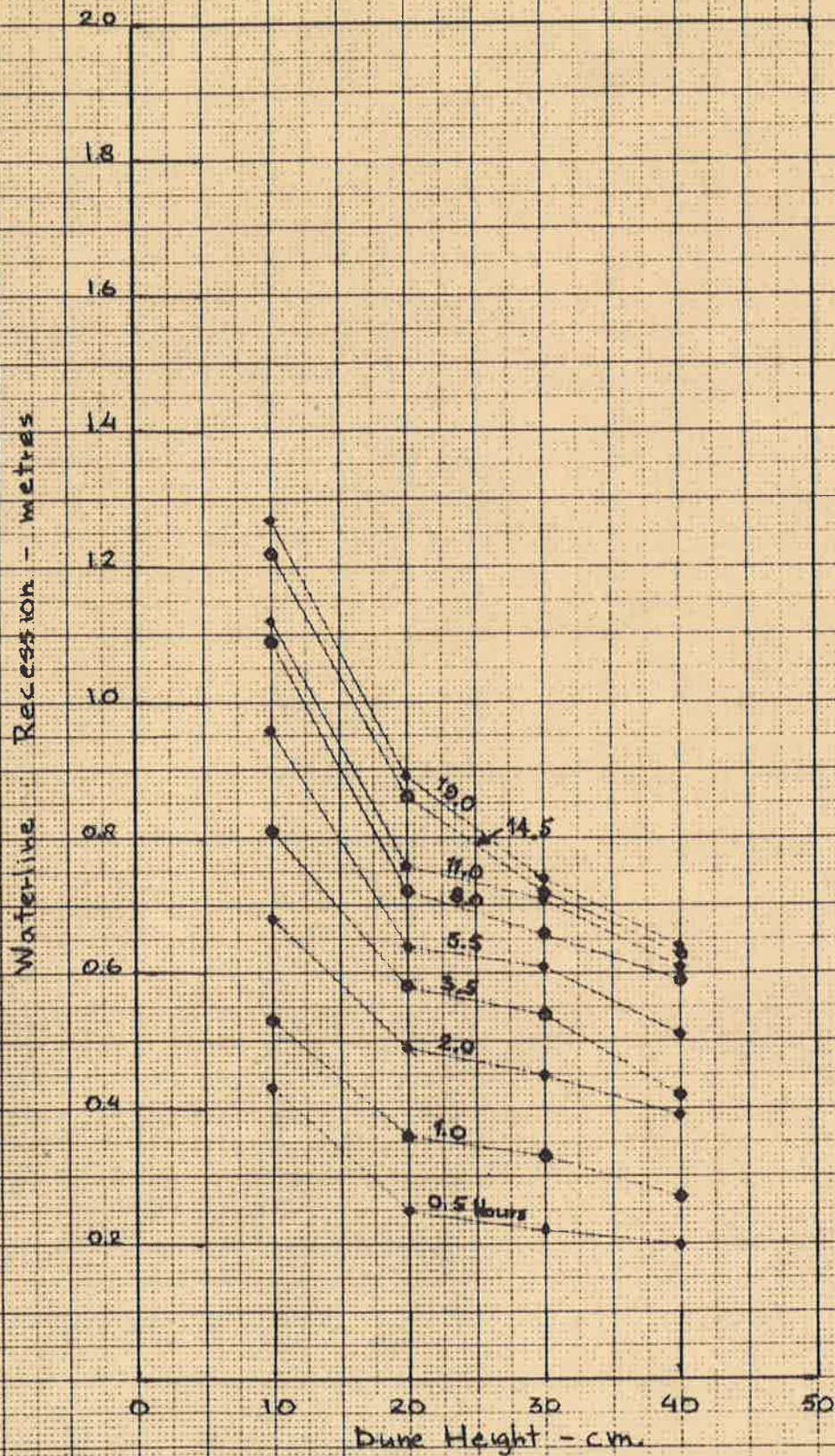
Legend (within figure):

•	T14	40 cm	1 : 1¾
■	T15	30	1 : 1¾
▲	T16	20	1 : 1¾
▼	T17	10	1 : 1¾
⊙	T26	80	1 : 1

Y-axis: Waterline Recession — metres

X-axis: Time — Hours

12

RECESSION OF DUNE FOOT
FOR VARIOUS DUNE HEIGHTS.

T14	40 cm	1 : 1⅝
T15	30	1 : 1⅝
T16	20	1 : 1⅝
T17	10	1 : 1⅝
T26	80	1 : 1

13

WATERLINE RECESSION AS FUNCTION OF DUNE HEIGHT.

14

DUNE FOOT RECESSION AS
FUNCTION OF DUNE HEIGHT

Chart axes:
- Y-axis: Waterline Recession - metres. (5.0, 2.0, 1.0, 0.5, 0.2, 0.1)
- X-axis: Dune Height - cm. (1, 2, 5, 10, 20, 50)

Curve labels: 19, 14.5, 11.0, 8.0, 5.5, 3.5, 2.0, 1.0, 0.5 Hours

WATERLINE RECESSION AS FUNCTION
OF DUNE HEIGHT - LOGARITHMIC SCALES

16

Upper chart:

$a = x\,h^{0.5}$

$a = x\,h^{0.5}$ – metre cm$^{0.5}$ (vertical axis)

$a = 0.41 \log t + 1.71$

Time - Hours

Lower chart:

$x\,h^{0.5}$ – metre . cm$^{0.5}$ (vertical axis)

Time - Hours

•	T 14	40 cm	1 : 1¾
■	T 15	30	1 : 1¾
▲	T 16	20	1 : 1¾
▼	T 17	10	1 : 1¾
◉	T 26	80	1 : 1
+	T 12	15	1 : 10
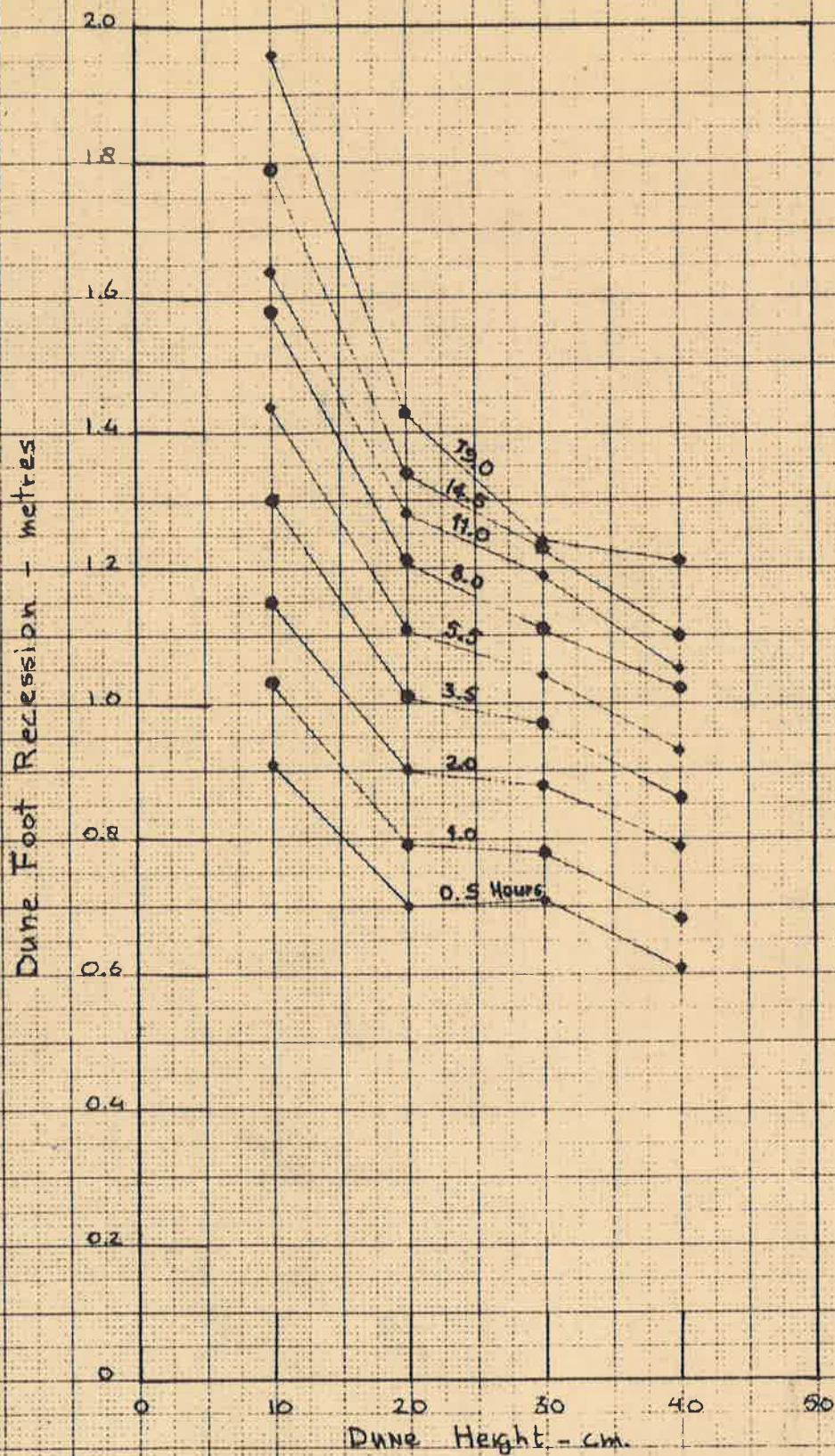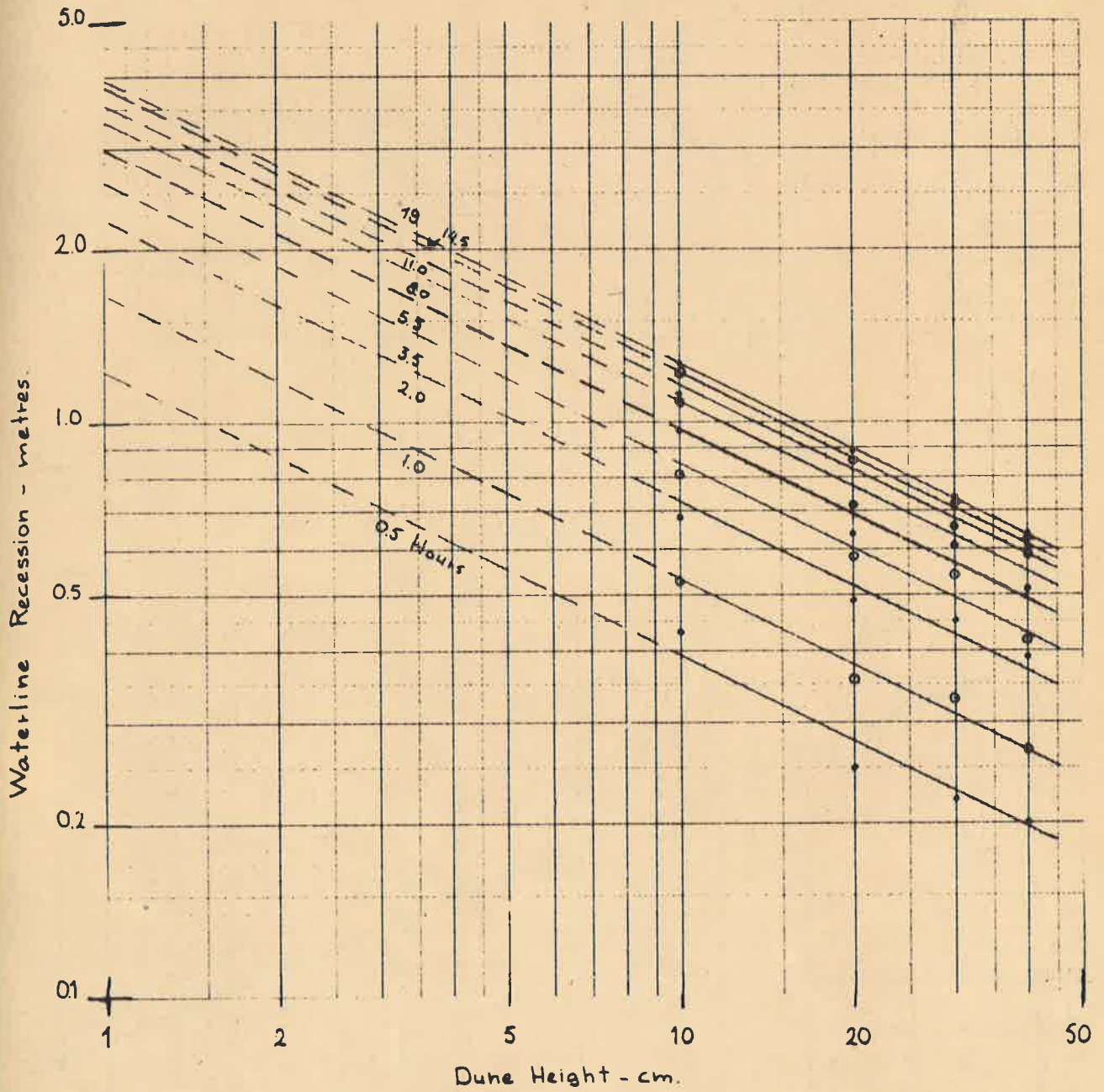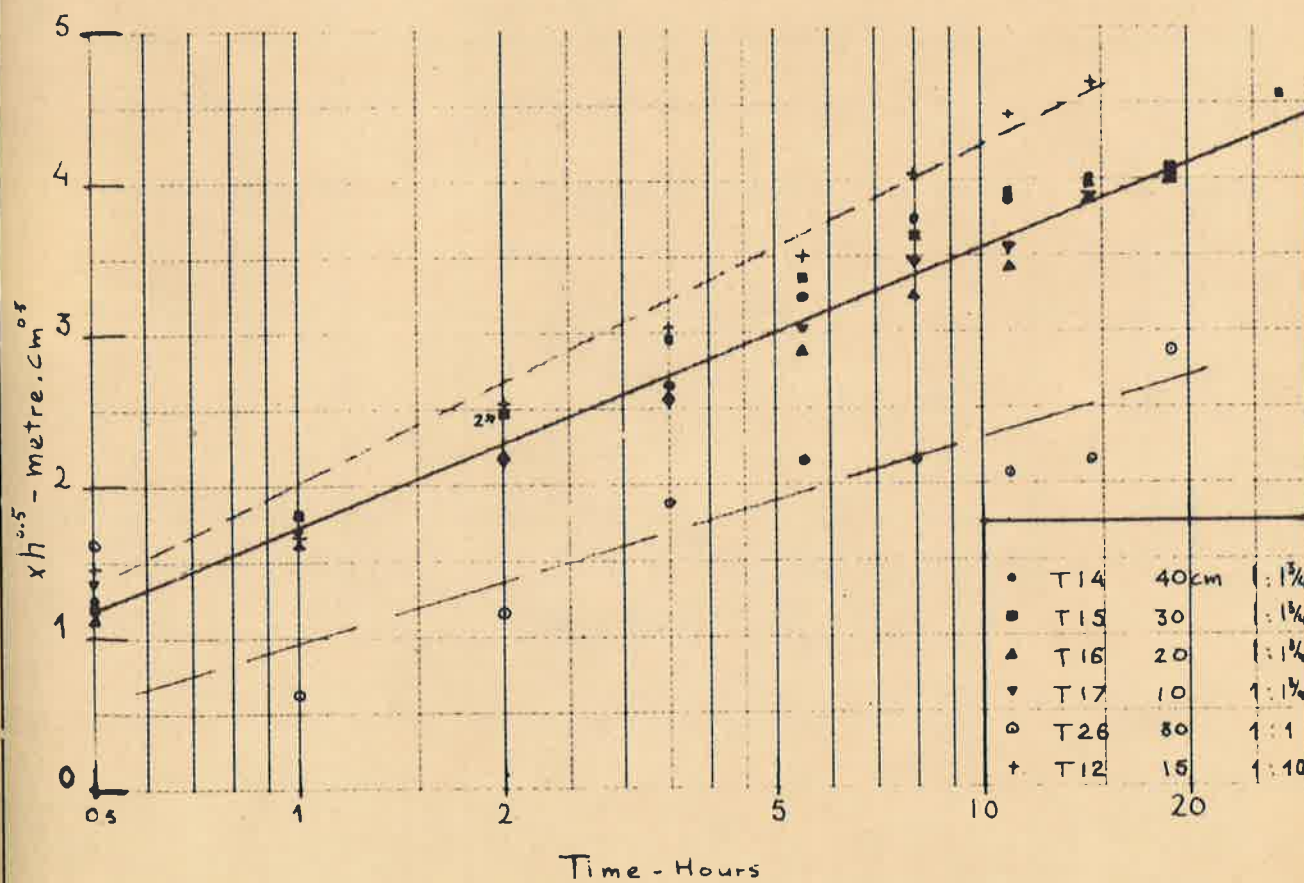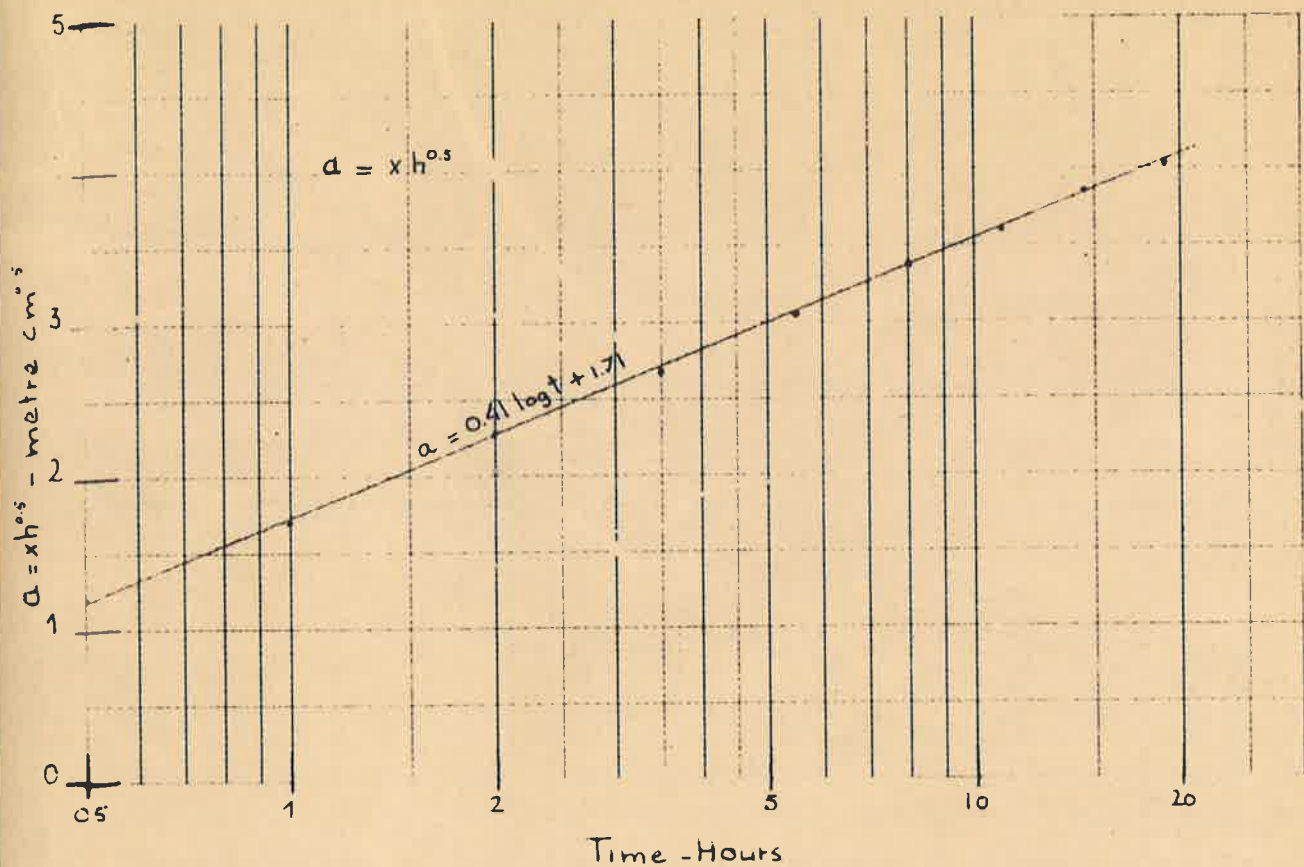
RELATION BETWEEN WATERLINE POSITION
DUNE HEIGHT AND TIME
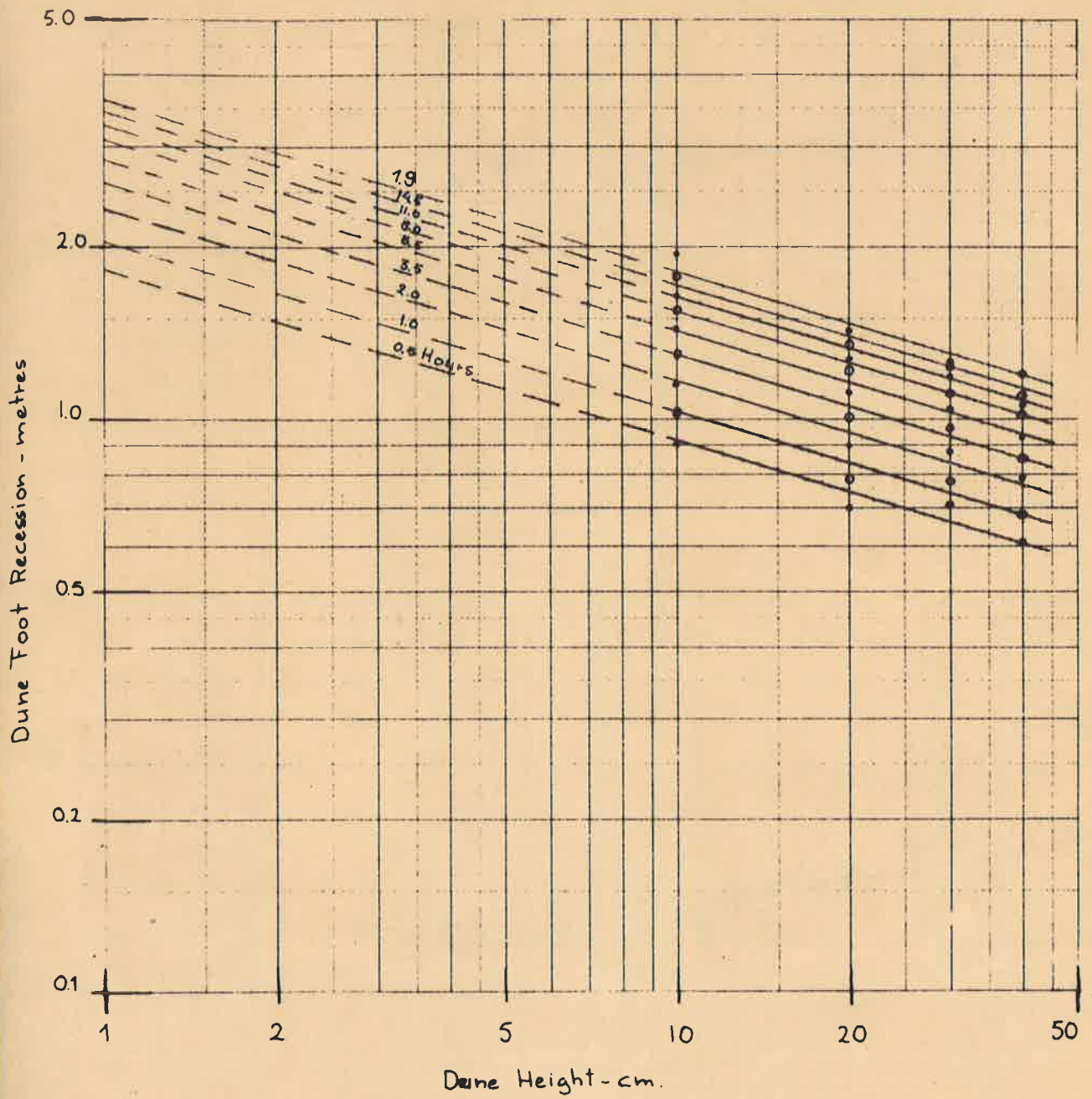
17

DUNE FOOT RECESSION AS FUNCTION OF
DUNE HEIGHT - LOGARITHMIC SCALES

18
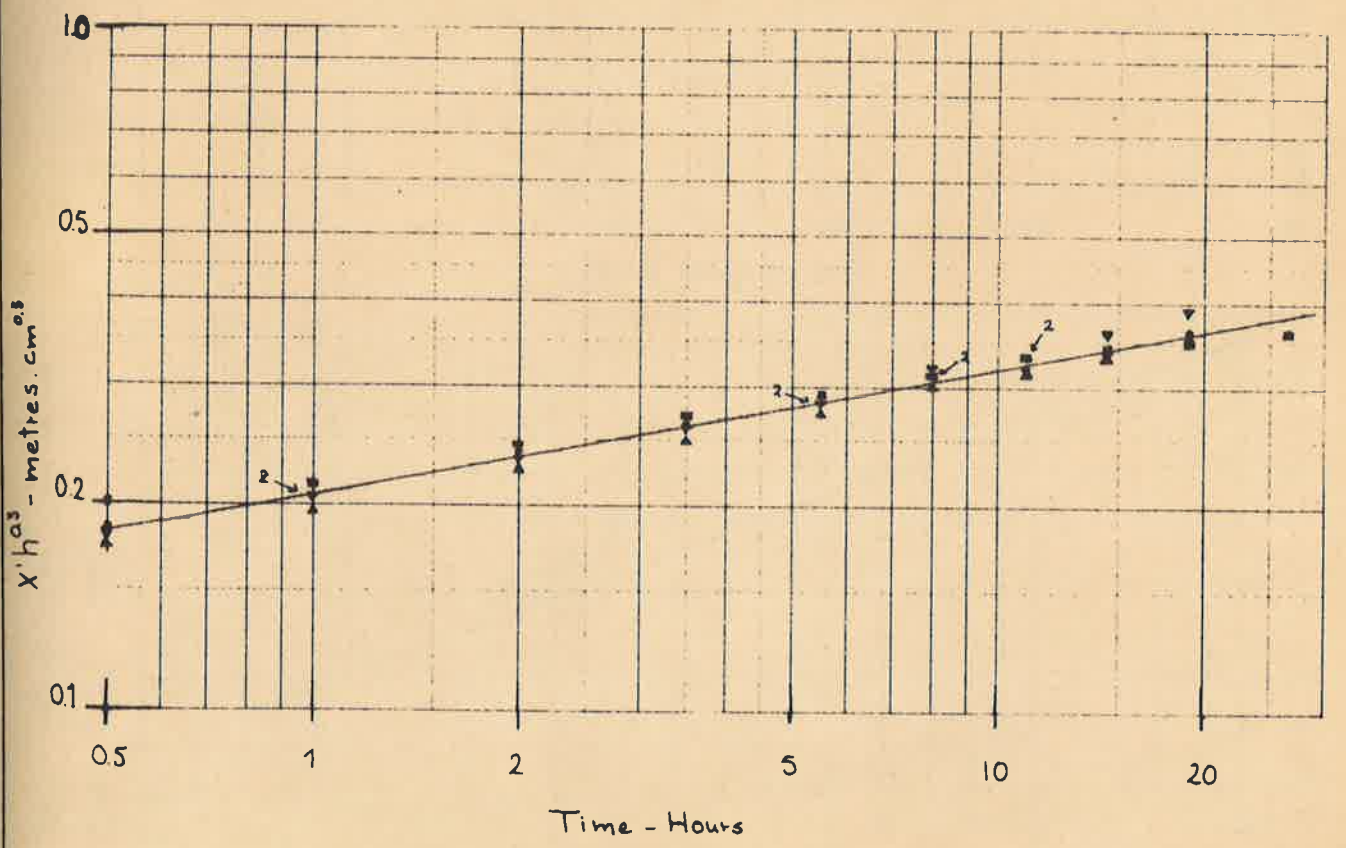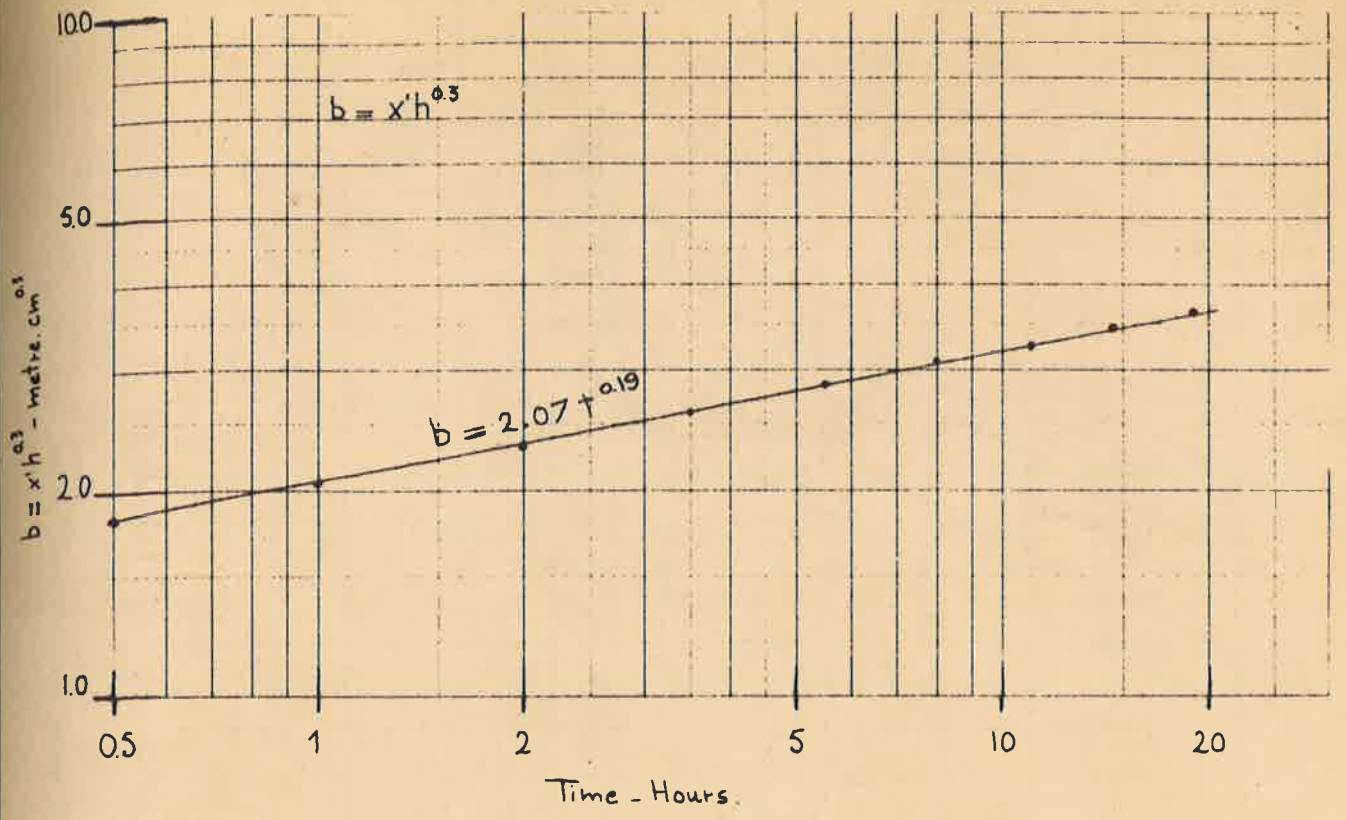
RELATION BETWEEN DUNE FOOT POSITION
DUNE HEIGHT AND TIME.

19
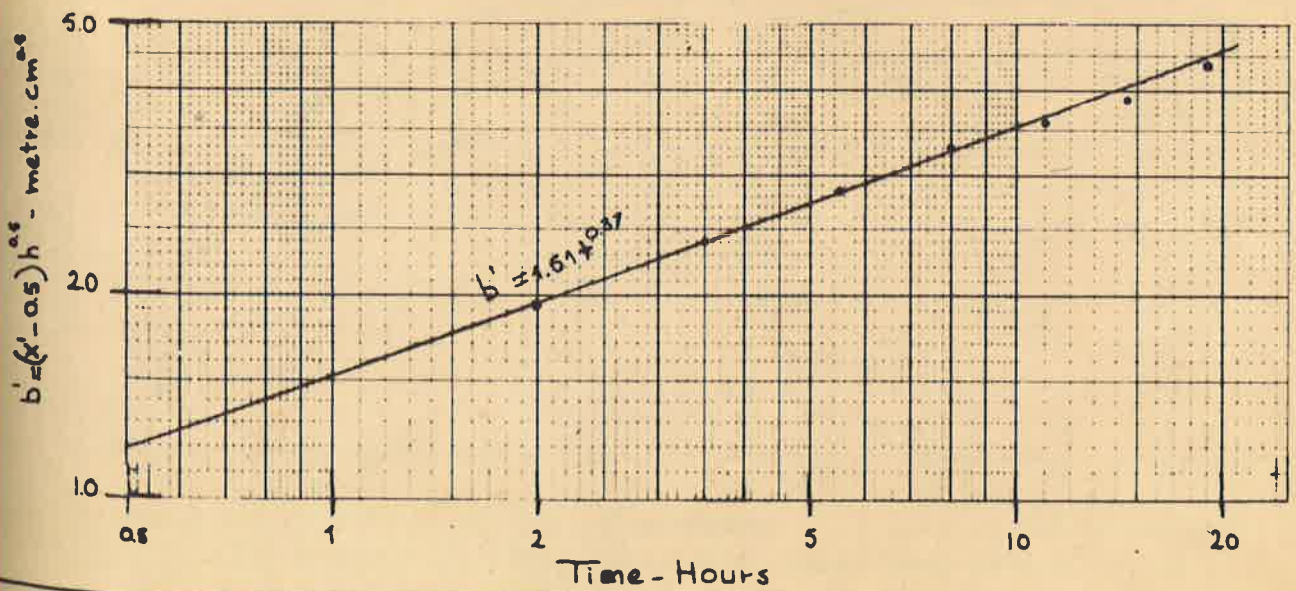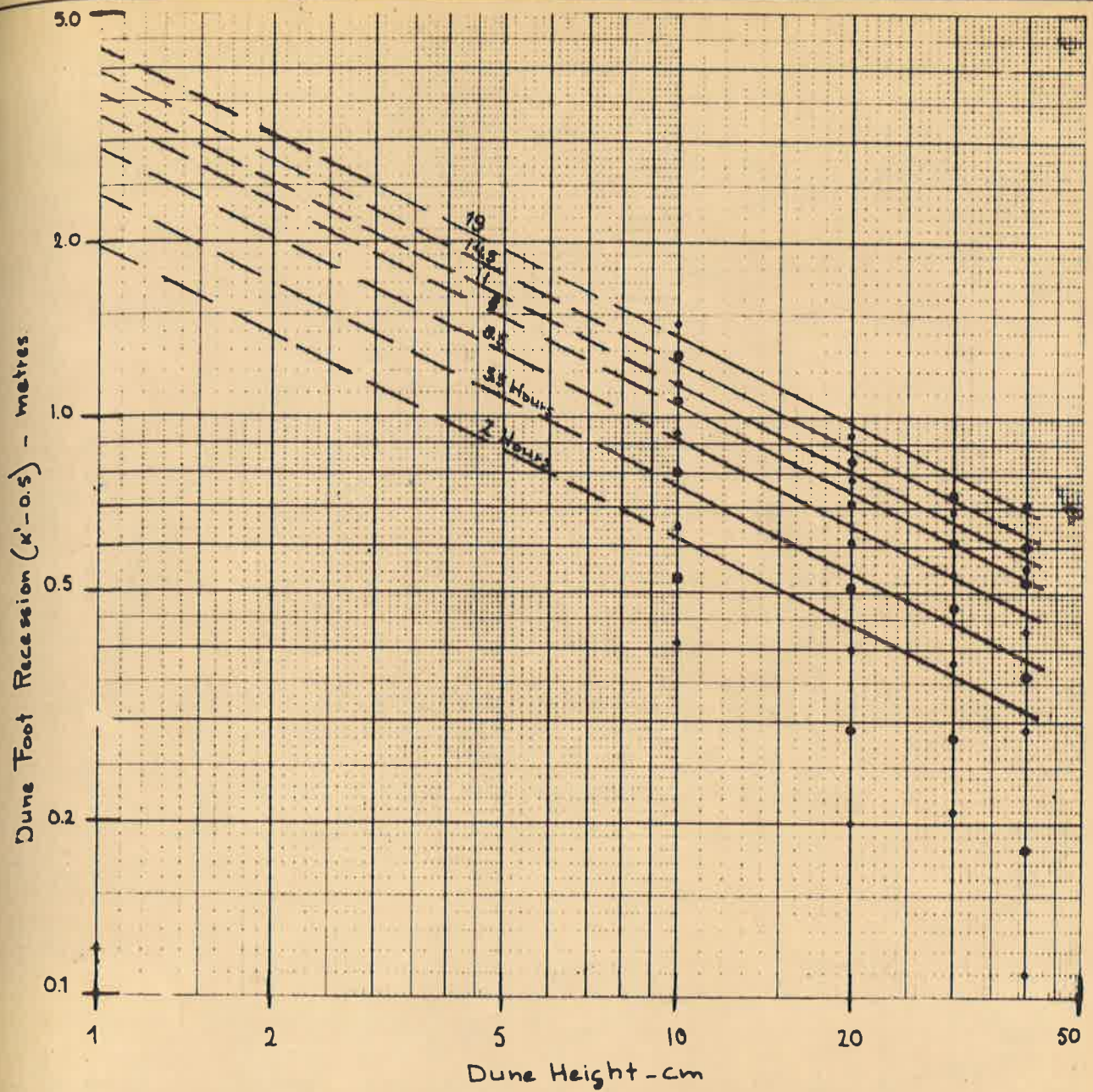
DUNE FOOT RECESSION (x'-0.5)
AS FUNCTION OF DUNE HEIGHT AND TIME

20
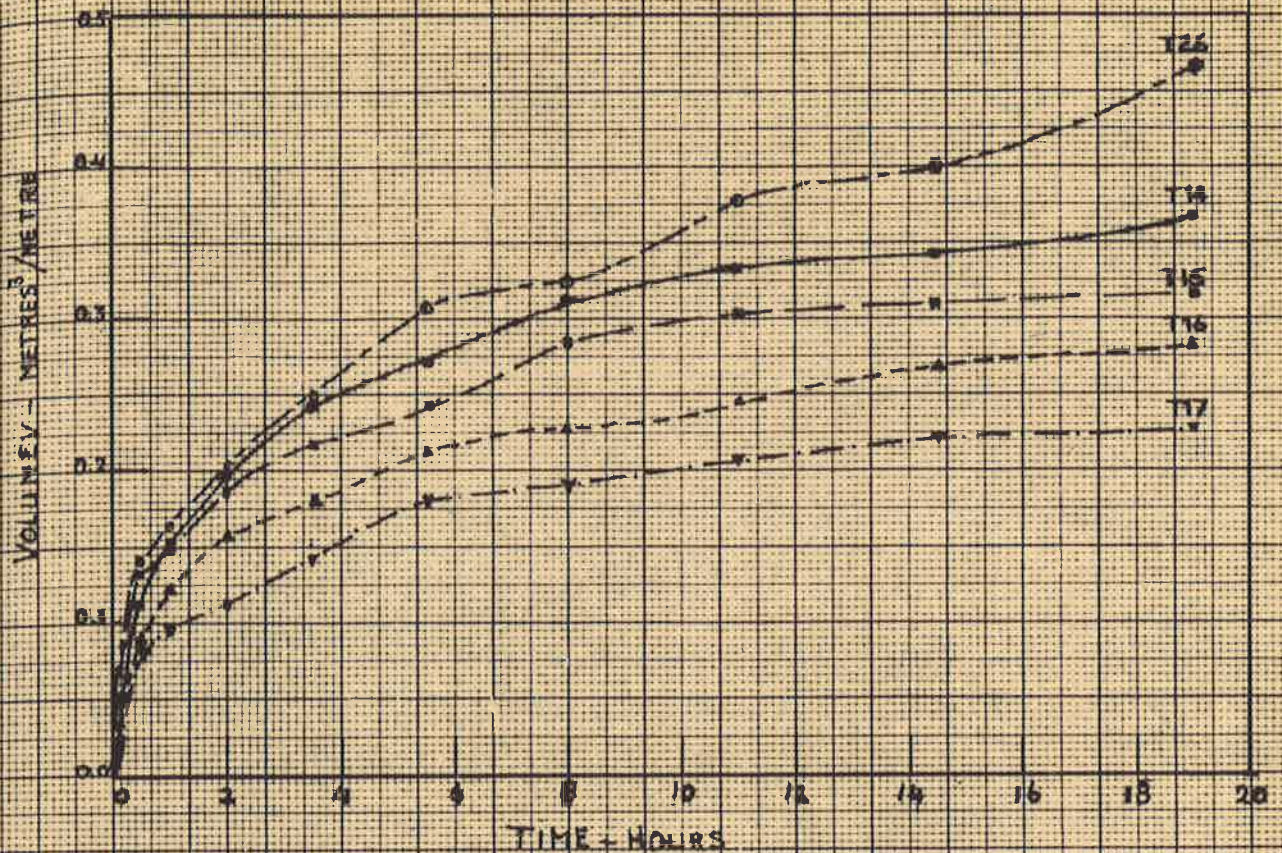
(a) TOTAL VOLUME ERODED FROM BEACH AND DUNE — V
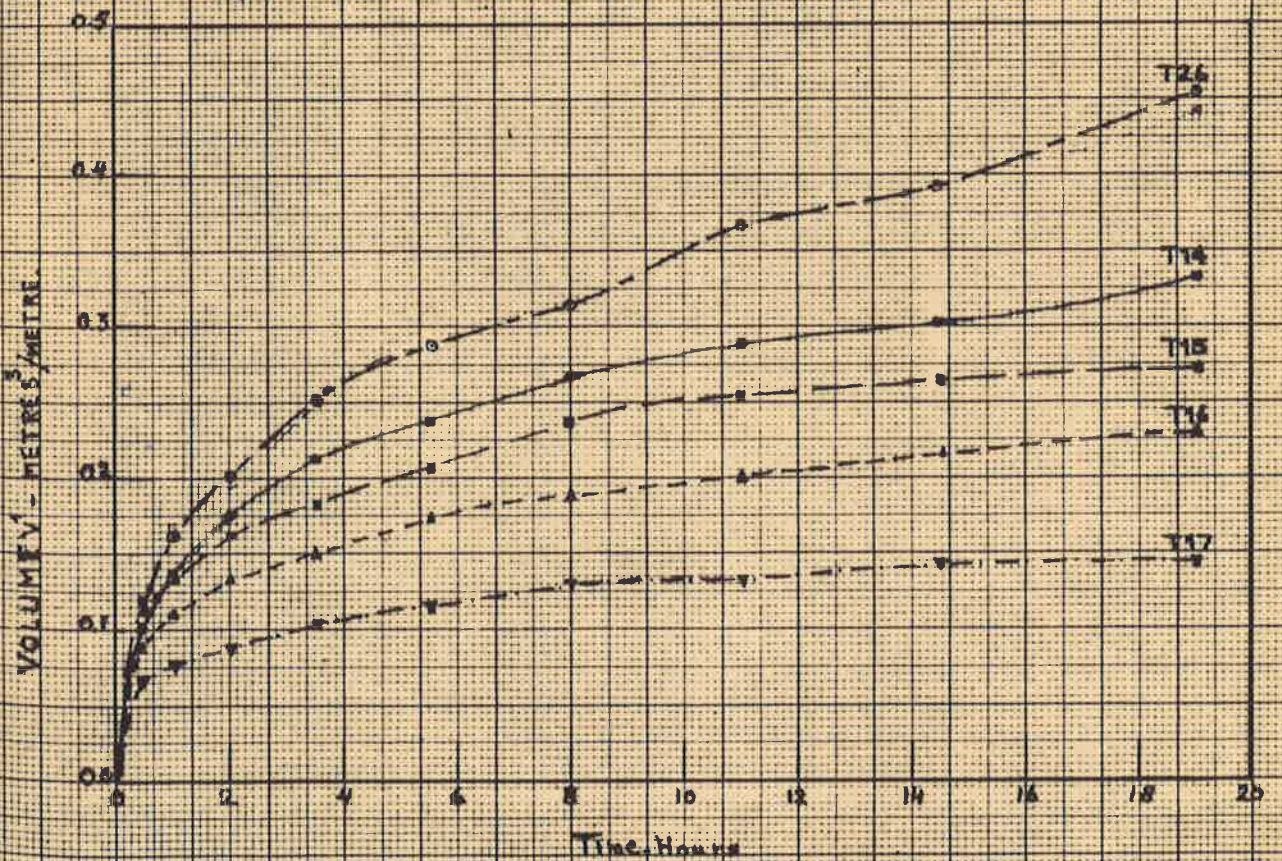
(b) VOLUME OF SAND ERODED ABOVE STORM SURGE LEVEL — V'

VOLUMES OF SAND ERODED AS

FUNCTIONS OF TIME FOR DIFFERENT
SAND DUNES

21

Upper graph:

Y-axis: Total Volume of Sand eroded from Beach and Dune - V - metres³/metre

Y-axis values: 0.4, 0.3, 0.2, 0.1, 0

X-axis: Dune Height - h - cm.

X-axis values: -40, -30, -20, -10, 0, 10, 20, 30, 40

Lower graph:

Y-axis: $m = \dfrac{h + 41}{V}$

Y-axis values: 1.0, 0.5, 0.2, 0.1

X-axis values: 0.5, 1, 2, 5, 10, 20
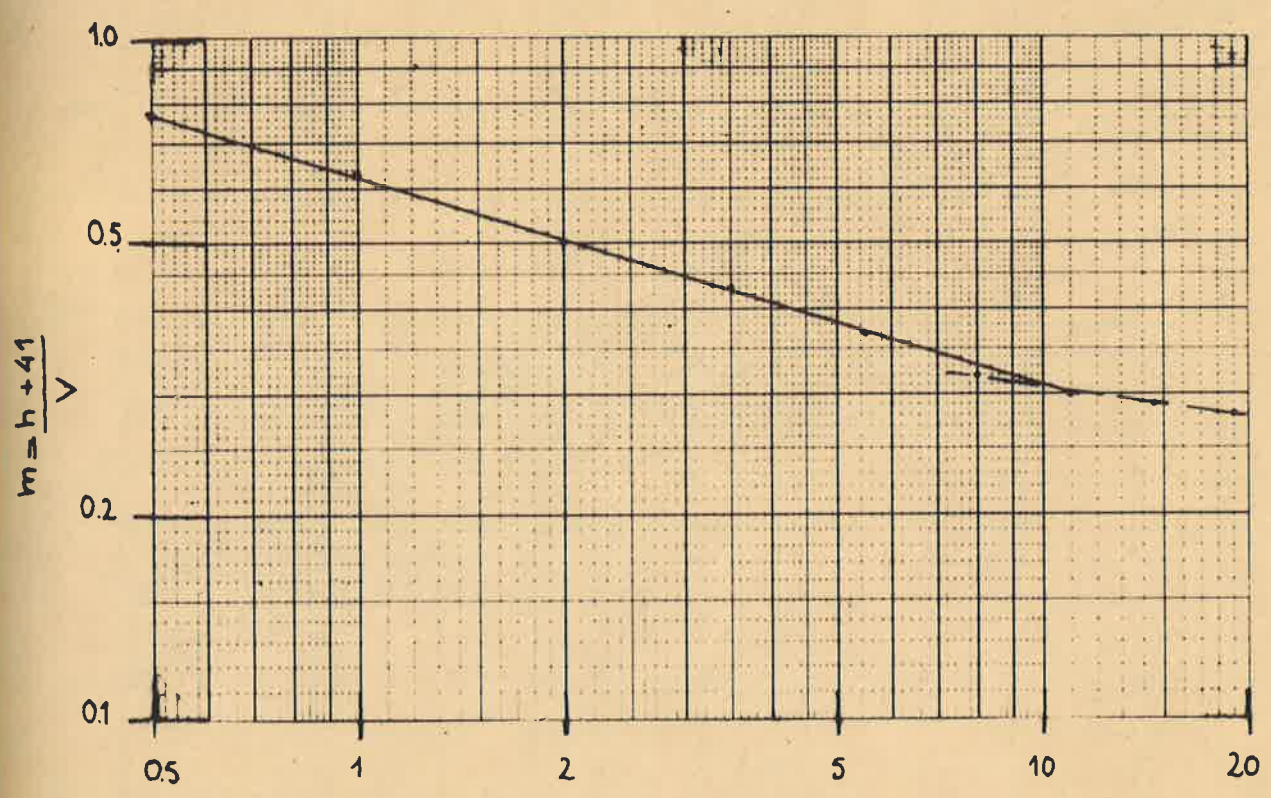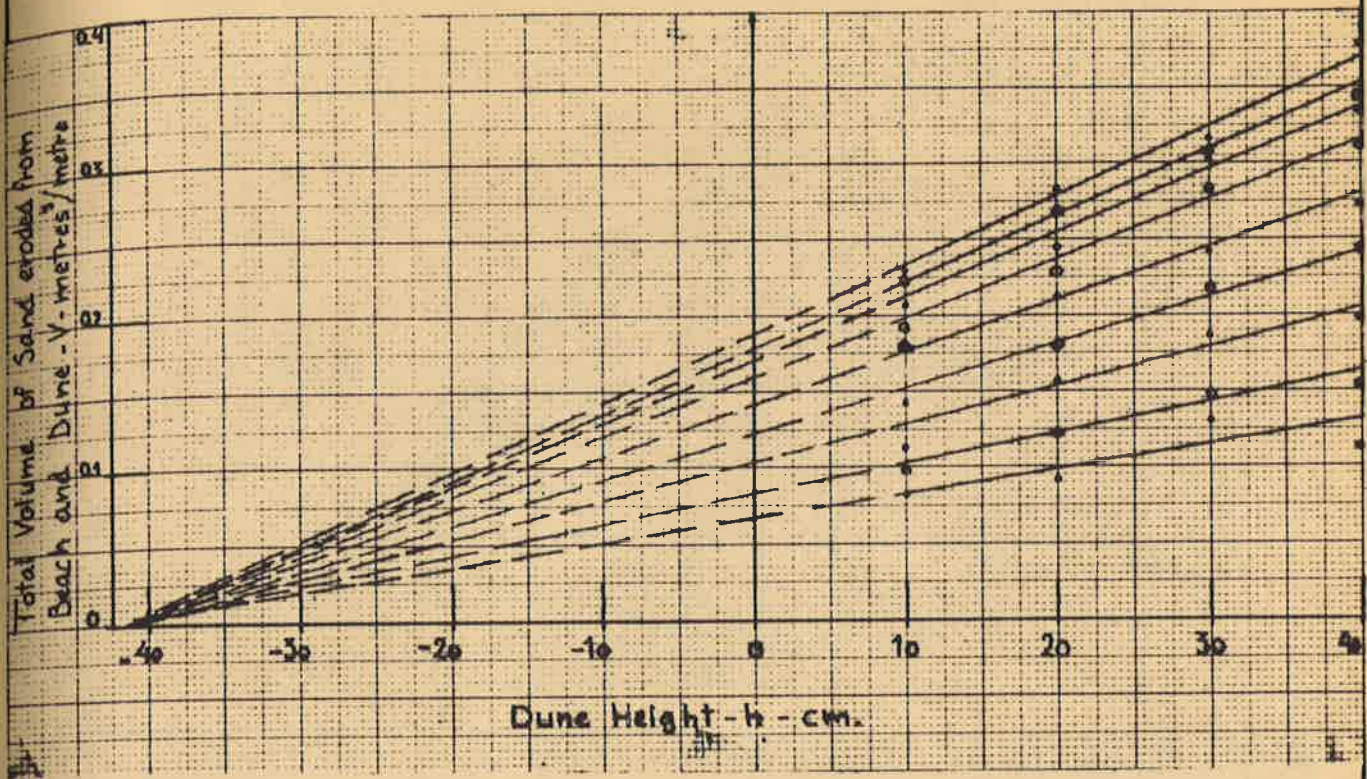
TOTAL VOLUME OF SAND ERODED FROM
BEACH AND DUNE AS FUNCTION OF
DUNE HEIGHT AND TIME

22

Upper figure axis labels: Volume of Sand Eroded above Storm Surge Level - V - metres³/metre (vertical), Dune Height - cm (horizontal), with curves labelled 19, 14.5, 11, 8, 5.5, 3.5, 2, 1, 0.5 Hours.

Lower figure axis labels: Volume of Sand eroded above Storm Surge Level - metres³/metre (vertical), Dune Height - cm (horizontal), with curves labelled 19, 5.5, 3.5, 2, 1, 0.5 Hours.
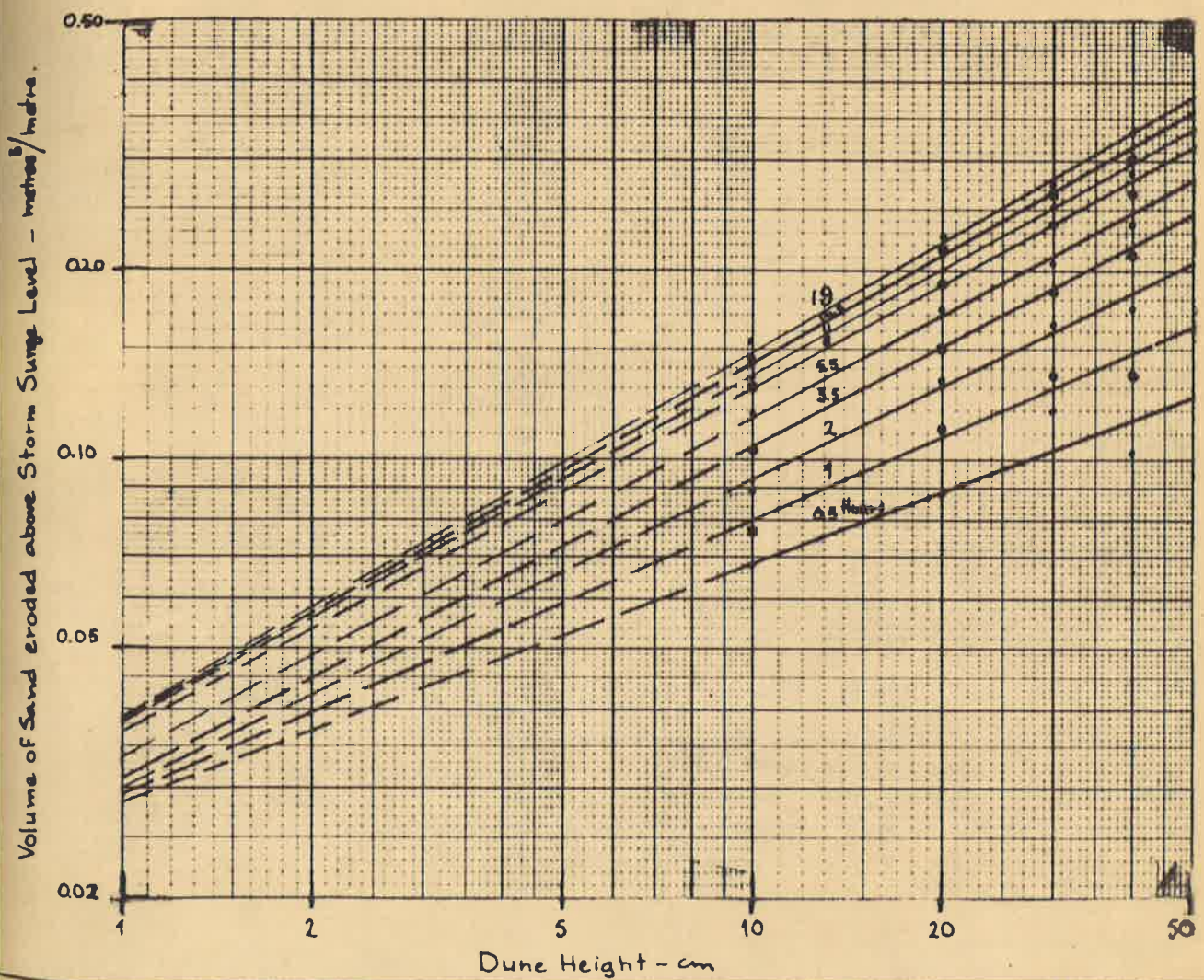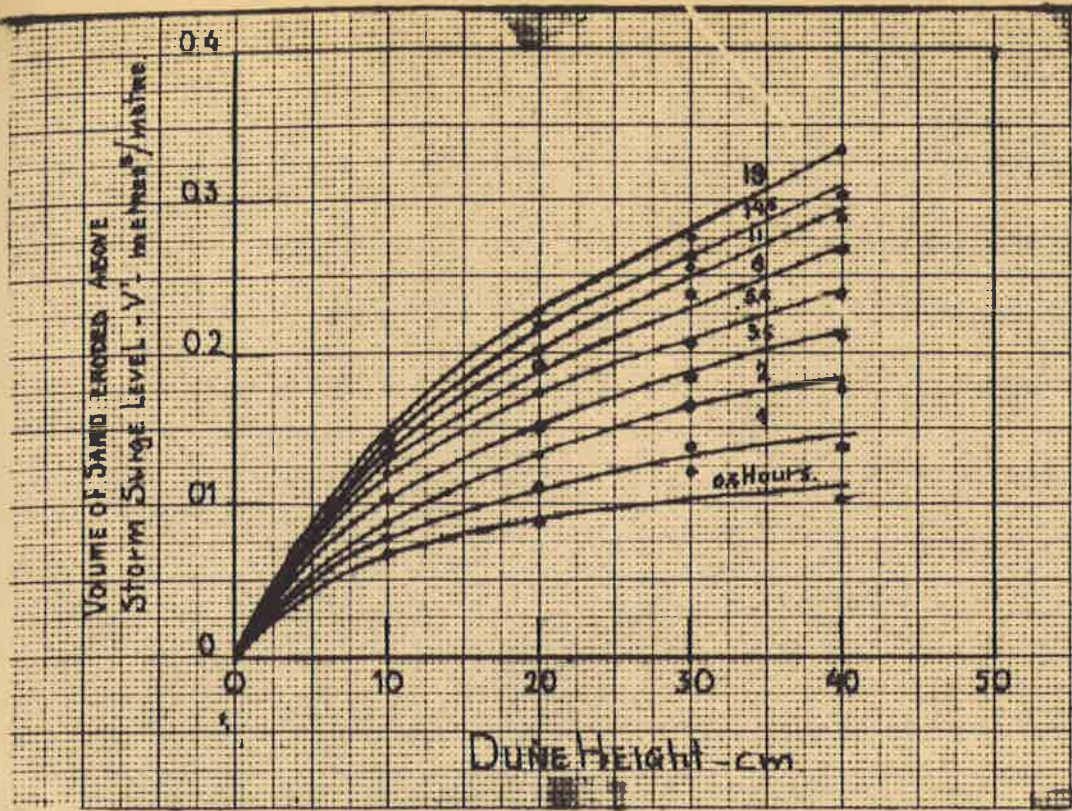
VOLUME OF SAND ERODED ABOVE STORM SURGE LEVEL
AS FUNCTION OF DUNE HEIGHT.

23

WATER LINE RECESSION AS FUNCTION
OF VOLUME ERODED FROM BEACH DUNE
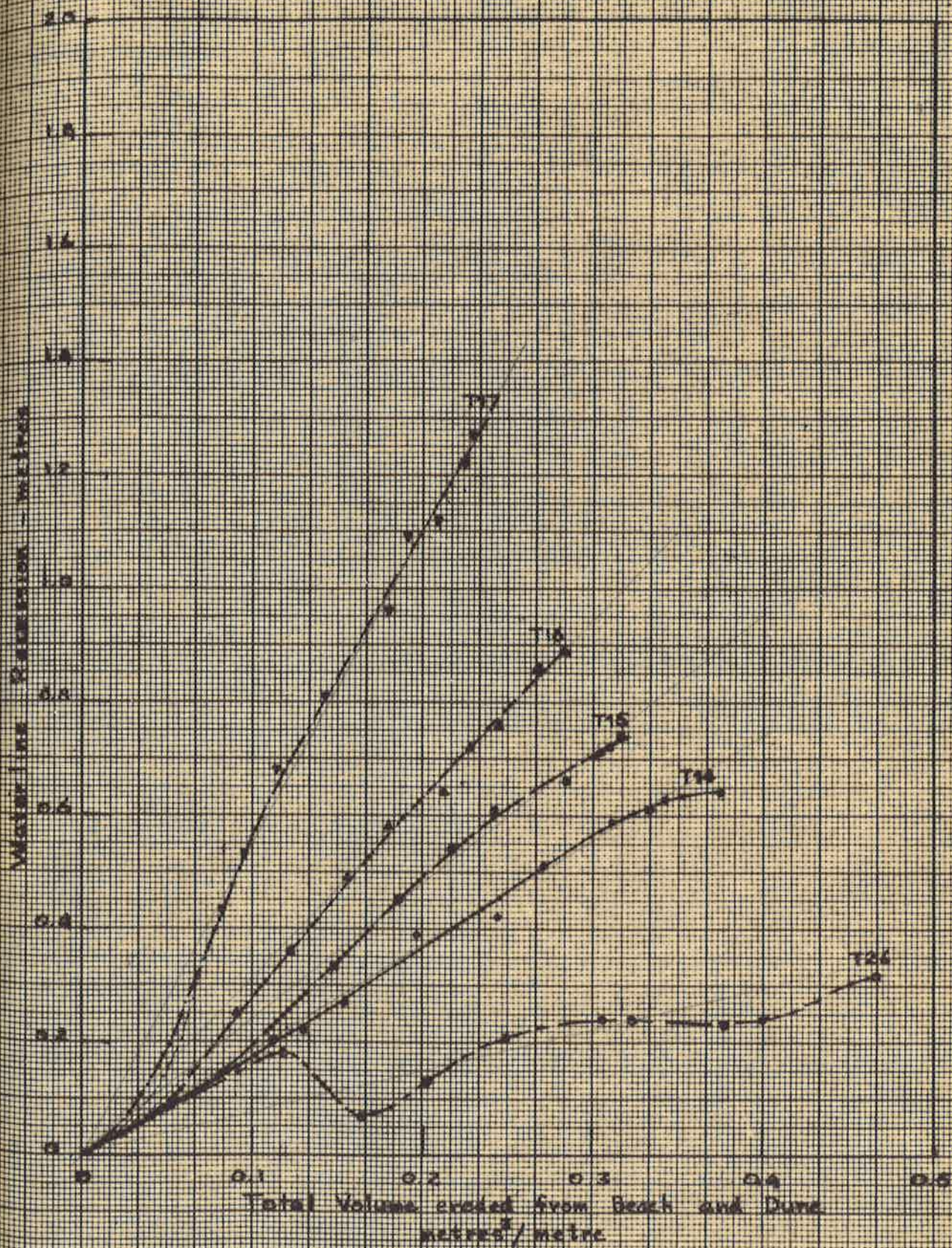
DUNE FOOT RECESSION AS FUNCTION
OF VOLUME ERODED FROM SAND DUNE
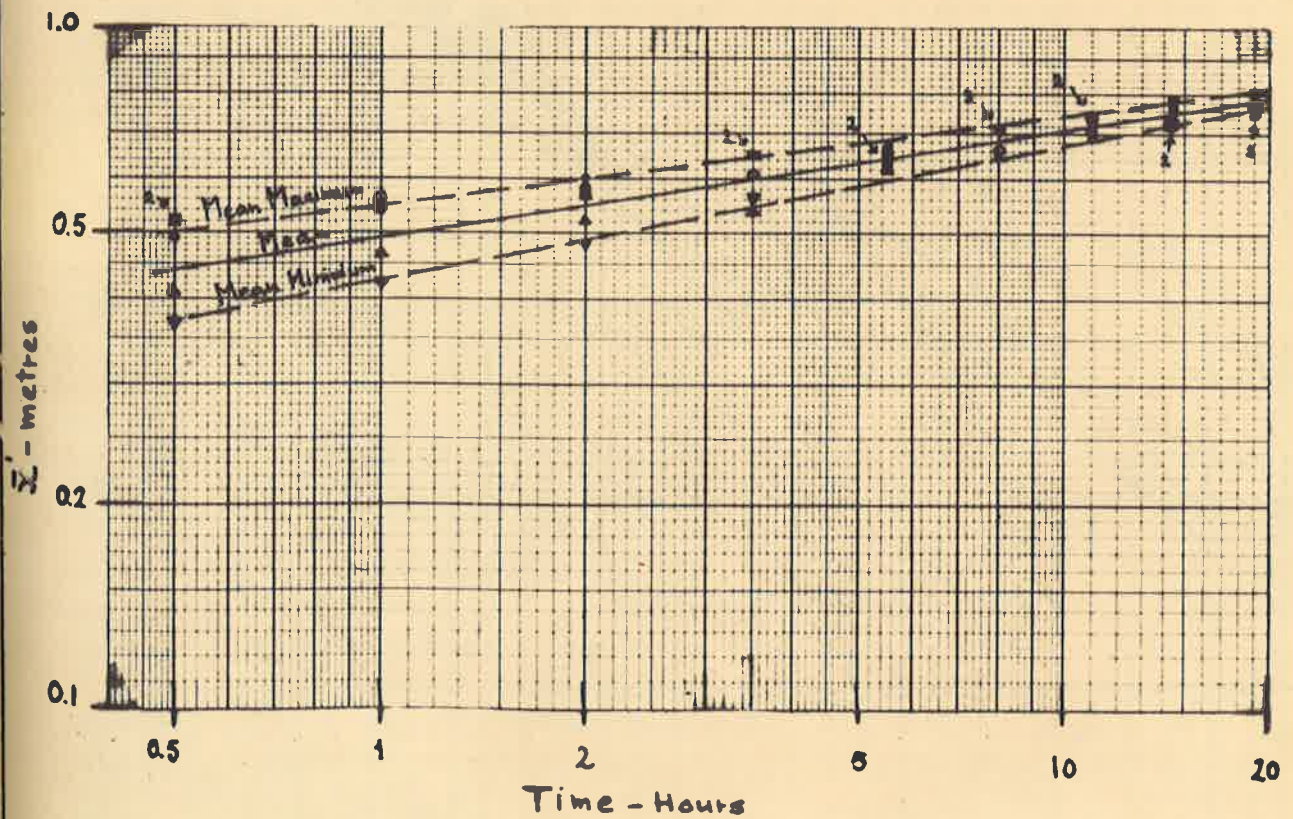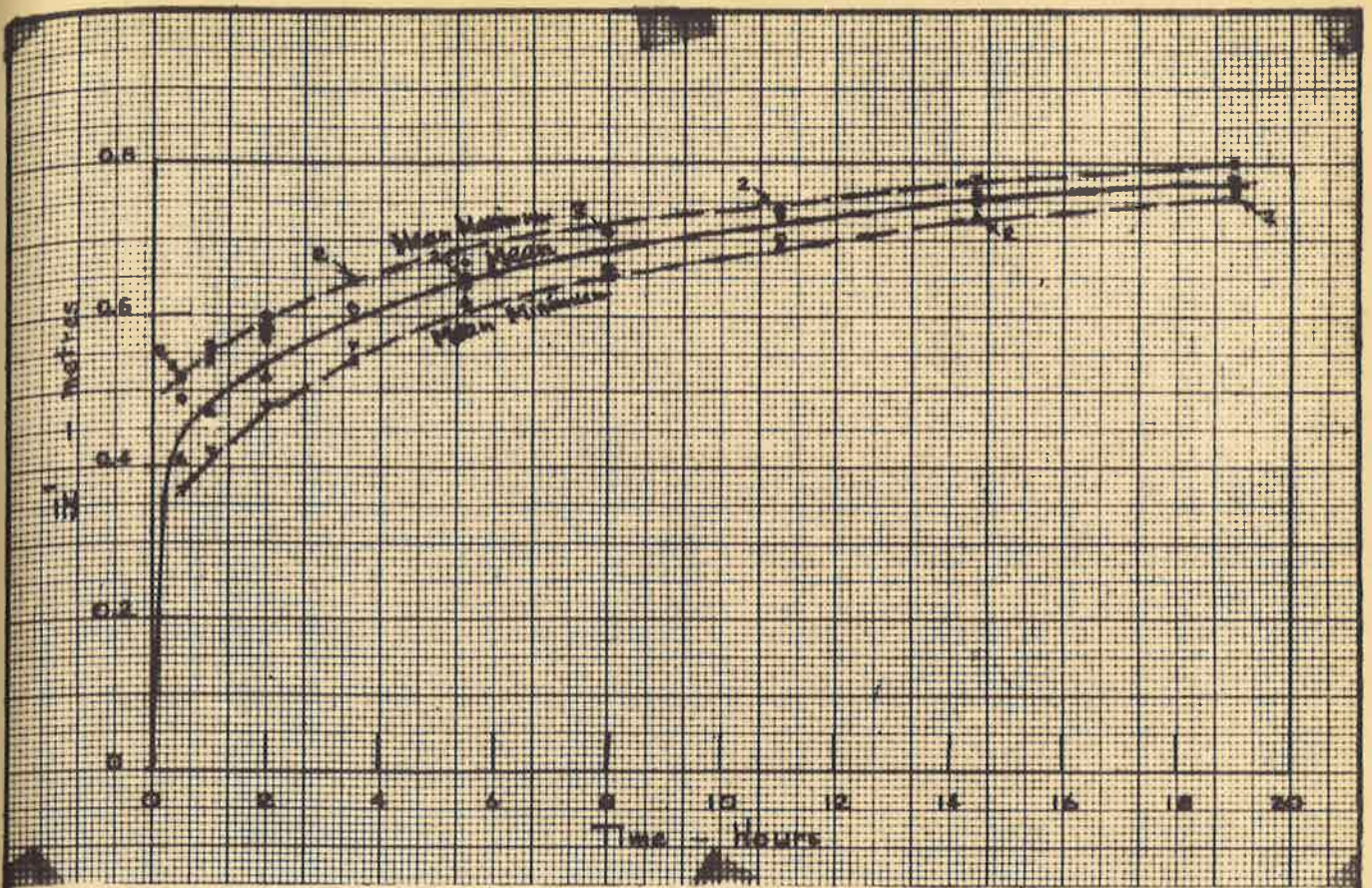
POSITION OF CENTROID OF VOLUMES ERODED
ABOVE STORM SURGE LEVEL FOR VARIOUS
SAND DUNES

26
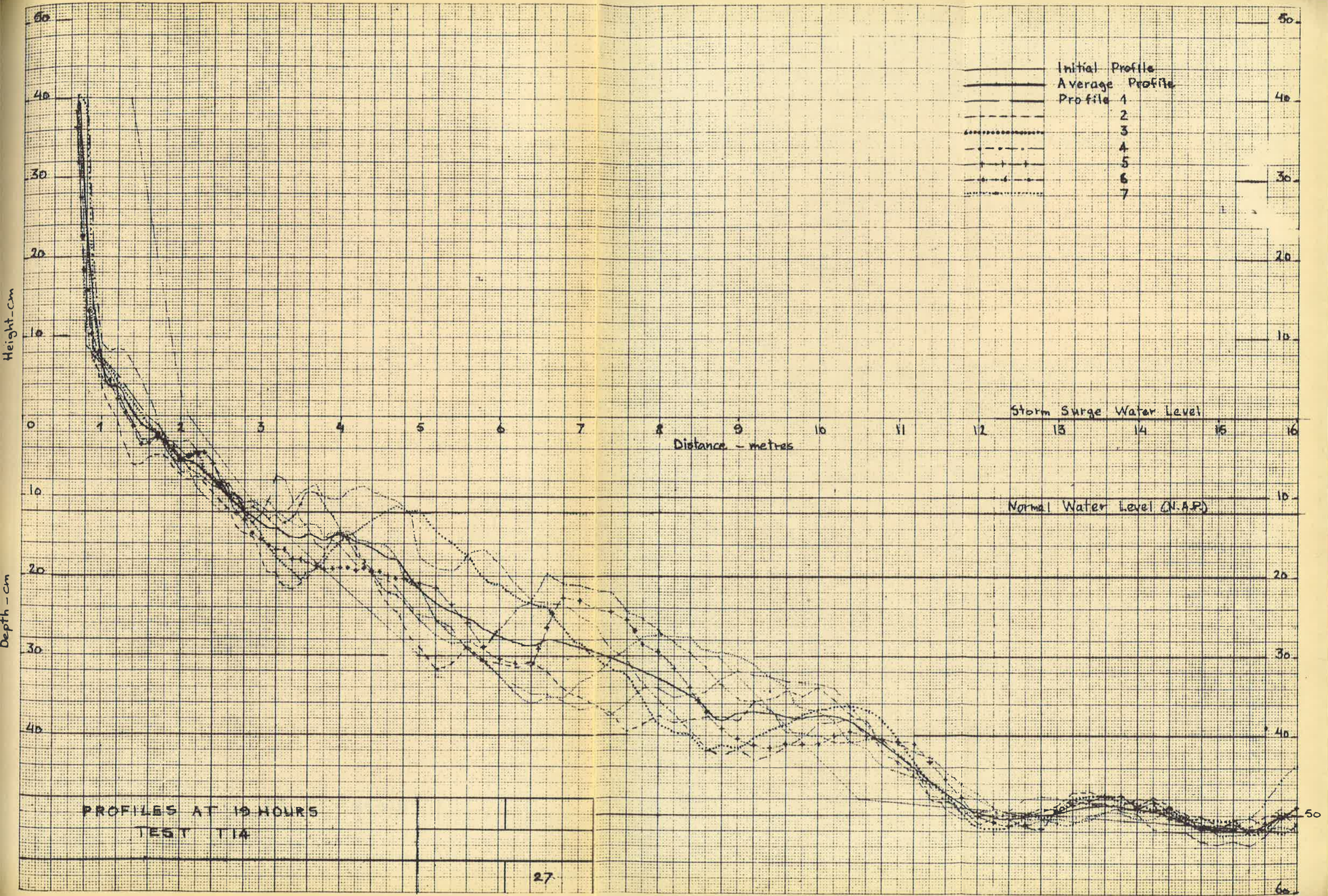
PROFILES AT 19 HOURS
TEST T14

Height - cm

Depth - cm

Distance — metres

Storm Surge Water Level

Normal Water Level (N.A.P.)

Initial Profile
Average Profile
Profile 1
2
3
4
5
6
7

M. R. GOURLAY

27

PROFILES AT CENTRE OF BASIN
TEST T 14
0 to 3½ Hours.

Height – cm

Depth – cm

Distance – metres

Storm Surge Water Level

Normal Water Level (N.A.P.)
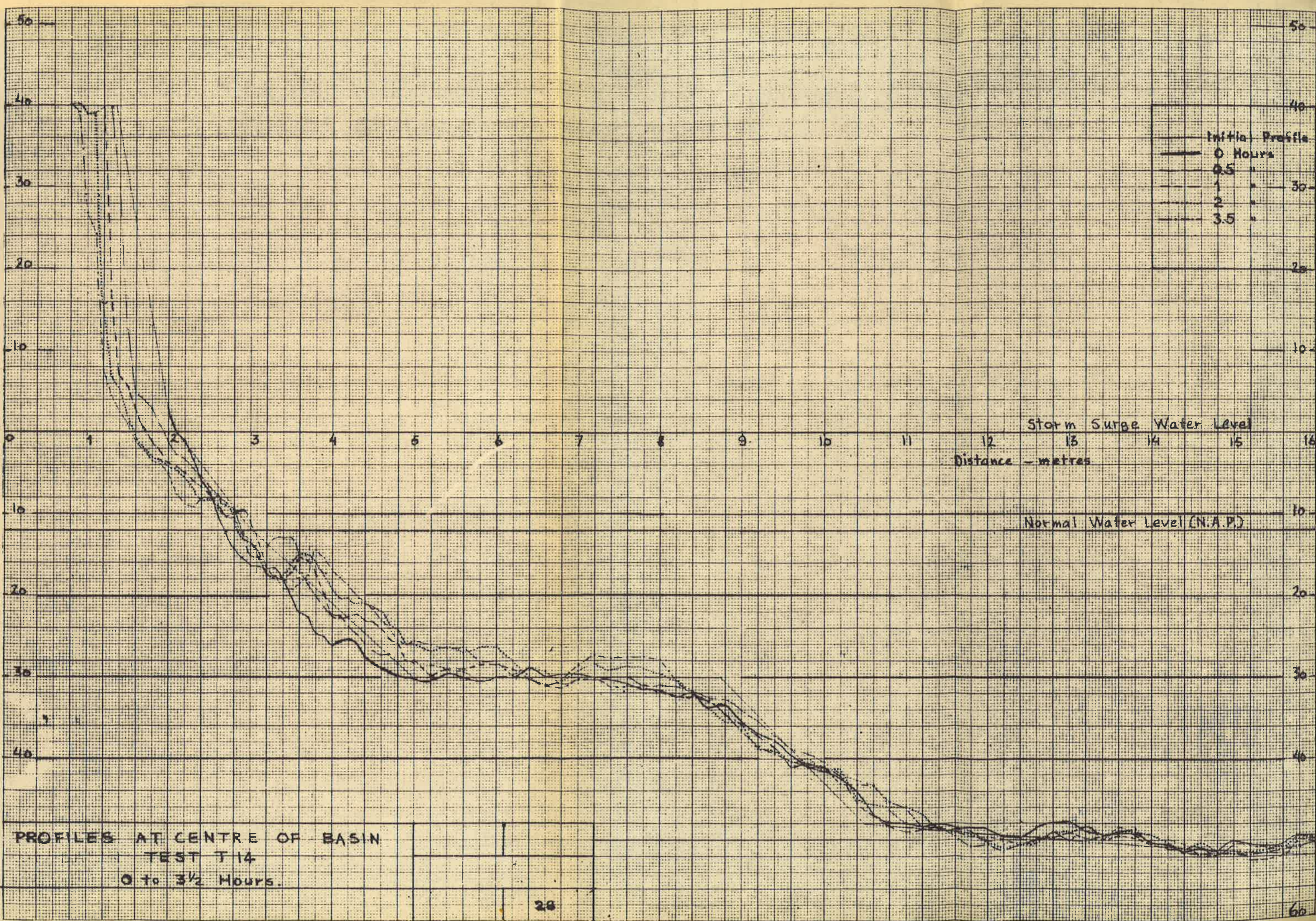
Initial Profile
0 Hours
0.5 "
1 "
2 "
3.5 "

PROFILES AT CENTRE OF BASIN
TEST T14
5½ to 19 Hours
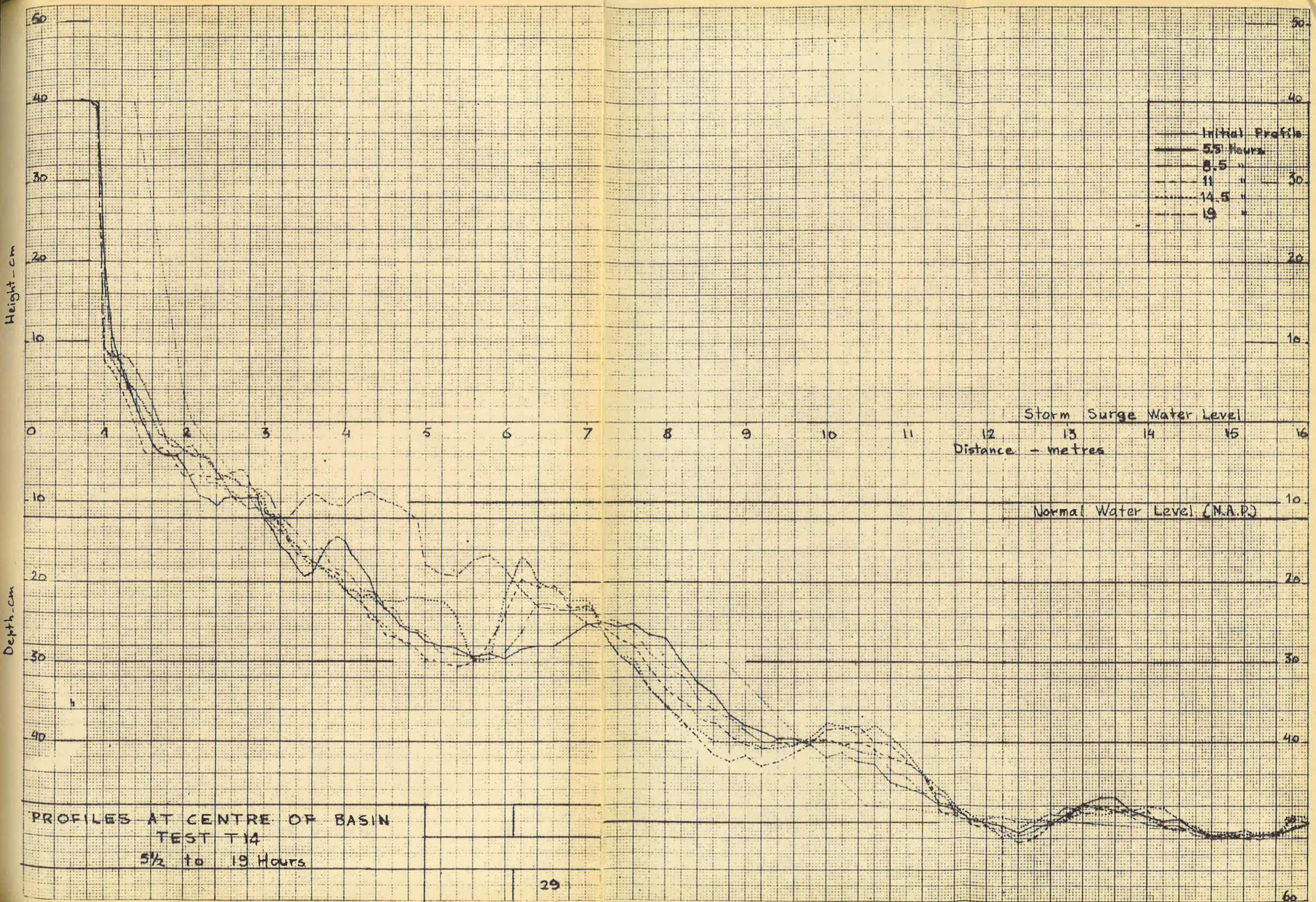
Legend:
- Initial Profile
- 5.5 Hours
- 8.5 "
- 11 "
- 14.5 "
- 19 "

Height - cm
Depth - cm
Distance - metres

Storm Surge Water Level
Normal Water Level (N.A.P.)

29

AVERAGE PROFILES AT 19 HOURS
FOR DIFFERENT SAND DUNES
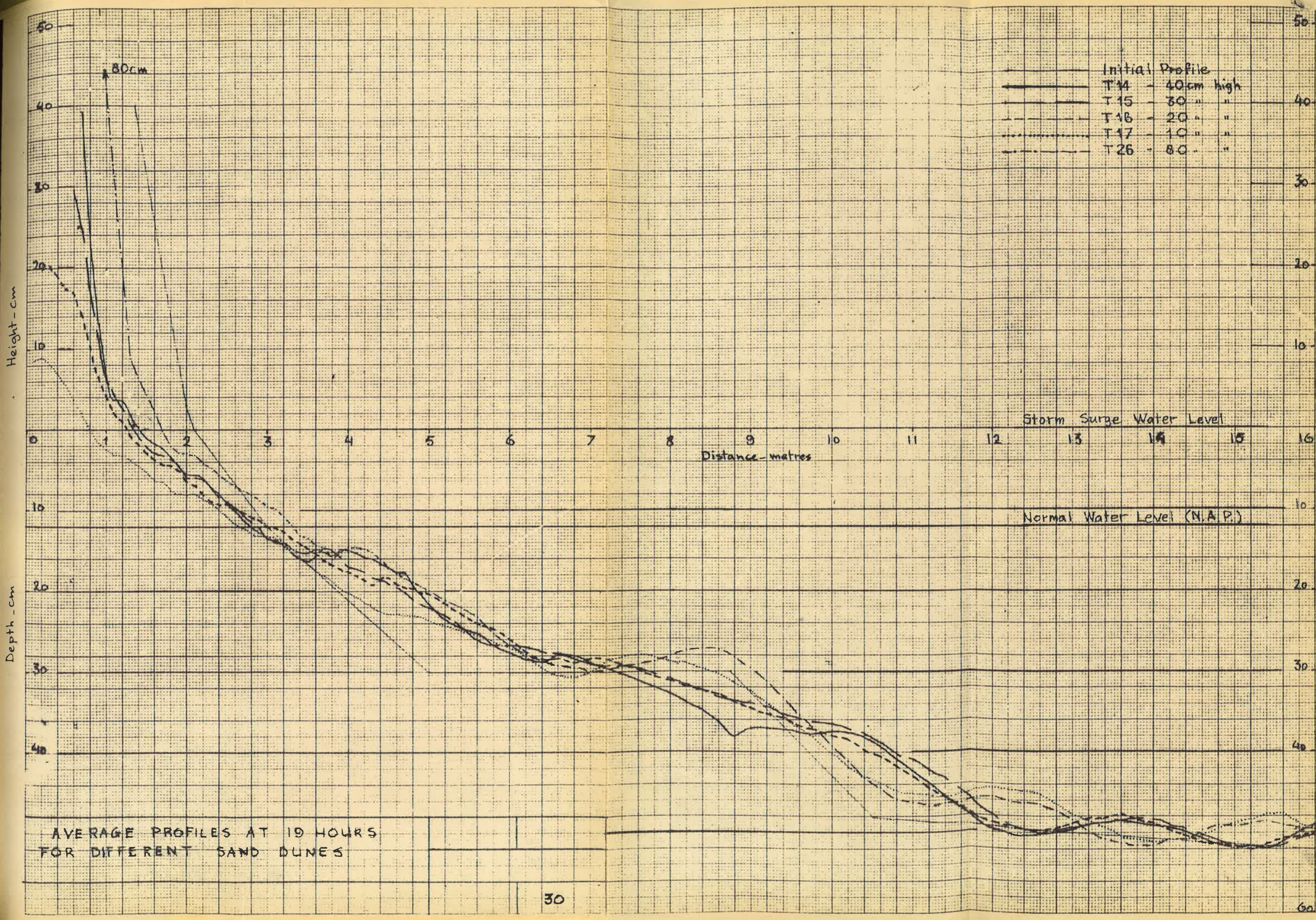
Initial Profile
T14 – 40 cm high
T15 – 80 " "
T16 – 20 " "
T17 – 10 " "
T26 – 80 " "

Storm Surge Water Level

Normal Water Level (N.A.P.)

Height – cm

Depth – cm

Distance – metres

80 cm

30

Dune Height 80 cms

Storm Surge Water Level

Distance — metres

Normal Water Level (N.A.P.)

Height — cm

Depth — cm

Initial Profile
Average Profile
Profile 1
" " 2
" " 3
" " 4
" " 5

PROFILES AT 18 HOURS
TEST T26
PROFILES 1 to 5

31

Dune Height : 80 cms.

Height - cm

Depth - cm

Storm Surge Water Level

Distance - metres
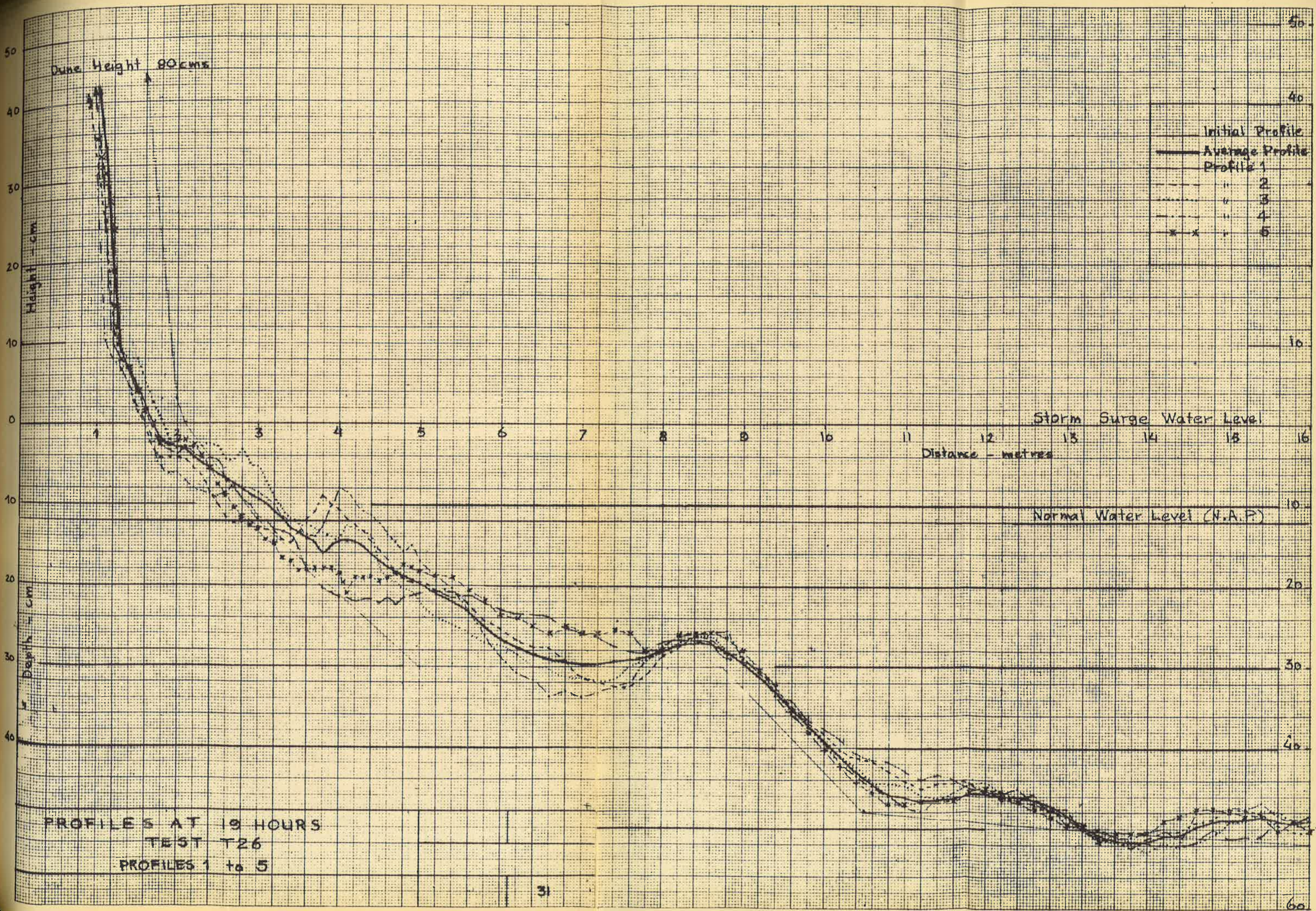
Normal Water Level (N.A.P.)

Initial Profile
Average Profile
Profile 6
" " 7
" " 8
" " 9
" " 10
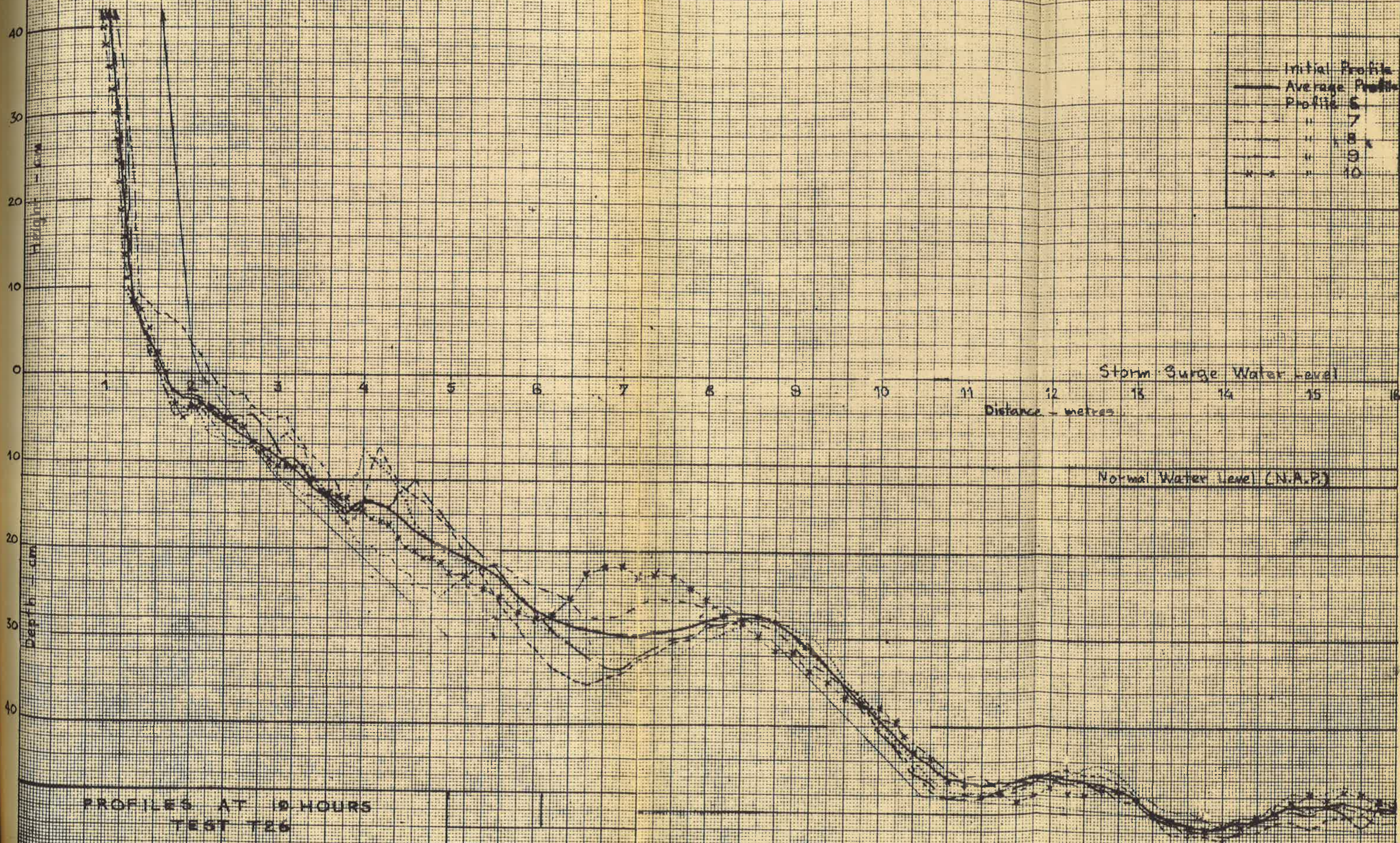
PROFILES AT 10 HOURS
TEST T26
PROFILES 6 to 10
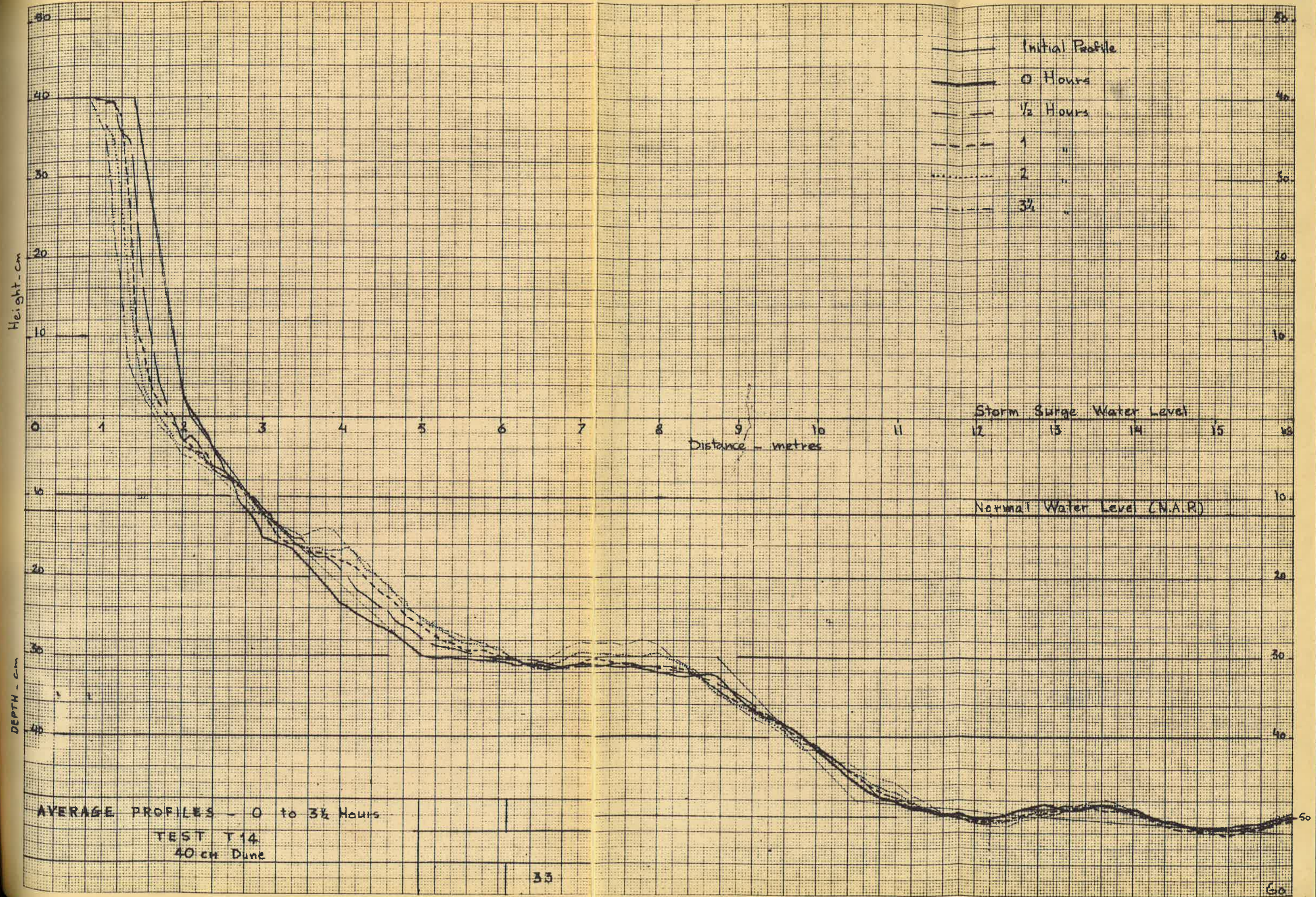
Height - cm

DEPTH - cm

Distance - metres

Initial Profile

0 Hours

½ Hours

1   "

2   "

3½ "

Storm Surge Water Level

Normal Water Level (N.A.R)

AVERAGE PROFILES - 0 to 3½ Hours

TEST T14

40 cm Dune

33

60

Height - cm

Depth - Cm

Distance - metres
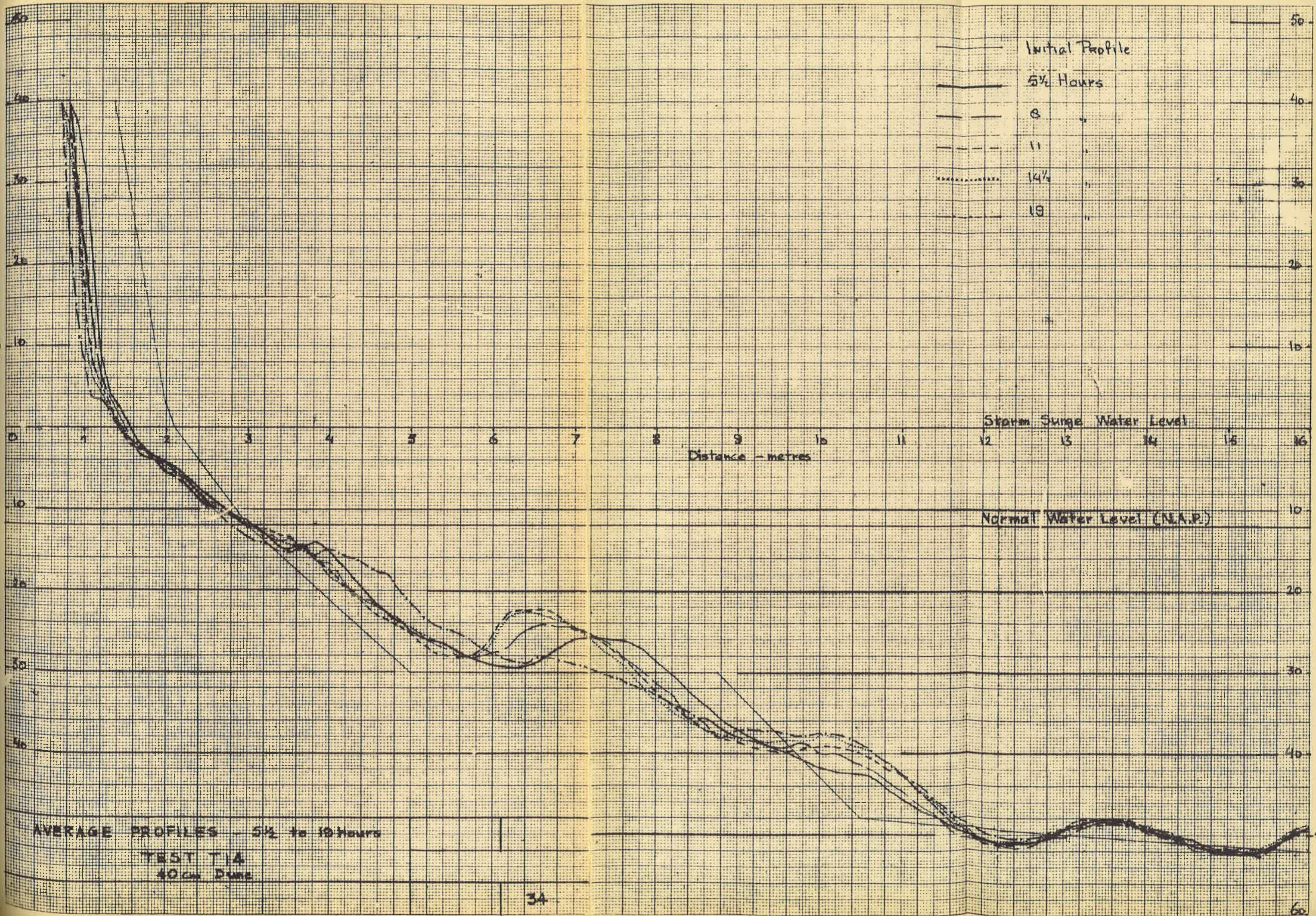
Initial Profile
5¼ Hours
8 „
11 „
14½ „
19 „

Storm Surge Water Level

Normal Water Level (N.A.P.)

AVERAGE PROFILES - 5¼ to 19 Hours
TEST T.14
40 cm Dune

34
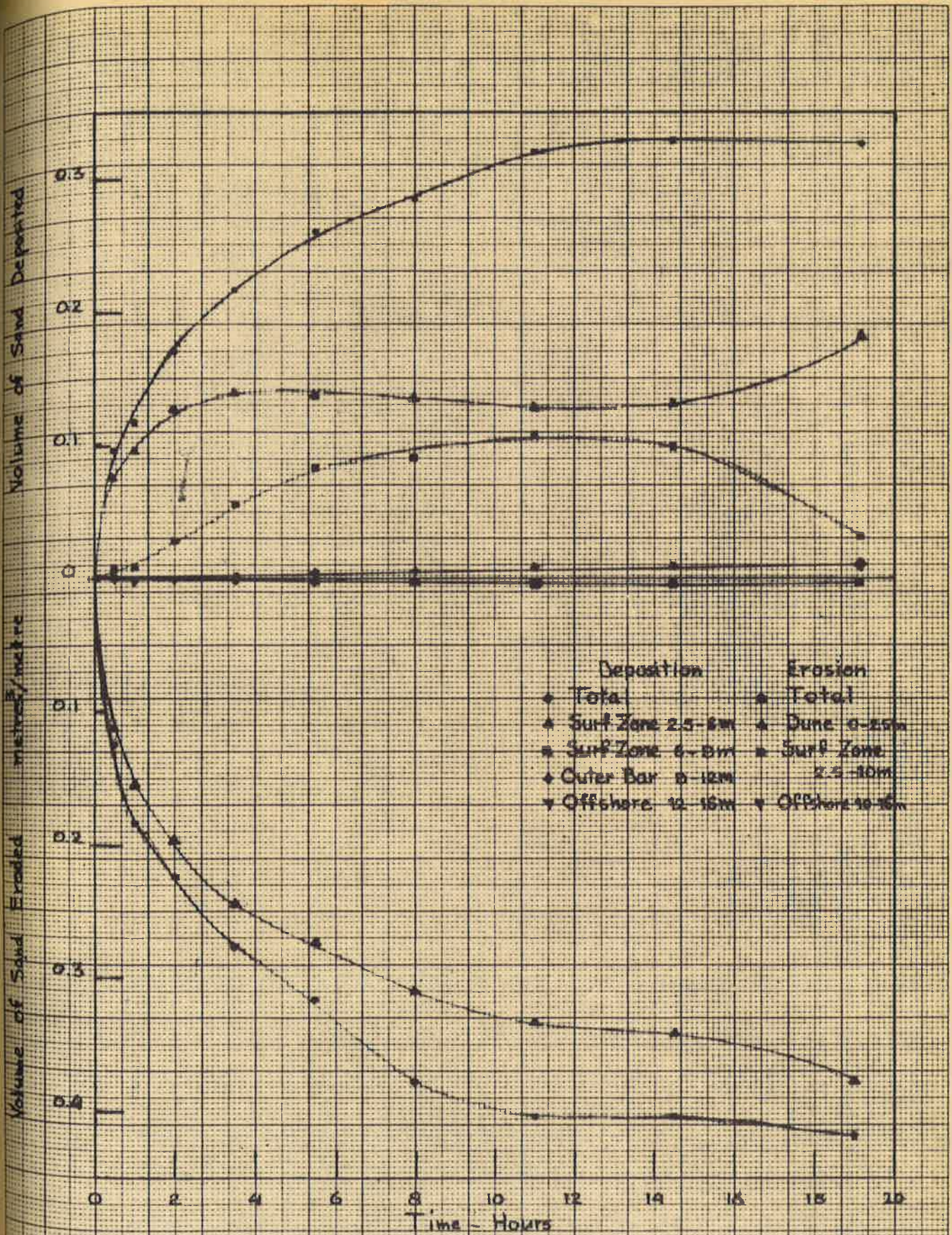
SAND VOLUMES ERODED AND DEPOSITED
AS FUNCTION OF TIME
TEST T 14
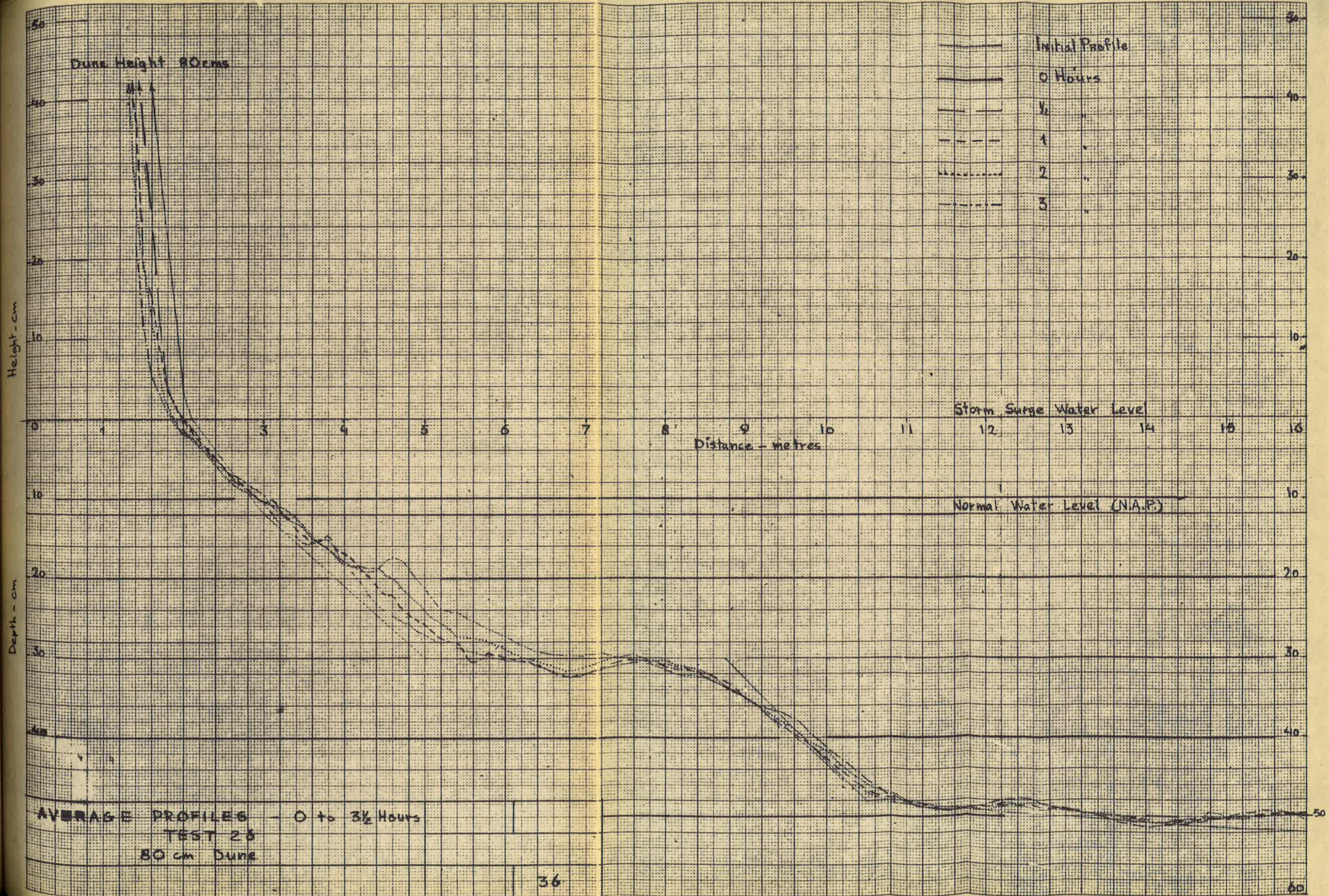
Dune Height 80cms

Height - cm

Depth - cm

Initial Profile
0 Hours
½ "
1 "
2 "
3 "

Storm Surge Water Level

Distance - metres

Normal Water Level (N.A.P.)

AVERAGE PROFILES — 0 to 3½ Hours
TEST 23
80 cm Dune

36
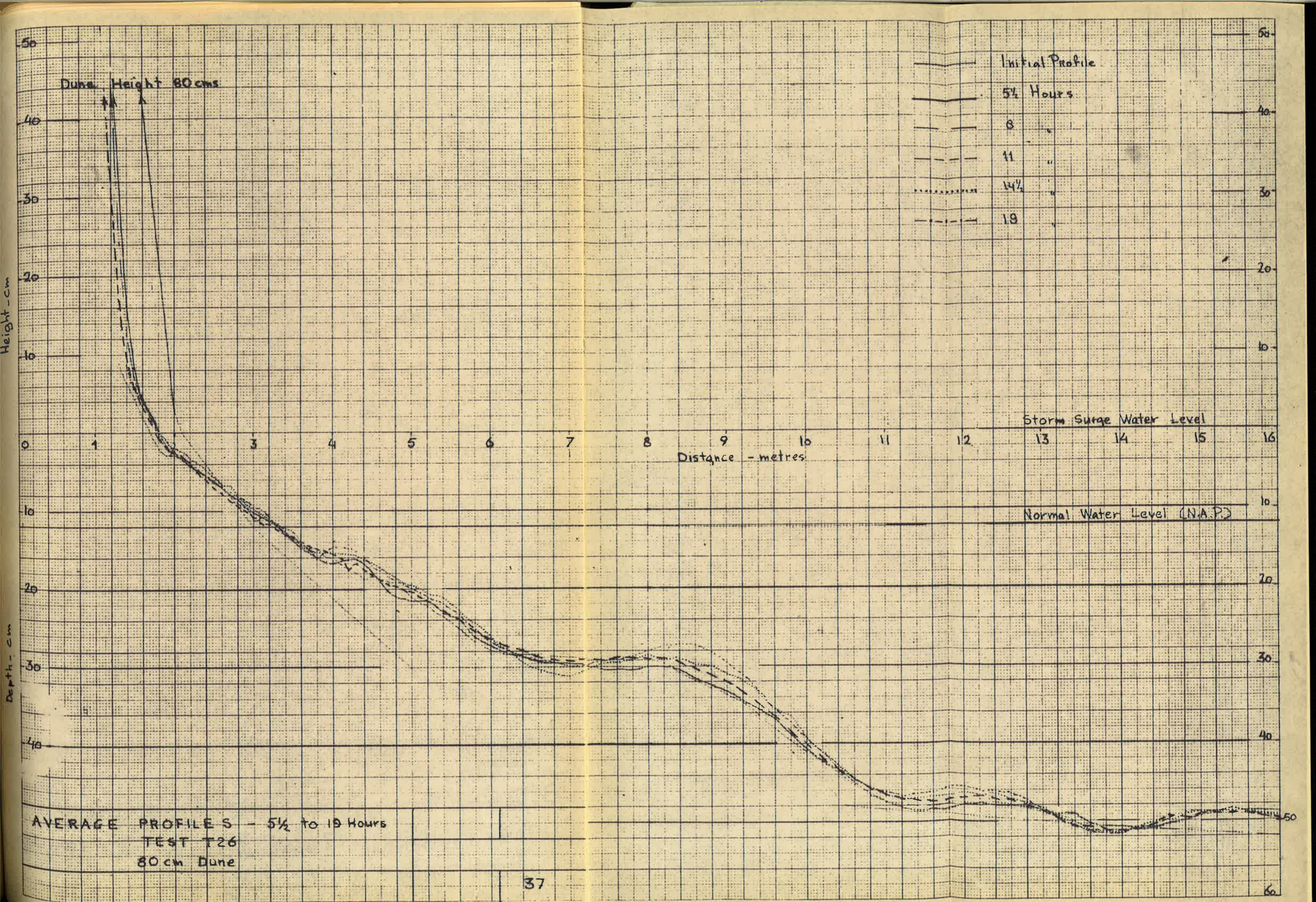
AVERAGE PROFILES – 5½ to 19 Hours
TEST T26
80 cm Dune
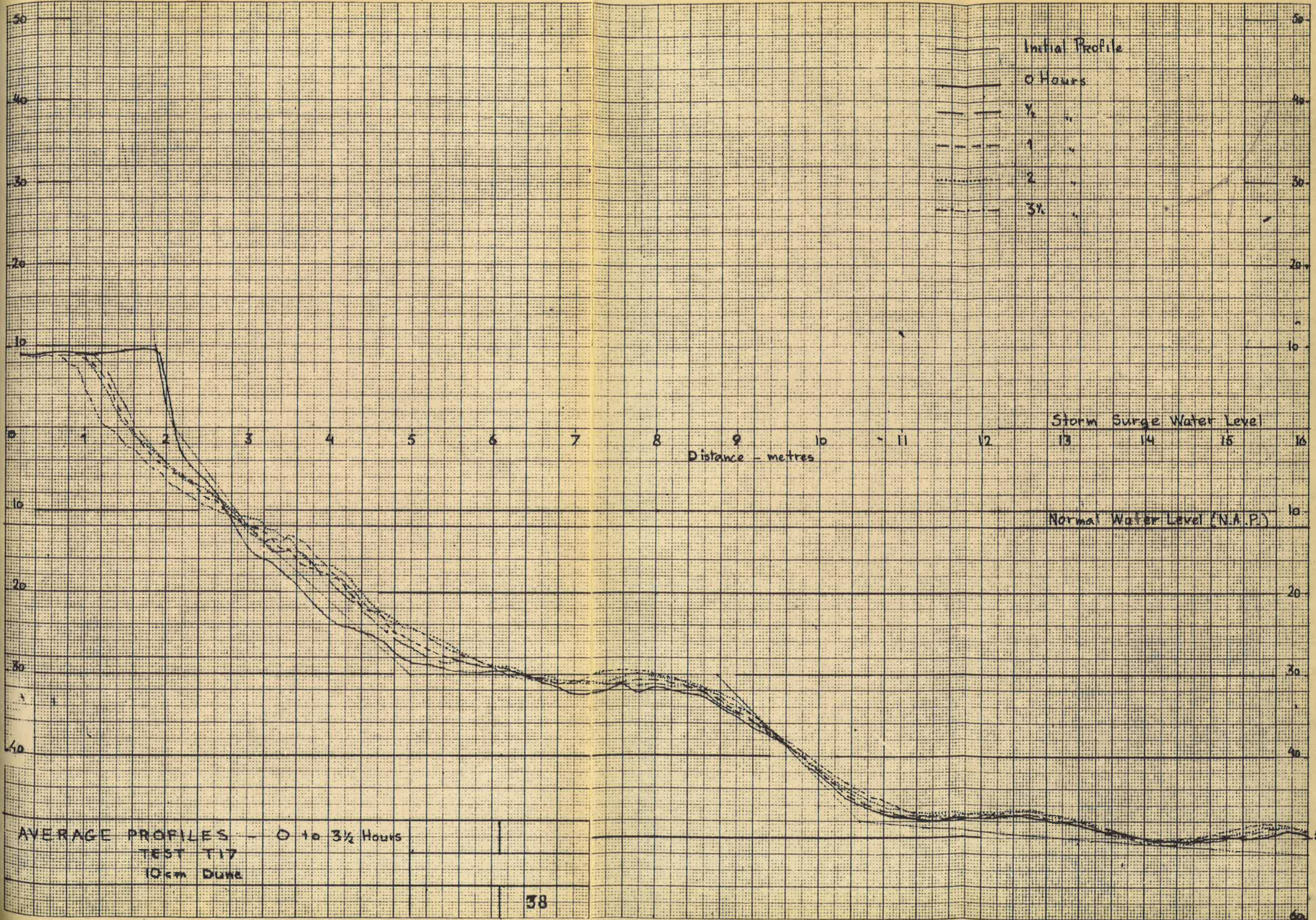
Dune Height 80 cms

Storm Surge Water Level

Normal Water Level (N.A.P.)

	Initial Profile
	5½ Hours
	8 „
	11 „
	14½ „
	19 „

Height – cm

Depth – cm

Distance – metres

37

Initial Profile

0 Hours

½ "

1 "

2 "

3½ "

Storm Surge Water Level

Normal Water Level (N.A.P.)

Height - cm

Depth - cm

Distance - metres

AVERAGE PROFILES — 0 to 3½ Hours
TEST T17
10cm Dune

38

Initial Profile
5½ Hours
8
11
14½
19

Height - cm

Depth - cm

Storm Surge Water Level

Normal Water Level (N.A.P)

Distance - metres

AVERAGE PROFILES — 5½ to 19 Hours
TEST T17
10 cm Dune

39

Depth - cm

Model $y = 0.083 x^{0.724}$

Larras $y = 0.0935 x^{0.724}$

T14 - 19 Hours.
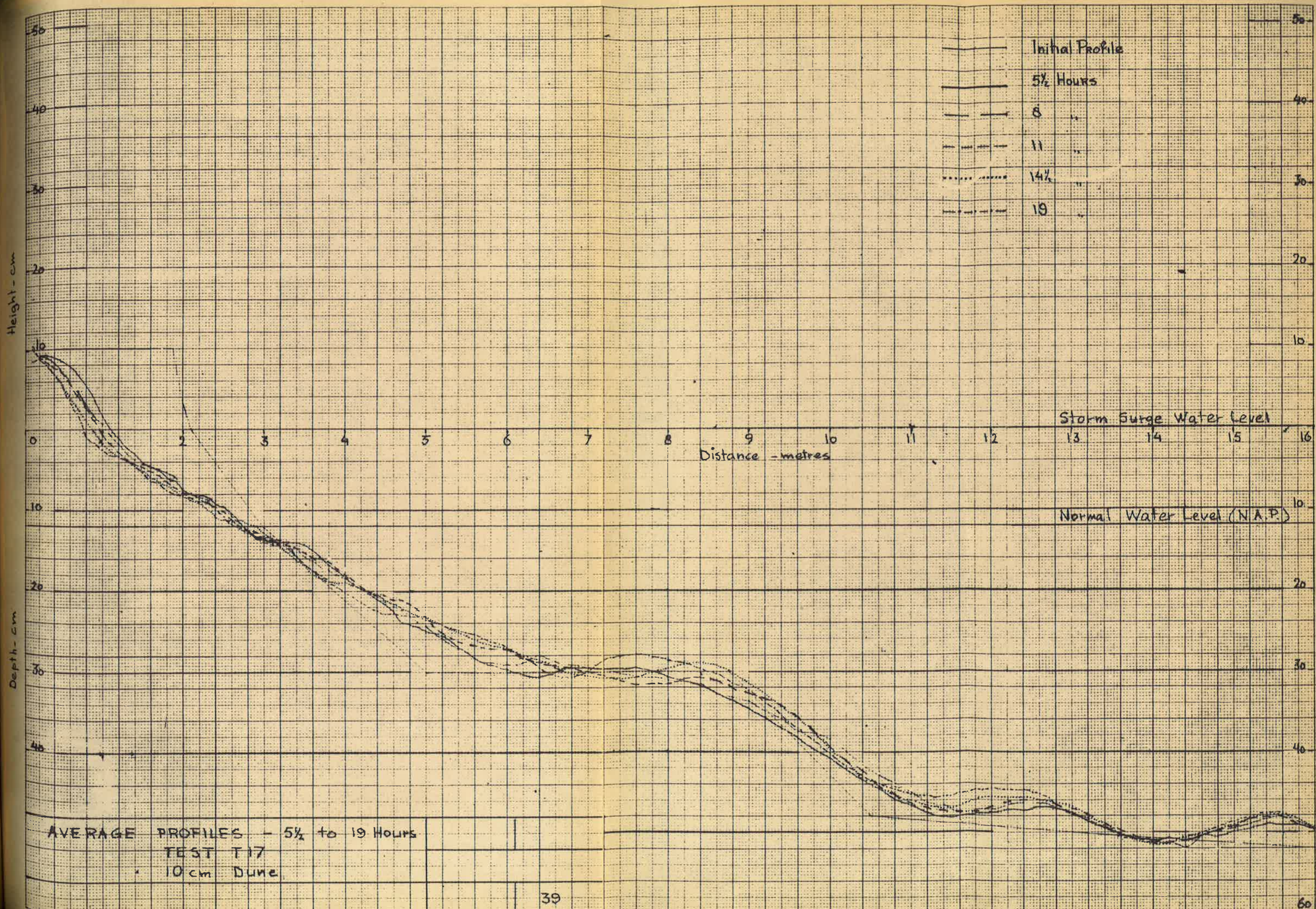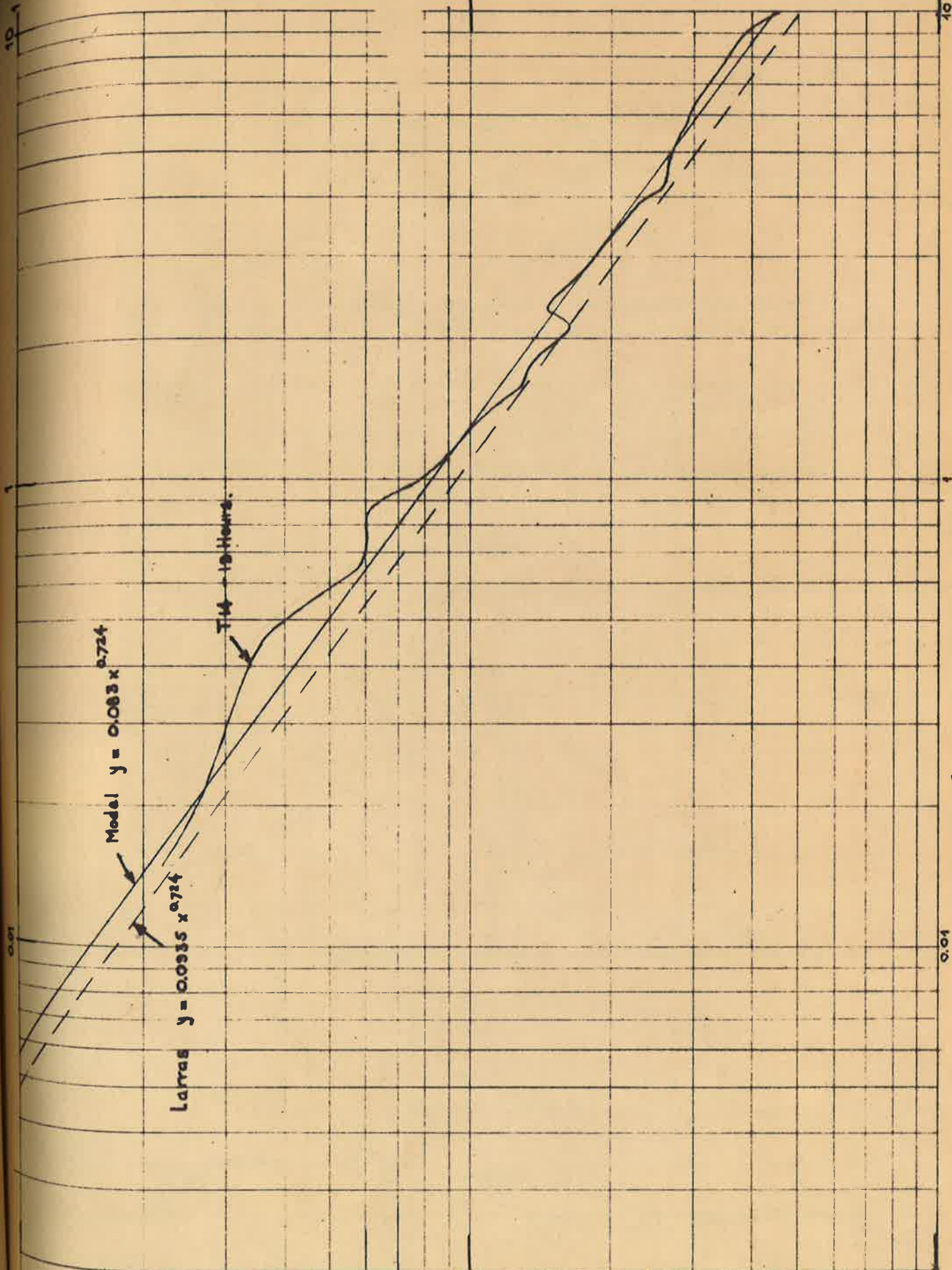
Distance from Storm Surge Water line - metres.

LOGARITHMIC PLOT OF AVERAGE
PROFILE AT 19HOURS   TEST T14

40
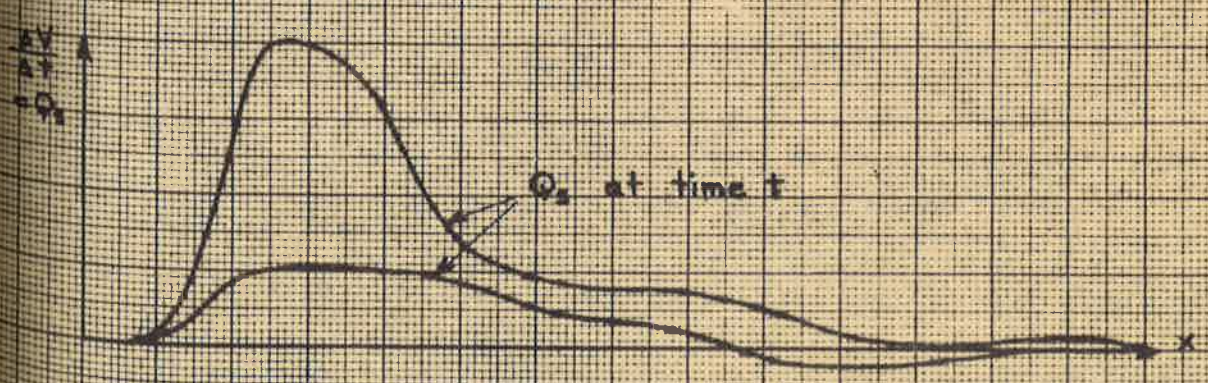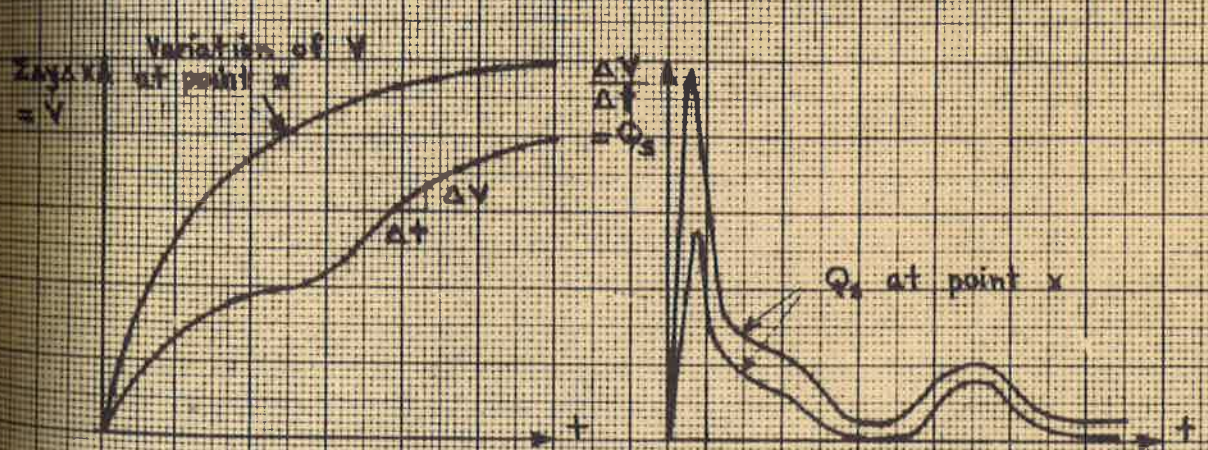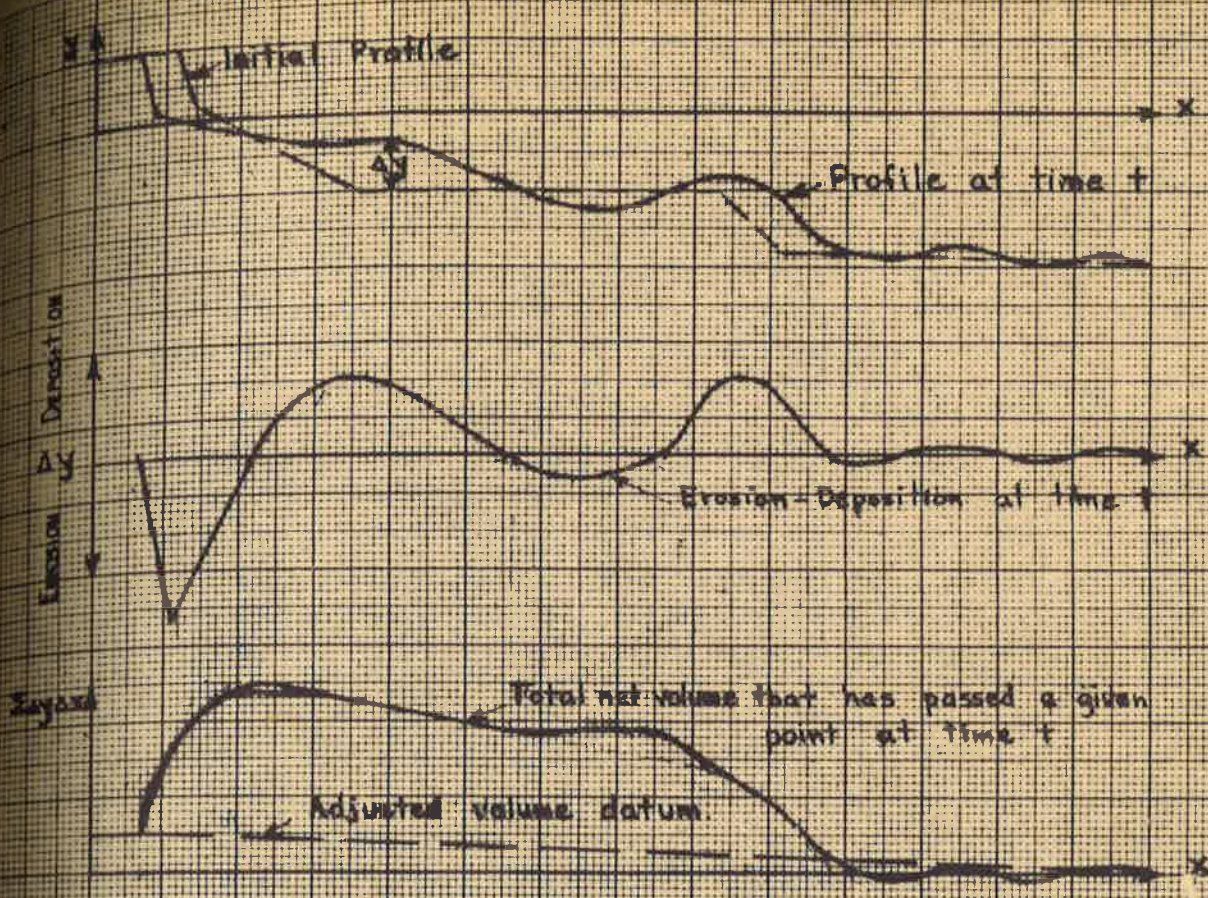
SCHEMATIC OUTLINE OF NET TRANSPORT RATE CALCULATION
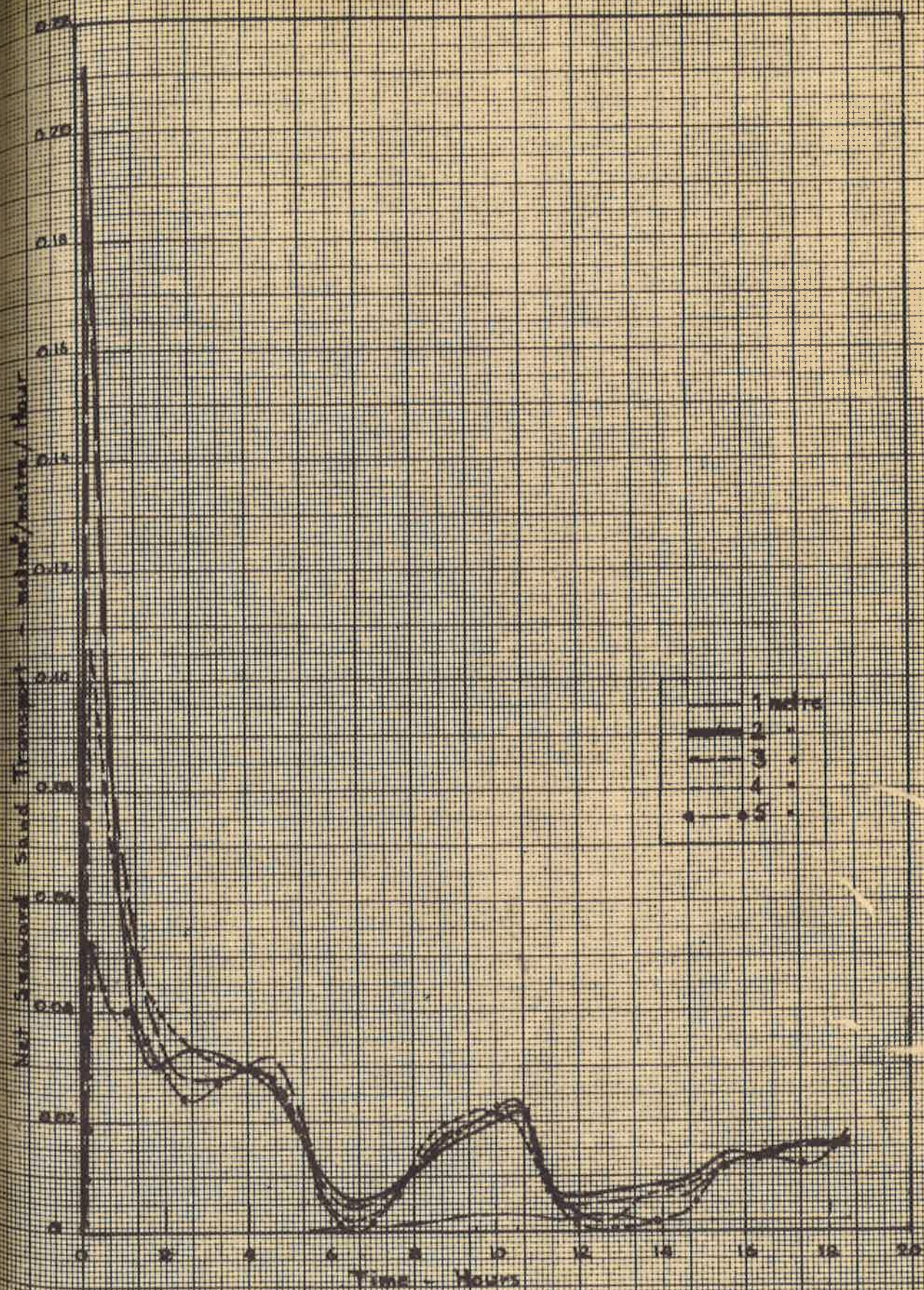
NET SEAWARD SAND TRANSPORT AS
FUNCTION OF TIME - TEST T26
TO 5 METRES
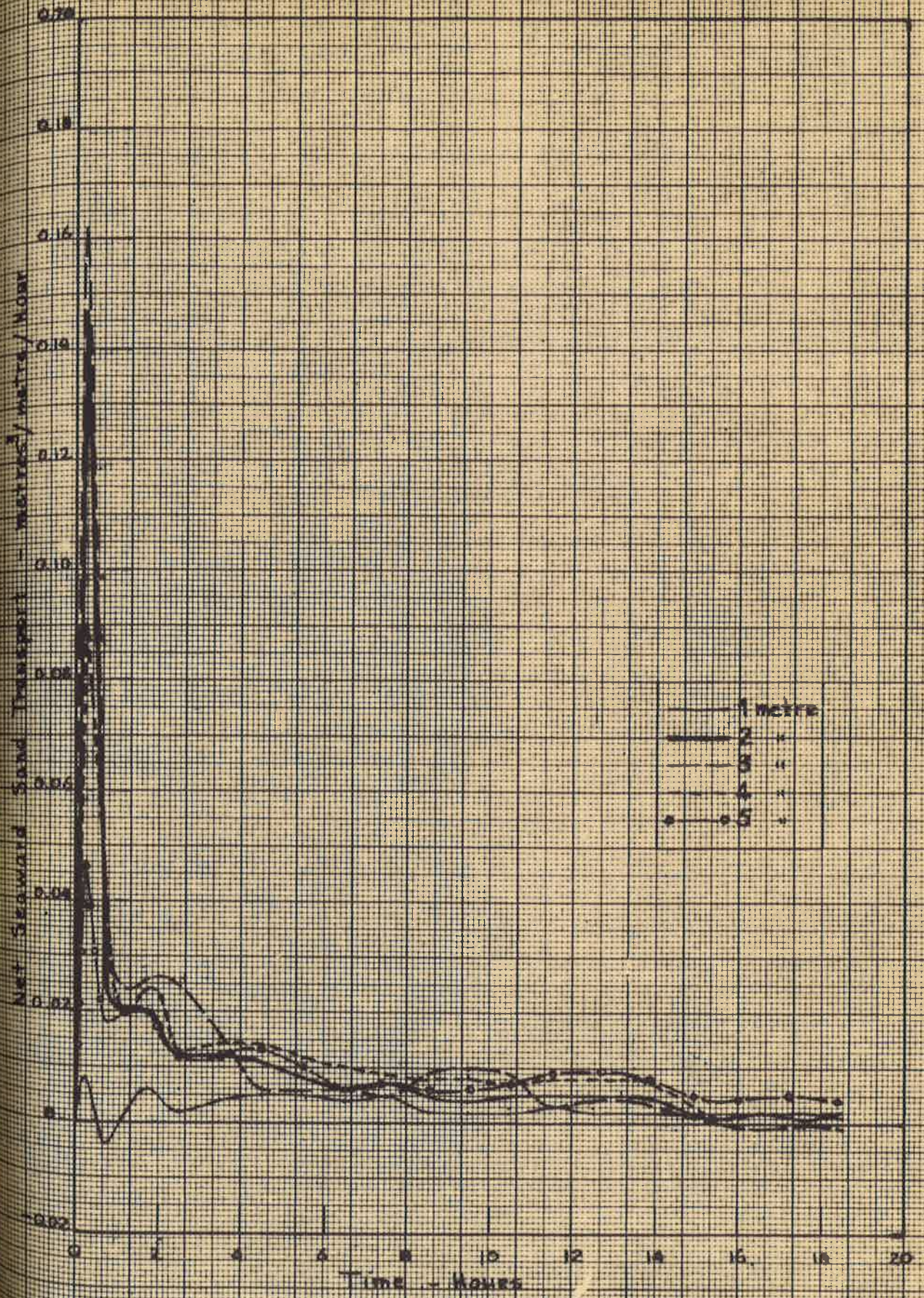
NET SEAWARD SAND TRANSPORT AS A
FUNCTION OF TIME — TEST T17
1 to 5 metres
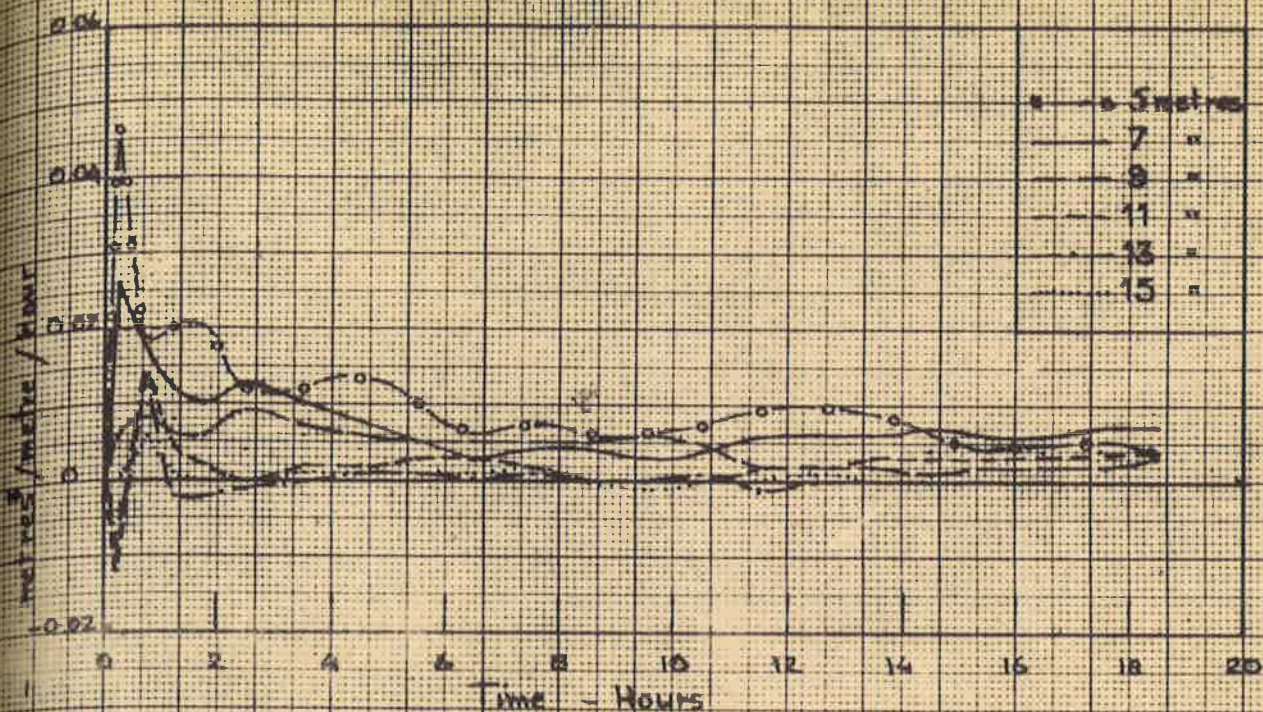
(a) Test T17
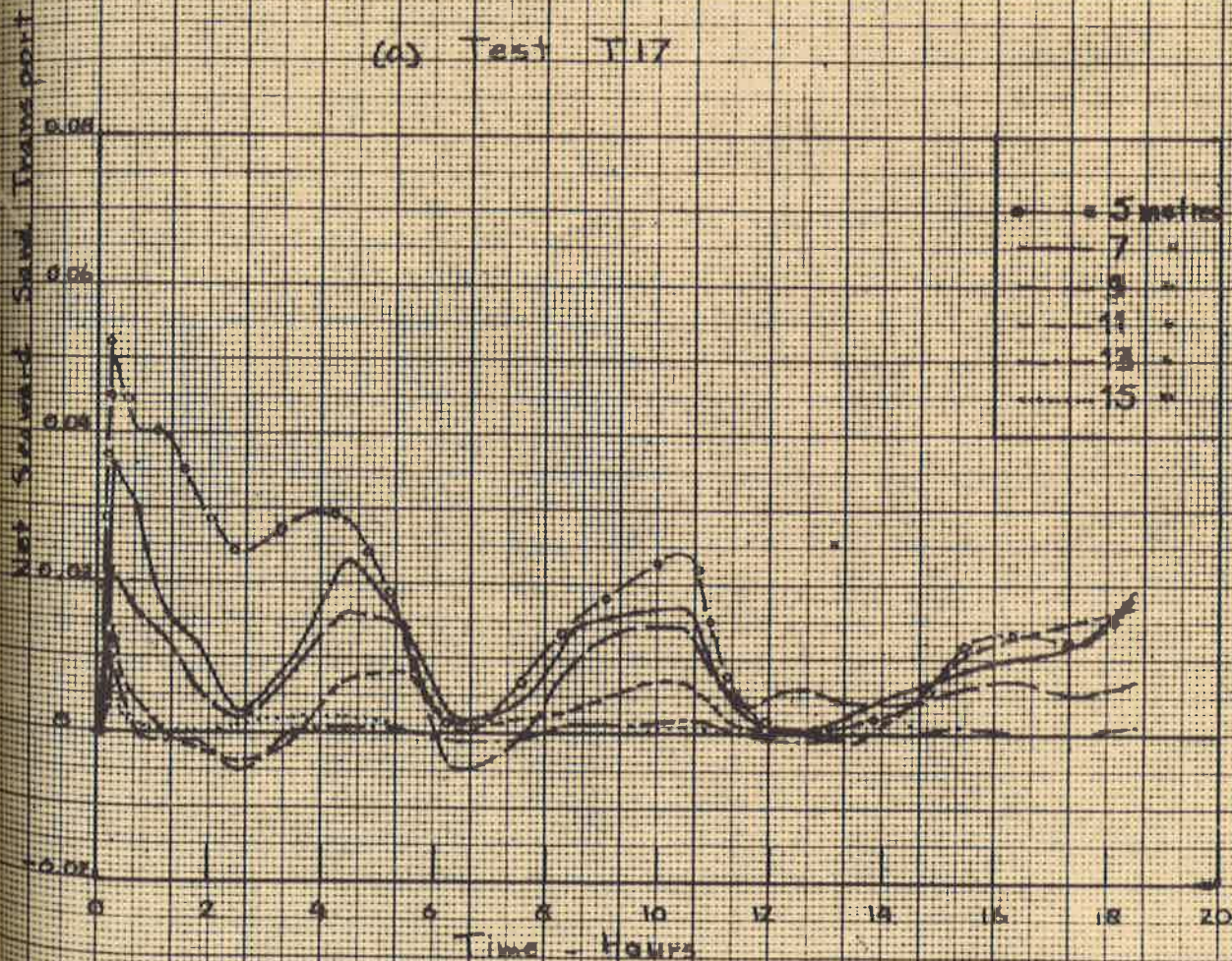
(b) Test T26

NET SEAWARD SAND TRANSPORT AS
FUNCTION OF TIME - TESTS T17 and T26
0 to 15 metres

44

NET SEAWARD SAND TRANSPORT OVER
BEACH PROFILES AT VARIOUS TIMES
TEST T26

Legend:
- 0.5 Hours
- 1 " Hours
- 2 Hours
- 3.5 "
- 5.5 "
- 8 "
- 11 "
- 14.5 "
- 19 "
- Initial Breakpoint

Y-axis: Net Seaward Sand Transport — metres³/metre/hour

X-axis: Distance — metres

45
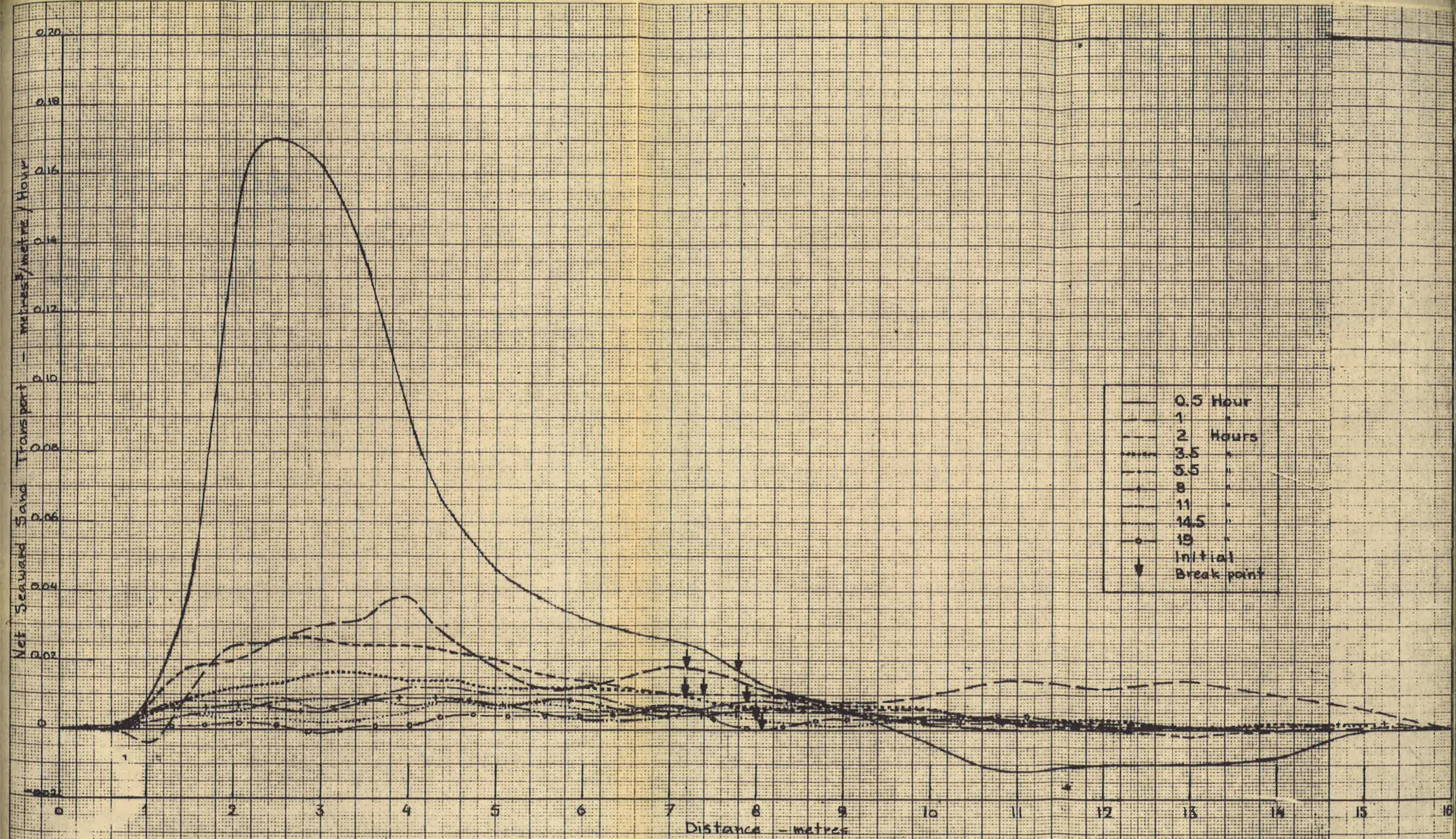
NET SEAWARD SAND TRANSPORT OVER
BEACH PROFILES AT VARIOUS TIMES
TEST T17

46
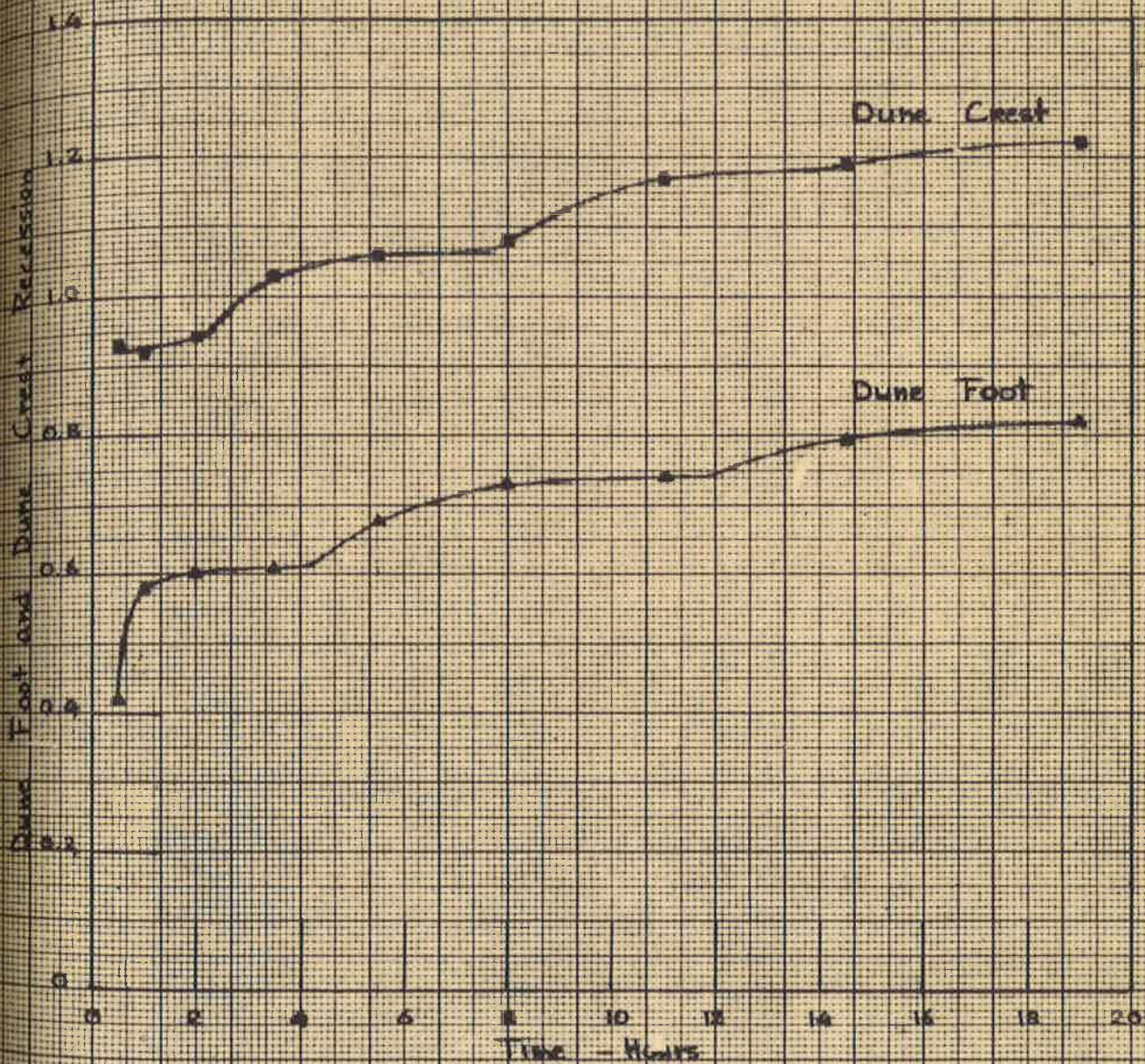
DUNE FOOT AND DUNE CREST RECESSION
TEST T26

47

RECESSION OF WATERLINE FOR
VARIOUS WAVE HEIGHS
T = 1.56 to 1.63 sec.
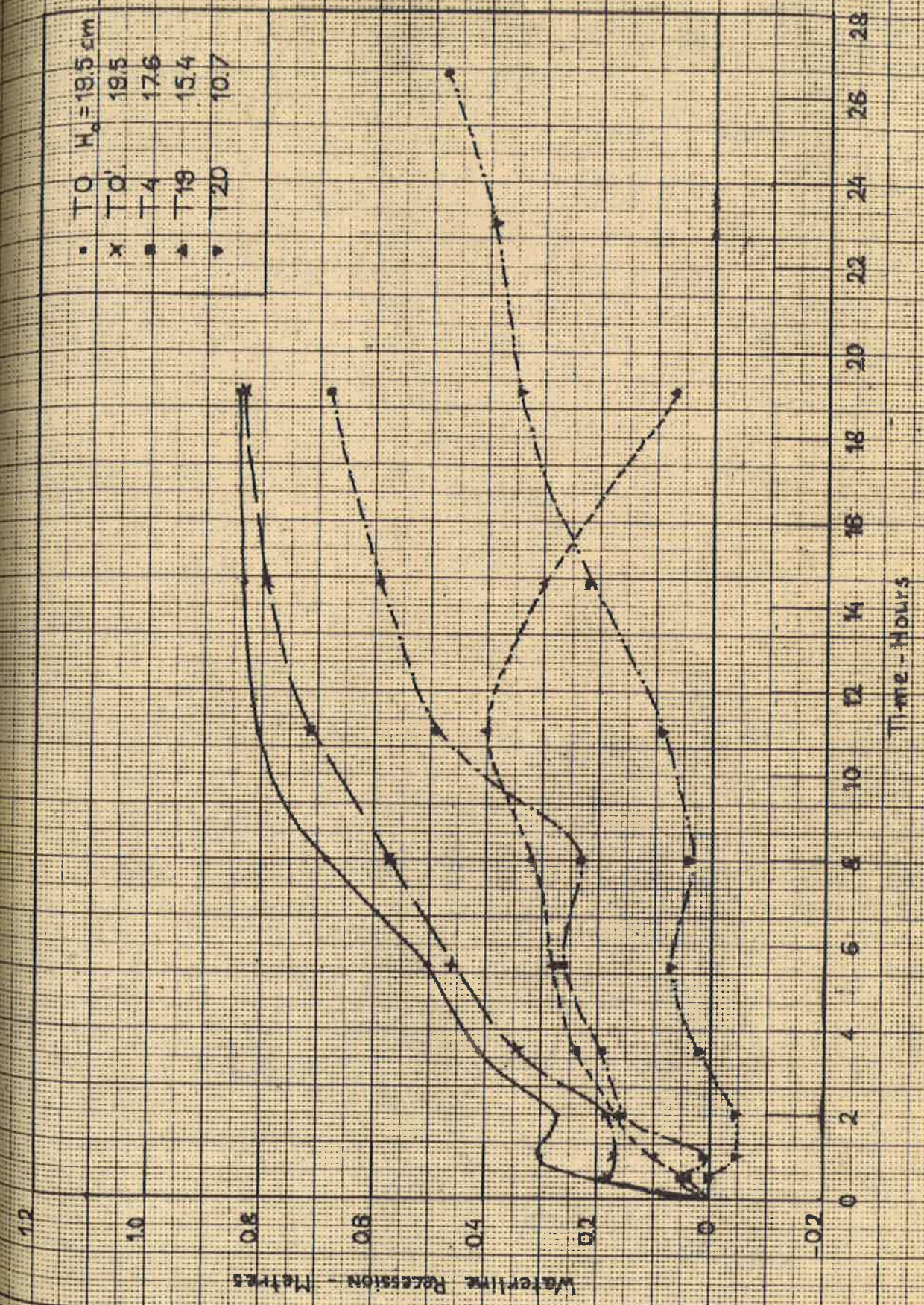
RECESSION OF DUNE FOOT FOR VARIOUS
WAVE HEIGHTS
T = 1.56 to 1.63 sec.

49

Deep Water Wave Height - H_0 - cm.
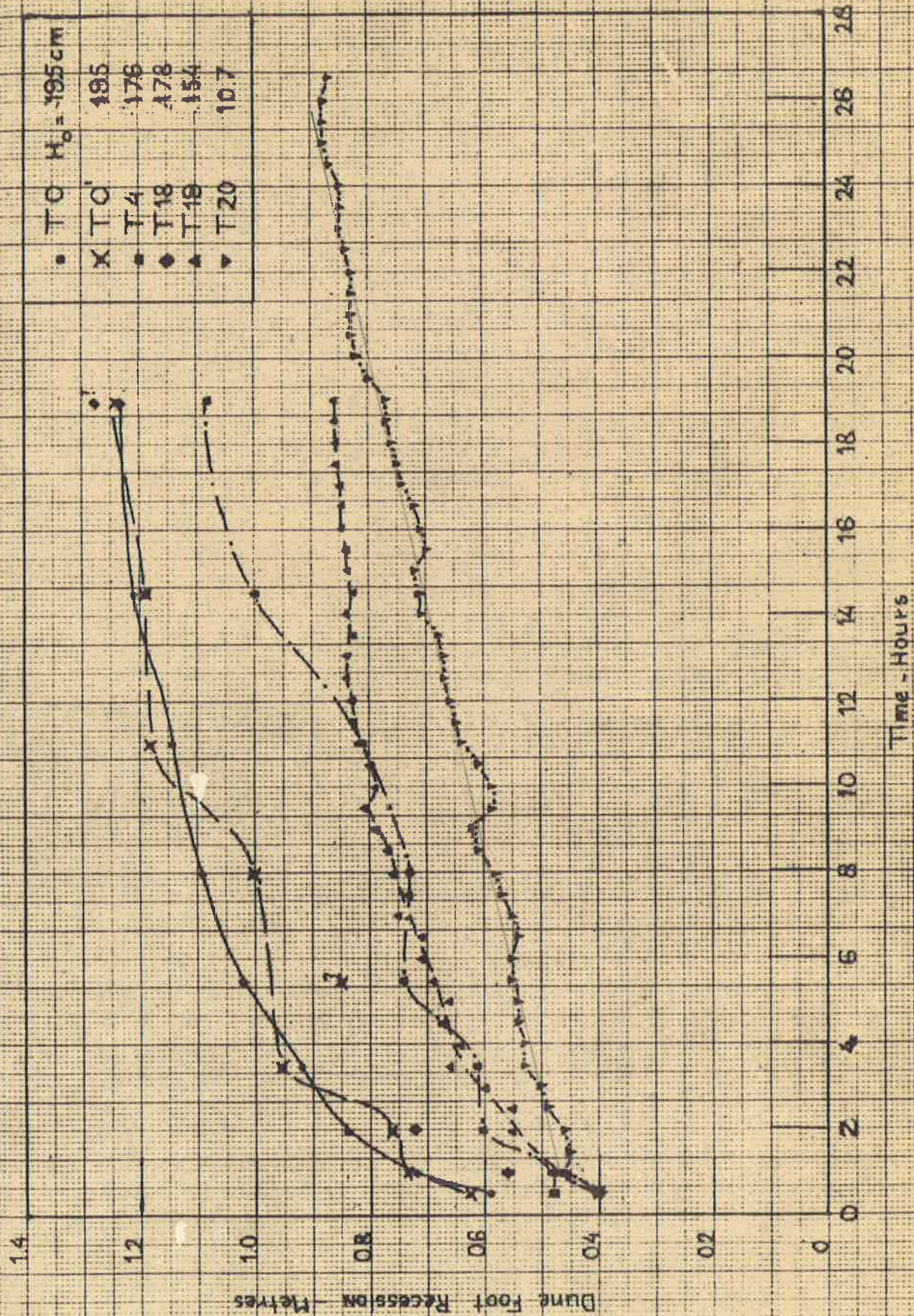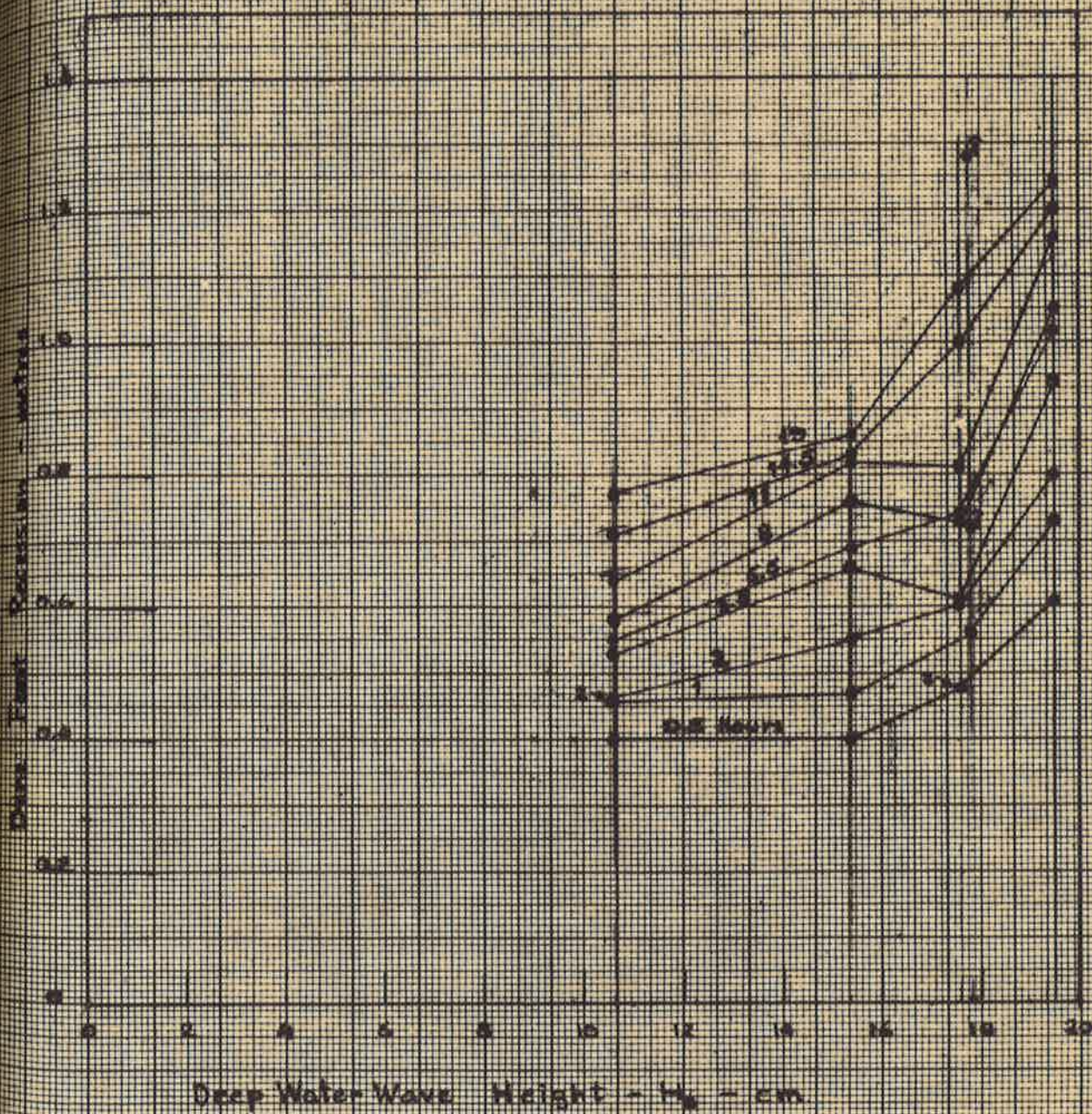
Note. The points plotted for $H_0 = 192$ cm represent the mean of the values given in table 5.2 for feets TO and TO' (omitting TO' at 5½ hours).

DUNE FOOT RECESSION AS FUNCTION OF WAVE HEIGHT.

RELATIVE DUNE FOOT RECESSION $\frac{x'}{L}$
AS FUNCTION OF NUMBER OF WAVES $\frac{t}{T}$

$\frac{\ddot{z}}{T}$ — metres/sec.²

0.6

0.5

0.4

0.3

0.2

0.1

$\frac{t}{T}$

▲ 40000

▲ 20000

▲ 10000

▲ 5000

▲ 2000

0   2   4   6   8   10   12

$\frac{H_0}{T^2}$ — cm/sec²

RELATIVE DUNE FOOT RECESSION $\frac{z'}{T}$ AS
FUNCTION OF WAVE STEEPNESS $\frac{H_0}{T^2}$

52

Number of Waves $\frac{t}{T}$

		$\frac{H}{T^2}$				$\frac{H}{T^2}$ = 9.2 cm/sec²
•	T 0	= 7.4 cm/sec²	+	T 22		9.2 cm/sec²
○	T 0	7.4	✦	T 23		10.1
✻	T 4	6.7	✶	T 24		11.1
▾	T 20	4.5	◆	T 14		8.3

RELATIVE DUNE EROSION VOLUME $\frac{V}{hT^2}$

AS FUNCTION OF NUMBER OF WAVES

FOR DIFFERENT WAVE STEEPNESS

53

RELATIVE DUNE EROSION VOLUME $\frac{V}{T}$ AS FUNCTION OF NUMBER OF WAVES FOR DIFFERENT WAVE STEEPNESS

54

(a) $\frac{V}{T^2}$ as function of $\frac{H}{T^2}$ for given $\frac{t}{T}$

(b) Volume (V) eroded as function of Time for various Tests

DUNE EROSION VOLUME AS FUNCTION
OF TIME AND WAVE CHARACTERISTICS
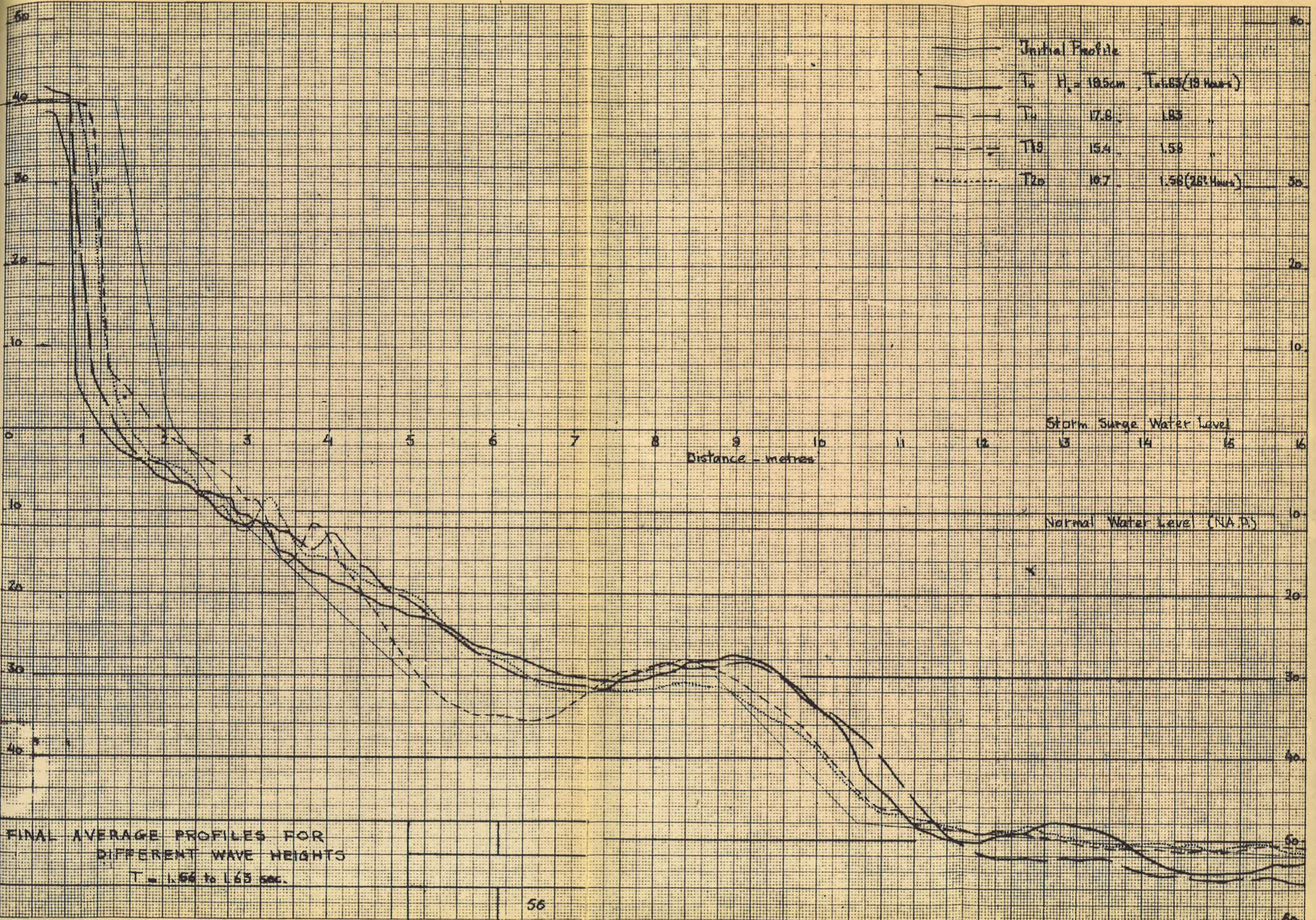
Initial Profile

		$H_s = 19.5$ cm	$T_s = 1.65$ (18 Hours)
T_{11}		17.8	1.83
T_{15}		15.4	1.53
T_{20}		10.7	1.58 (26⅓ Hours)

Height - cm

Depth - cm

Distance - metres

Storm Surge Water Level

Normal Water Level (NA.P.)

FINAL AVERAGE PROFILES FOR
DIFFERENT WAVE HEIGHTS
T = 1.56 to 1.65 sec.

Time - Hours

After H.W. Waves - T21   After L.W. Waves - T21   Constant Level Waves - T0
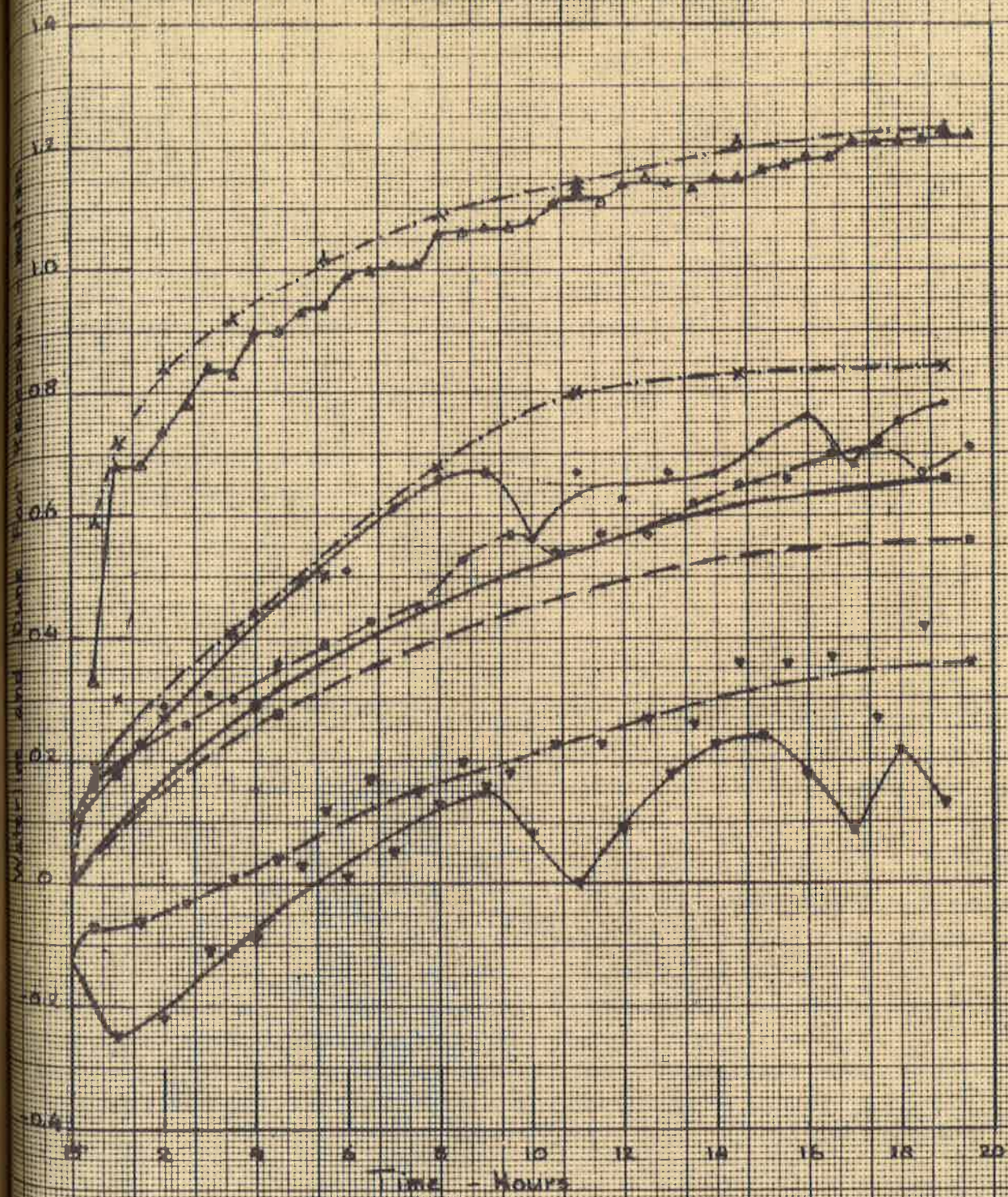
▲	Dune Foot	▲ Dune Foot	▲ Dune Foot
⊕	I.W. Line	⊕ H.W. Line	✕ Water Line (Mean Level)
■	M.W. Line	■ M.W. Line	
▼	L.W. Line	▼ L.W. Line	

RECESSION OF WATER LINE AND DUNE FOOT
FOR CHANGING AND CONSTANT LEVEL TESTS
(T21 and T0)

57

Height - cm

Depth - cm

Distance — metres
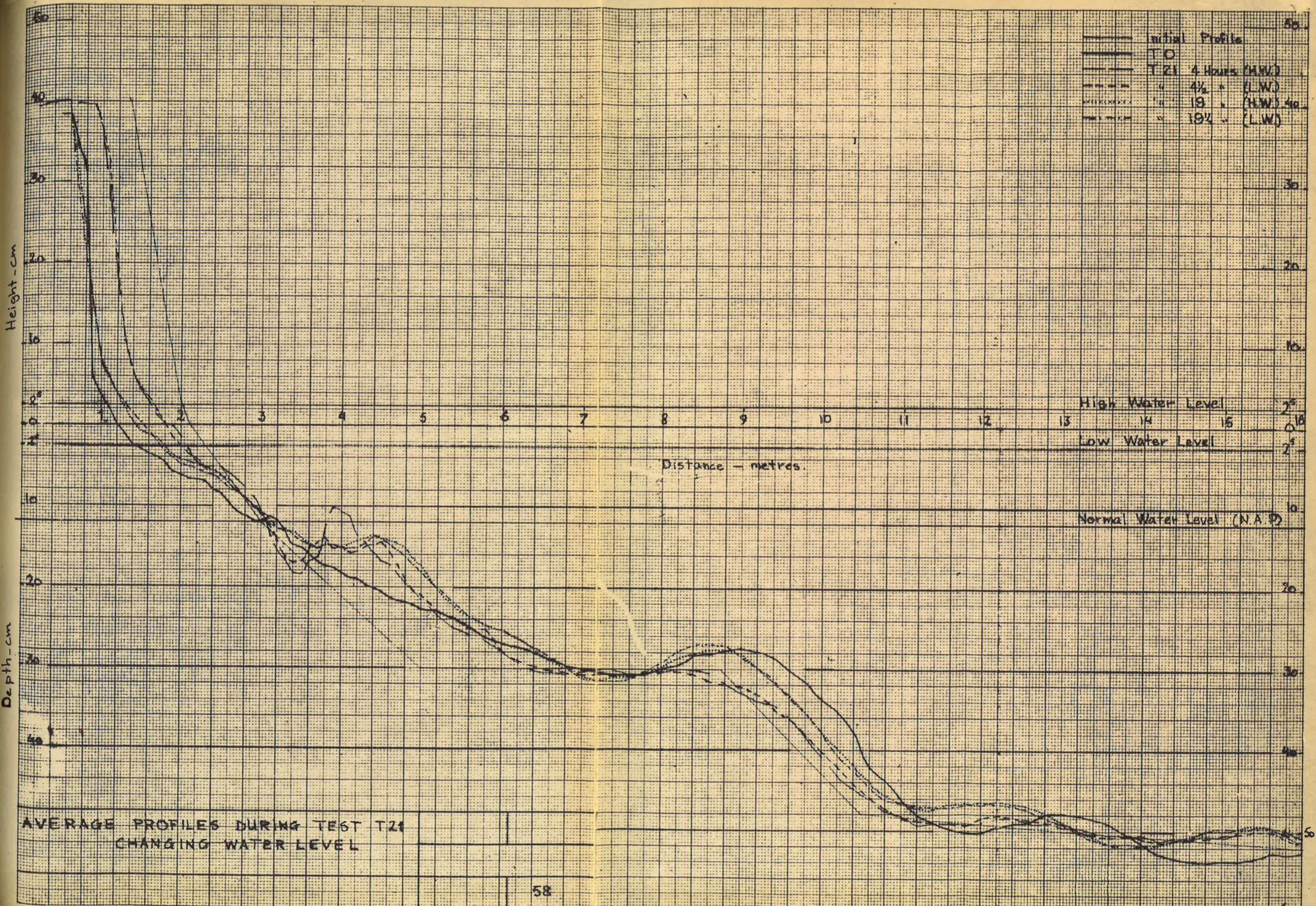
Initial Profile
T O
T 21   4 Hours (H.W.)
"   4½ "   (L.W.)
"   19 "   (H.W.)
"   19½ "   (L.W.)

High Water Level

Low Water Level

Normal Water Level (N.A.P.)

AVERAGE PROFILES DURING TEST T21
CHANGING WATER LEVEL

58

(b) Tests T7 and T22

(c) Tests T8 and T23

RECESSION OF WATERLINE AND
DUNE FOOT FOR WIND WAVES AND
REGULAR WAVES

59
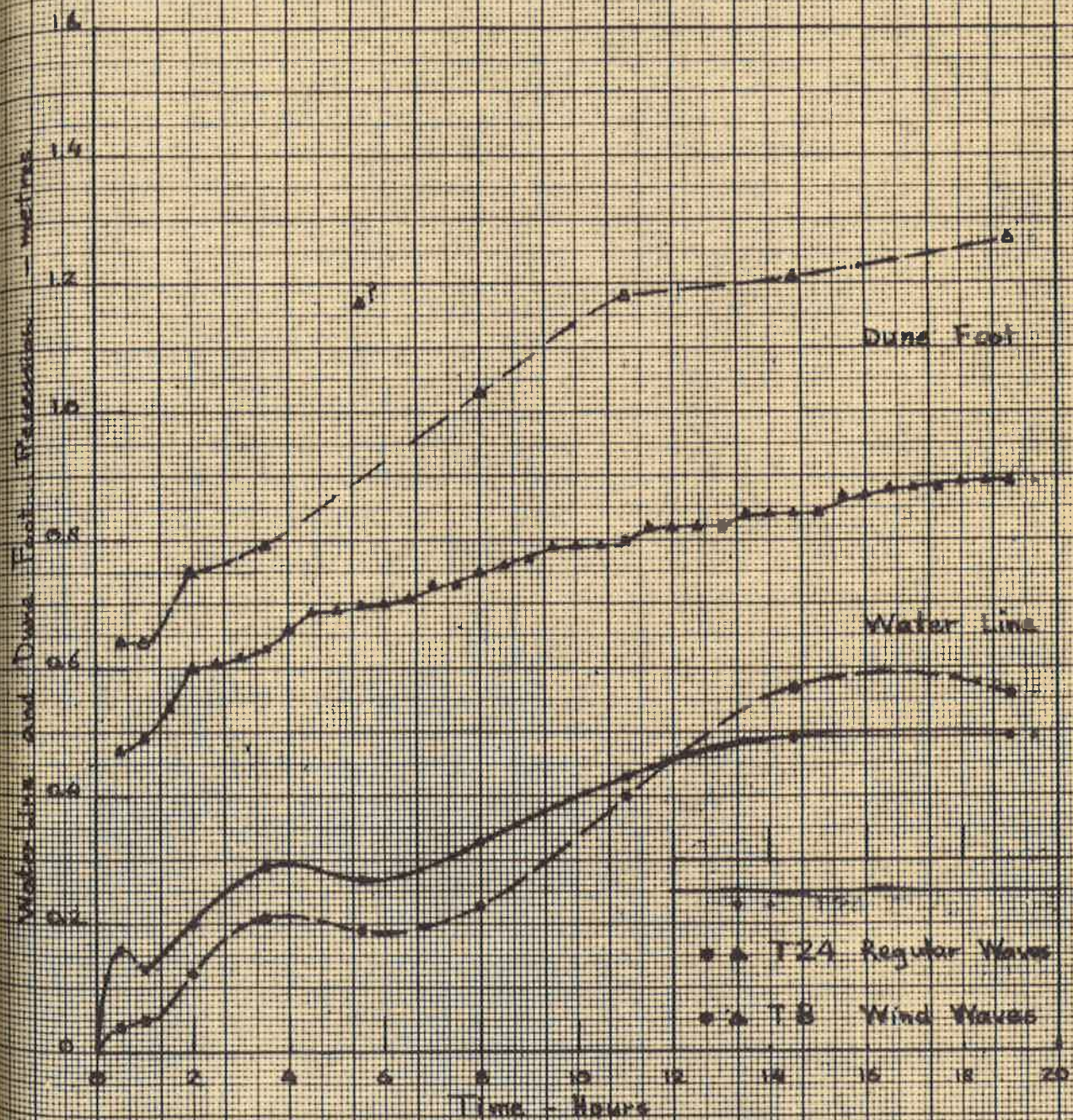
Tests T8 and T24

RECESSION OF WATERLINE AND
DUNE FOOT FOR WIND WAVES AND
REGULAR WAVES

Dune Foot

Water Line

• • T24 Regular Waves
• • T8 Wind Waves

Time - Hours

RELATIVE EROSION VOLUME $\frac{V}{H_0 T^2}$ AS FUNCTION OF NUMBER OF WAVES $\frac{t}{T}$ FOR WIND WAVES AND REGULAR WAVES

RELATIVE EROSION VOLUME $\frac{V}{T^4}$ AS FUNCTION OF NUMBER OF WAVES $\frac{t}{T}$ FOR WIND WAVES AND REGULAR WAVES.

Height - cm

Depth - cm

Distance - metres

Initial Profile

T 7 H$_{mo}$ = 6.7 cm , T = 1.50 sec

T 6   9.4   1.11

T 8   11.1   1.29

Water Level

AVERAGE PROFILES AT 19 HOURS
FOR WIND WAVES
TESTS T 7, T 6 and T 8

63

Initial Profile

T22 Regular Waves

$H_{rms} = 6.6$ cm, $T = 1.04$ sec.

T7 Wind Waves

$H_{rms} = 6.7$, $T_s = 1.00$ sec

Water Level

Distance – cm
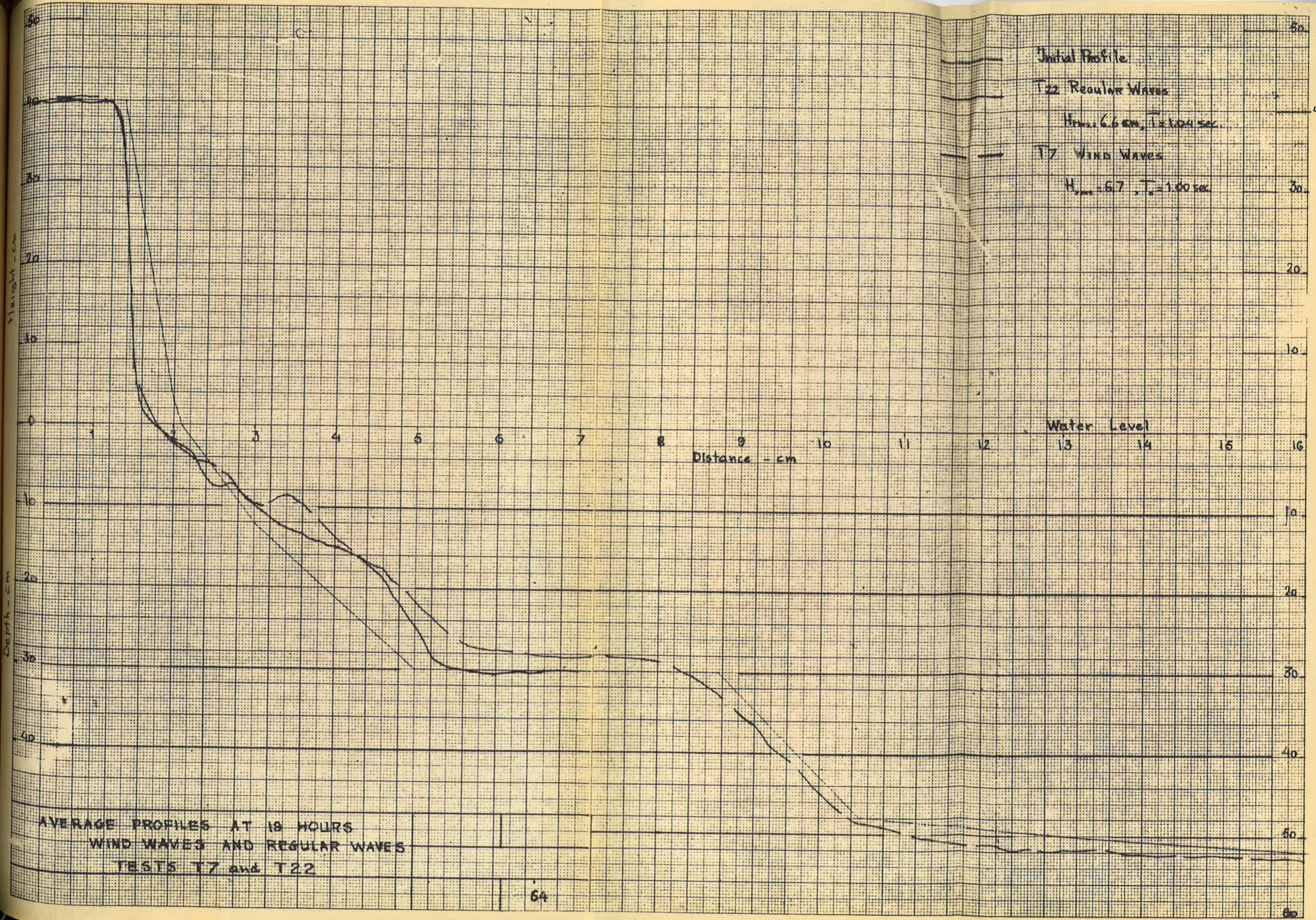
Height – cm

Depth – cm

AVERAGE PROFILES AT 18 HOURS
WIND WAVES AND REGULAR WAVES
TESTS T7 and T22

Legend:
- Initial Profile
- T25 Regular Waves
- $H_{rms} = 8.9$ cm, $T = 1.15$ sec.
- T6 Wind Waves
- $H_{rms} = 9.4$ cm, $T = 1.15$ sec.

Height - cm

Depth - cm

Distance - metres

Water Level
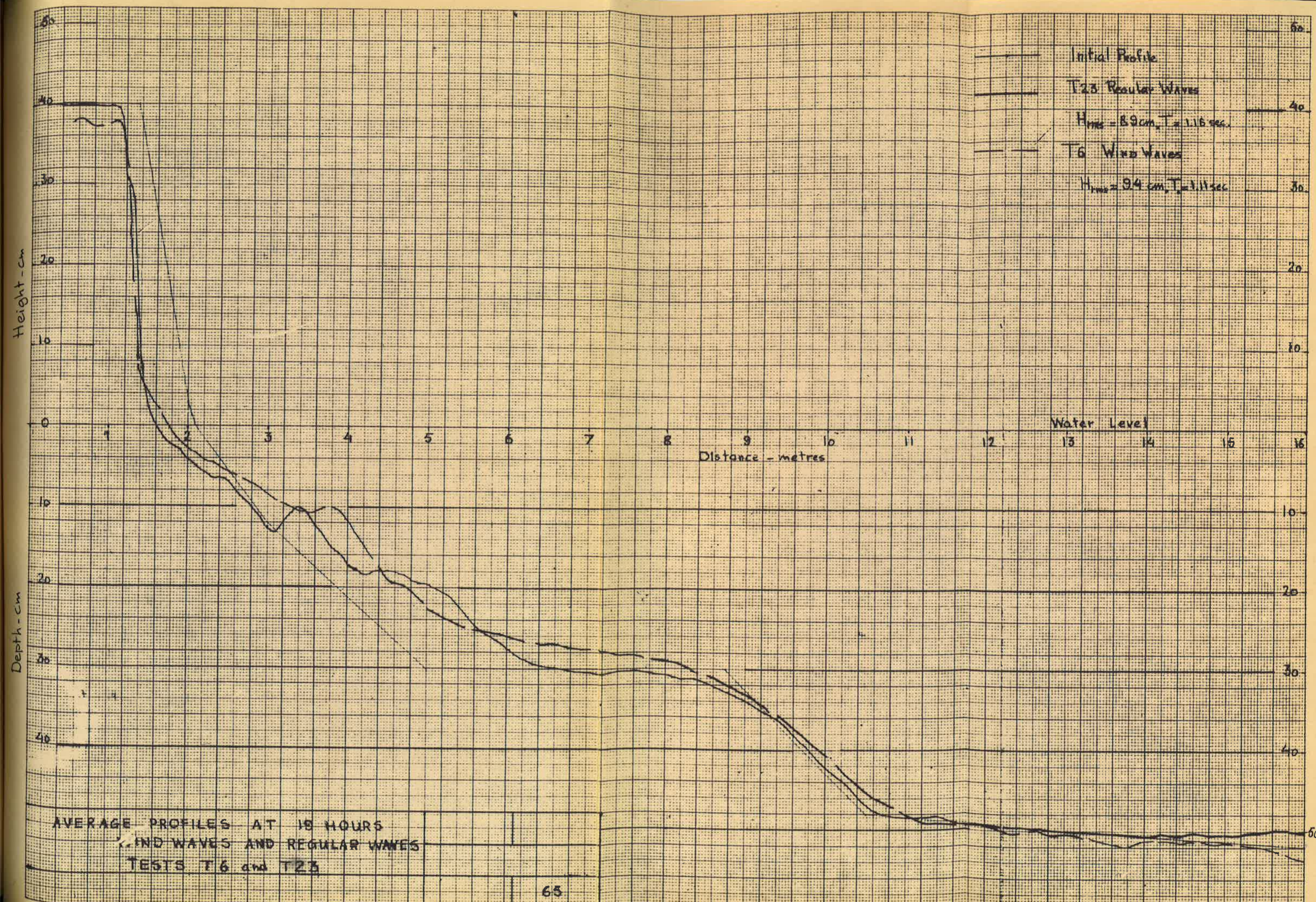
AVERAGE PROFILES AT 18 HOURS
WIND WAVES AND REGULAR WAVES
TESTS T6 and T25
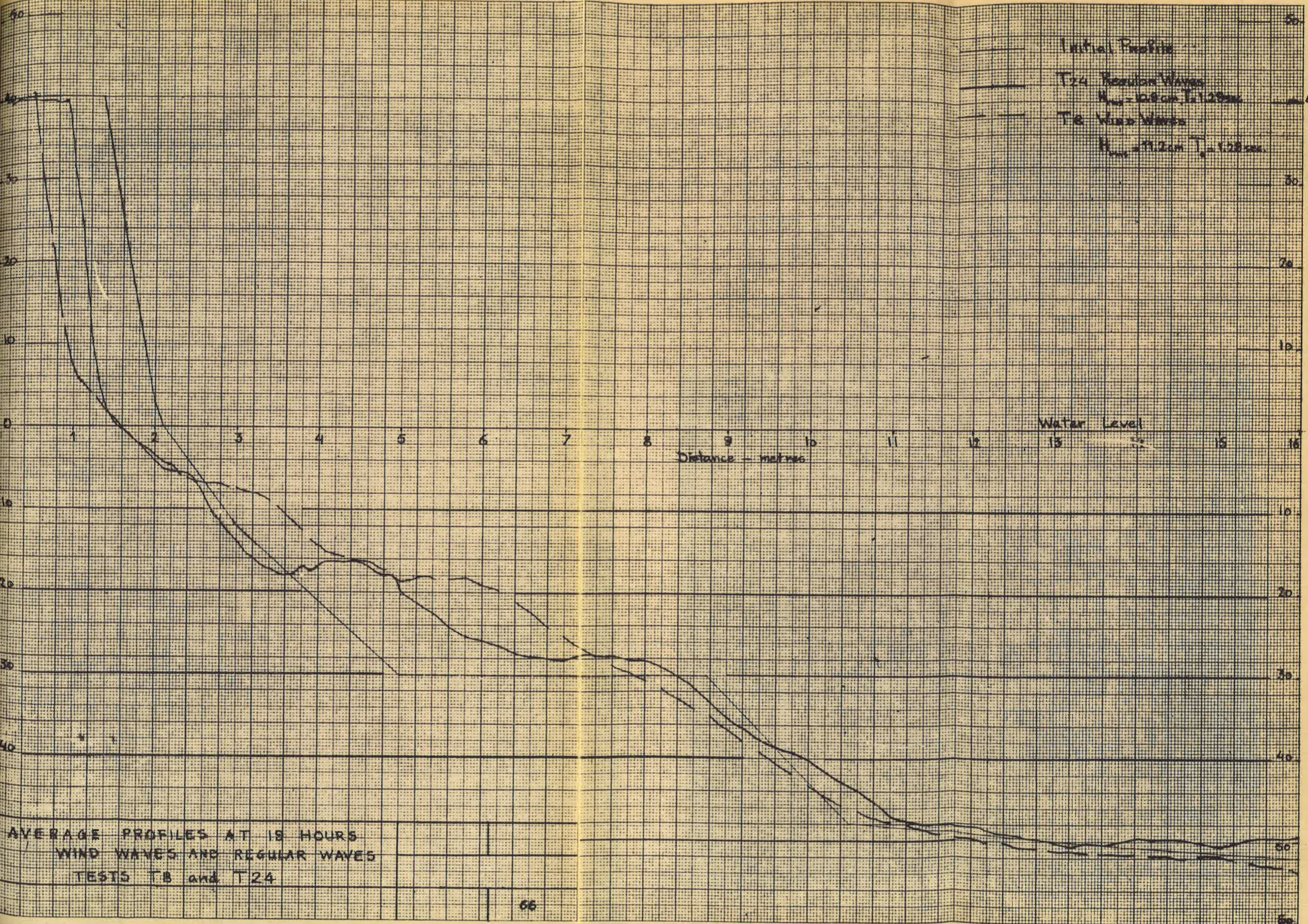
Average profiles at 18 hours. Wind waves and regular waves. Tests T8 and T24.

PROFILES AT 10 HOURS
TEST T24 - REGULAR WAVES

Height - cm

Depth - cm

Distance - metres
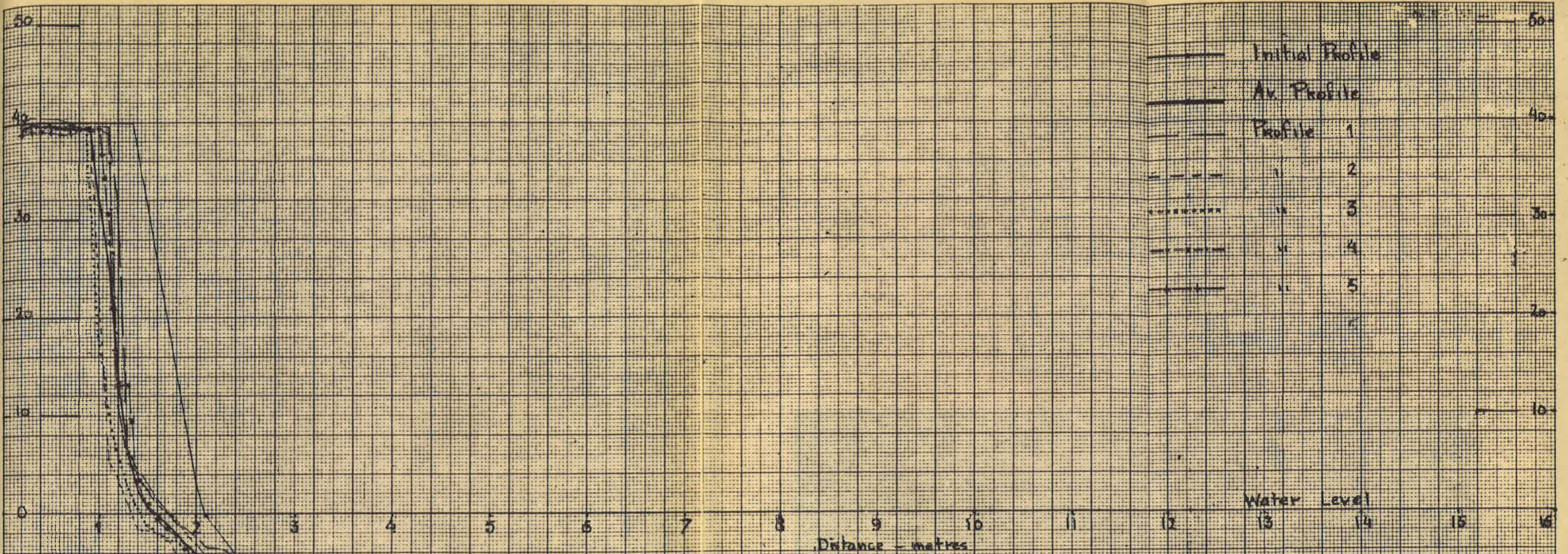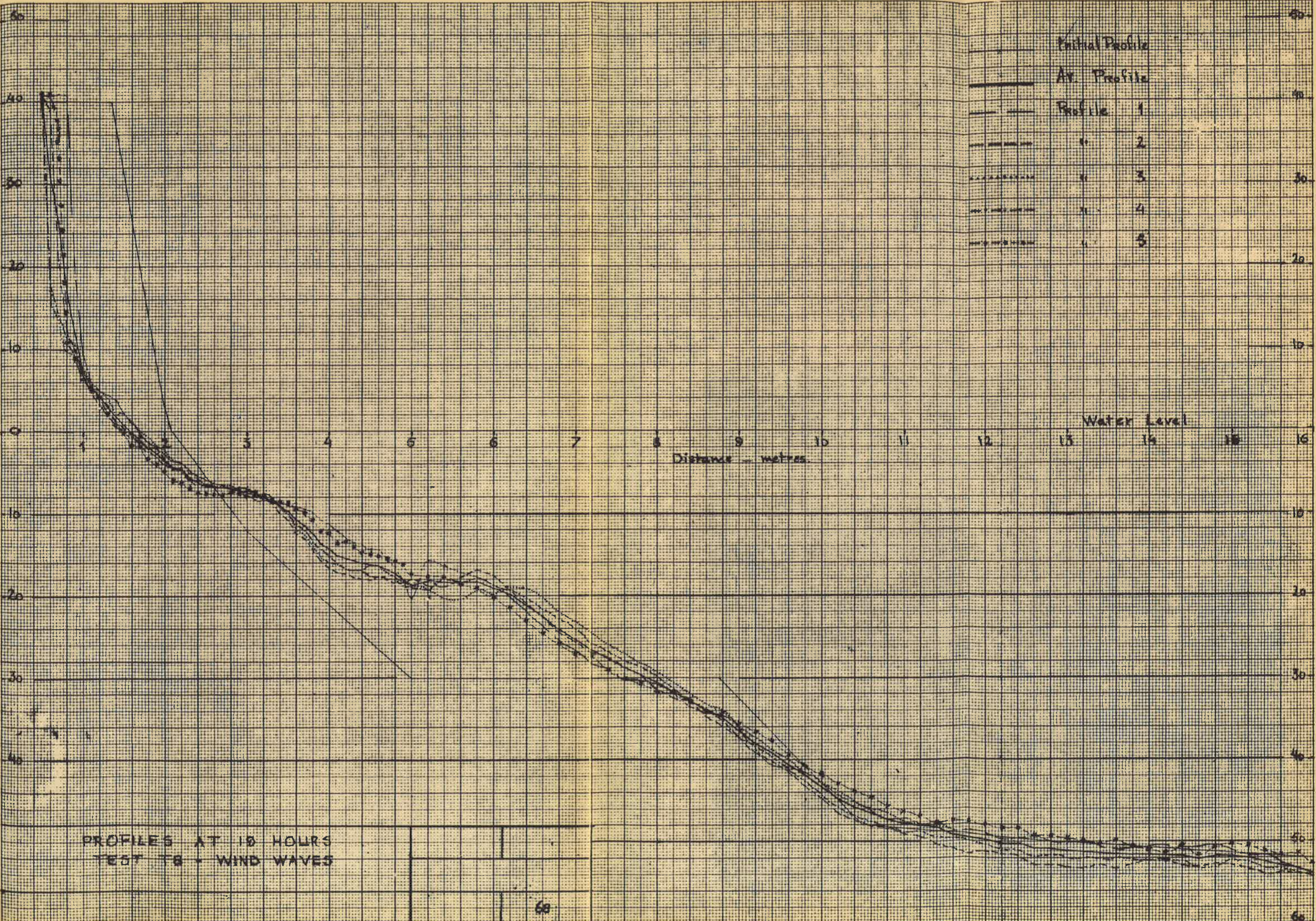
Water Level

Initial Profile
Av. Profile
Profile 1
         2
         3
         4
         5

67

PROFILES AT 18 HOURS
TEST T8 - WIND WAVES
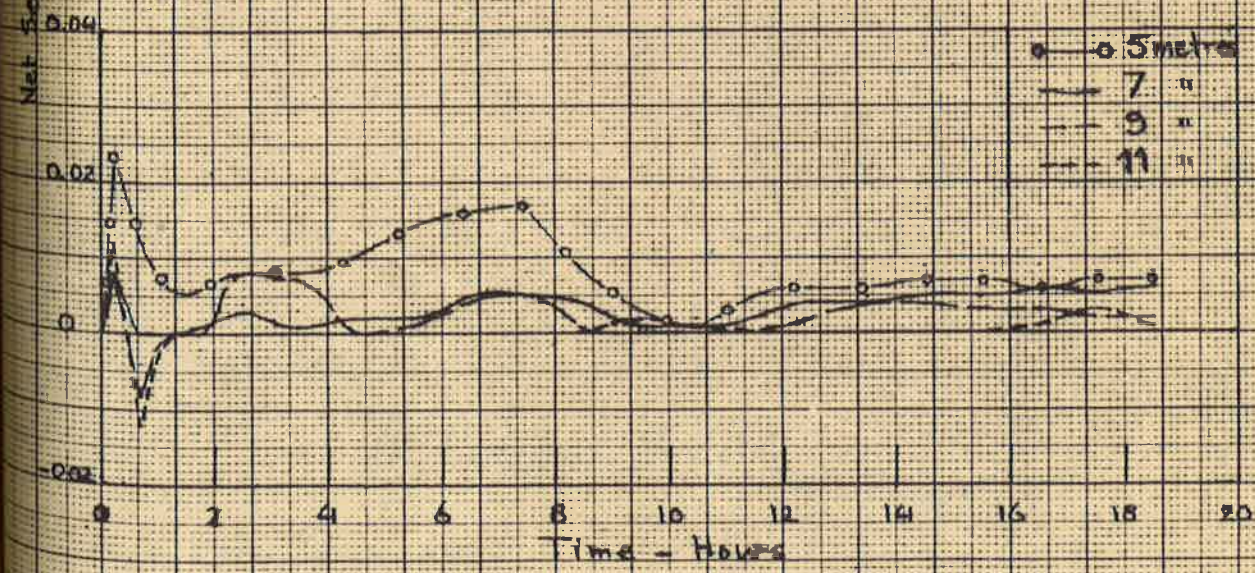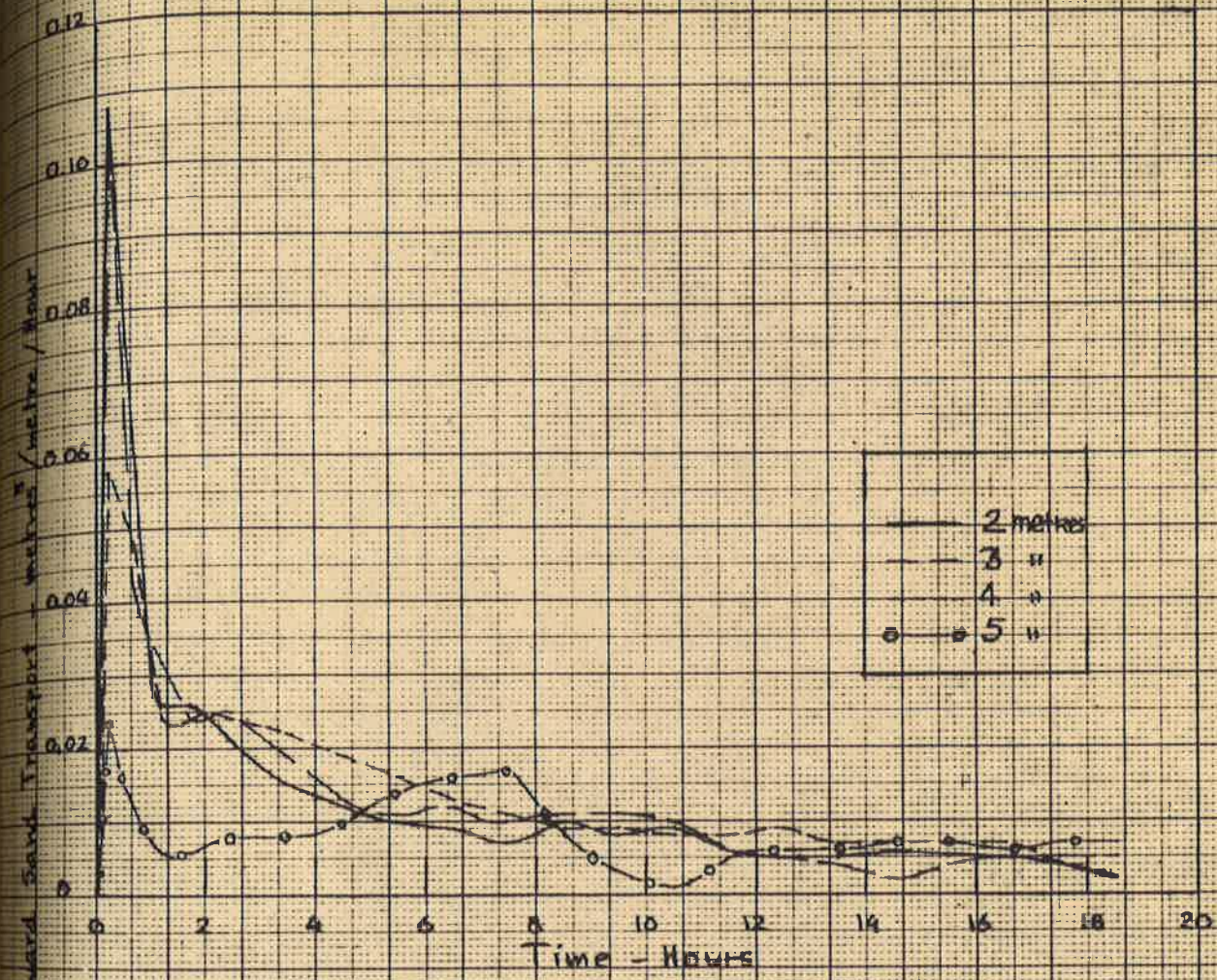
NET SEAWARD SAND TRANSPORT AS
FUNCTION OF TIME — TEST T24
1 to 11 metres
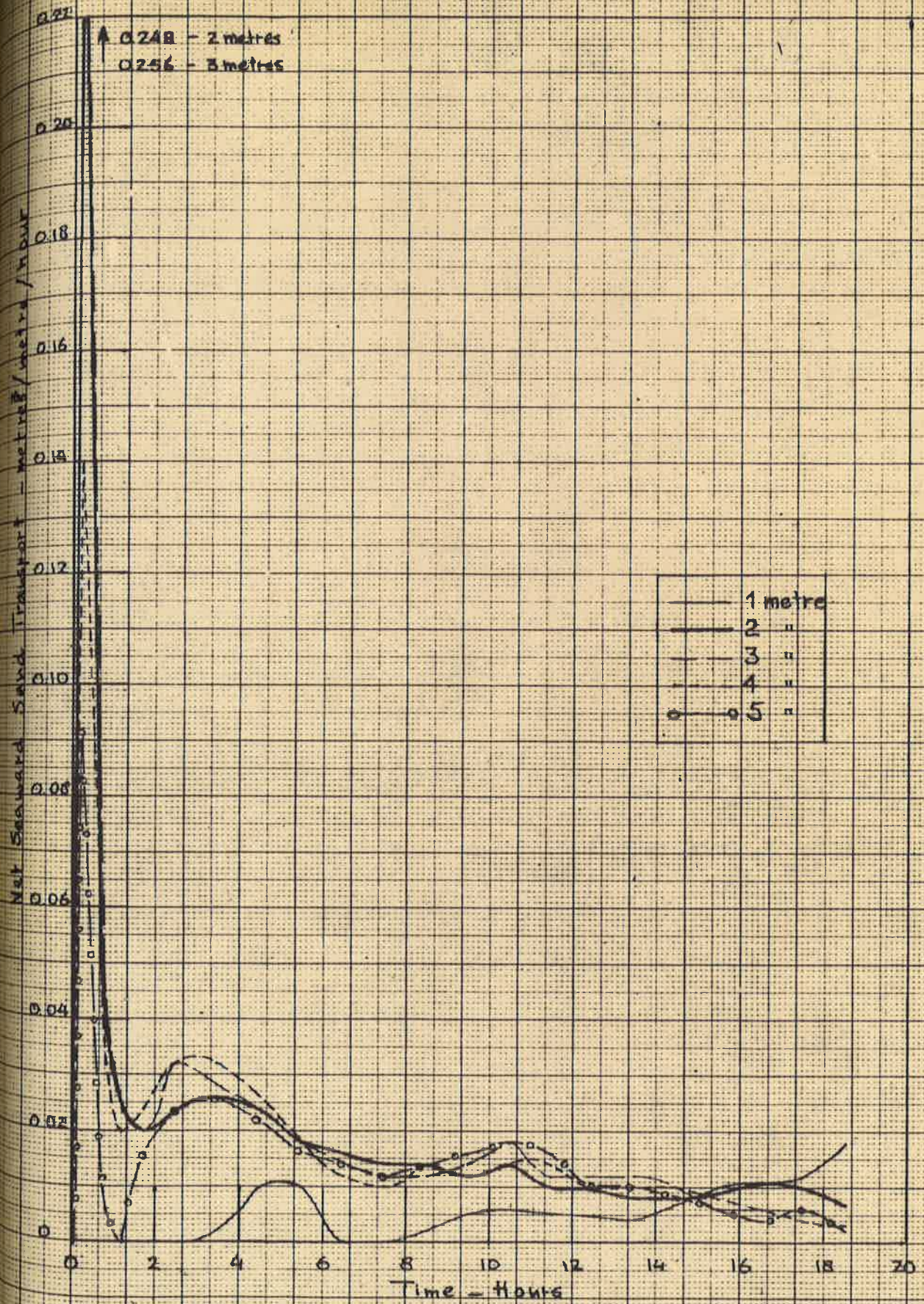
NET SEAWARD SAND TRANSPORT AS
FUNCTION OF TIME — TEST T8
1 to 5 metres
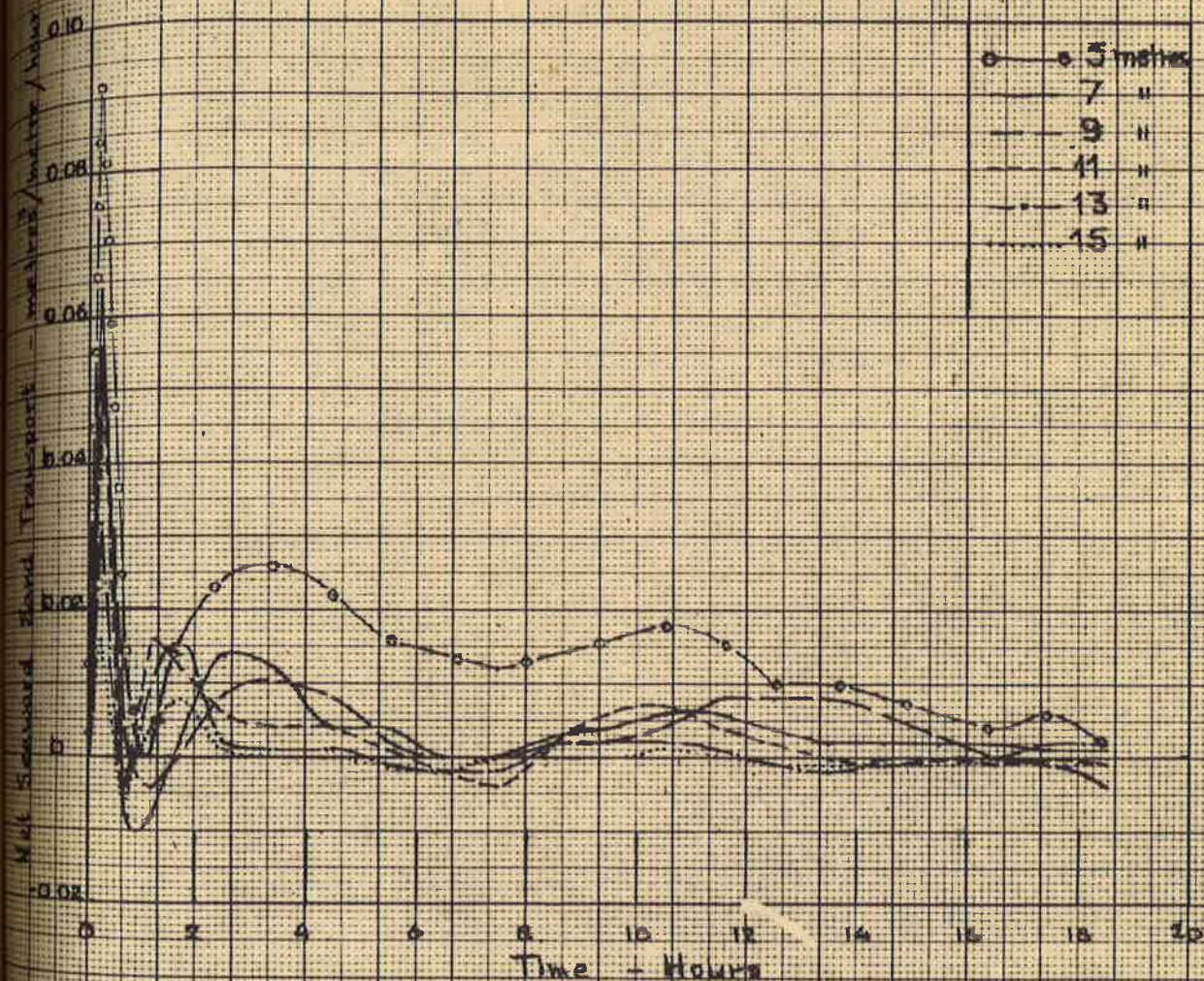
NET SEAWARD SAND TRANSPORT AS
FUNCTION OF TIME — TEST T8
5 to 15 metres.
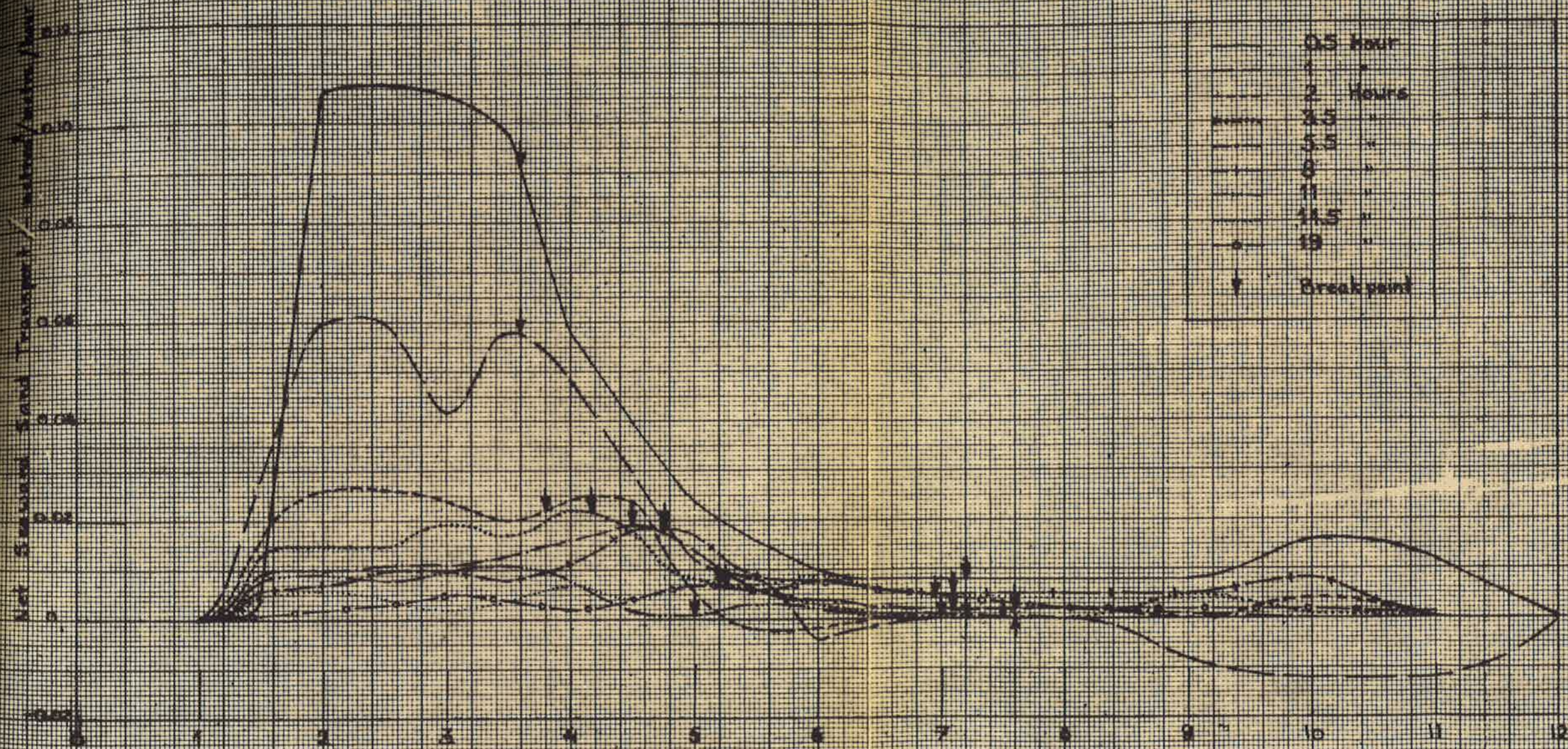
NET SEAWARD SAND TRANSPORT OVER
BEACH PROFILES AT VARIOUS TIMES
TEST T24
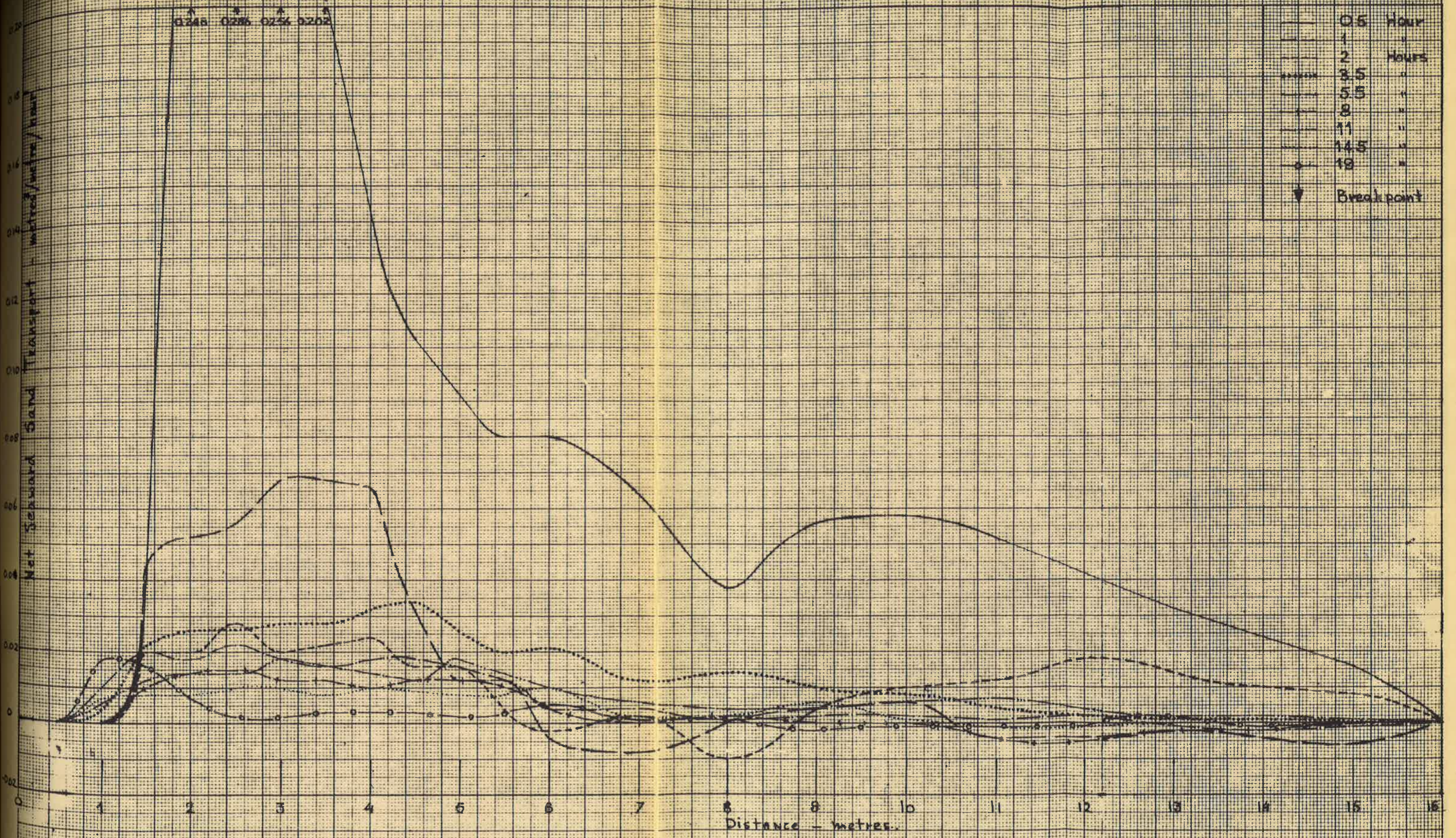
NET SEAWARD SAND TRANSPORT OVER
BEACH PROFILES AT VARIOUS TIMES
TEST 18
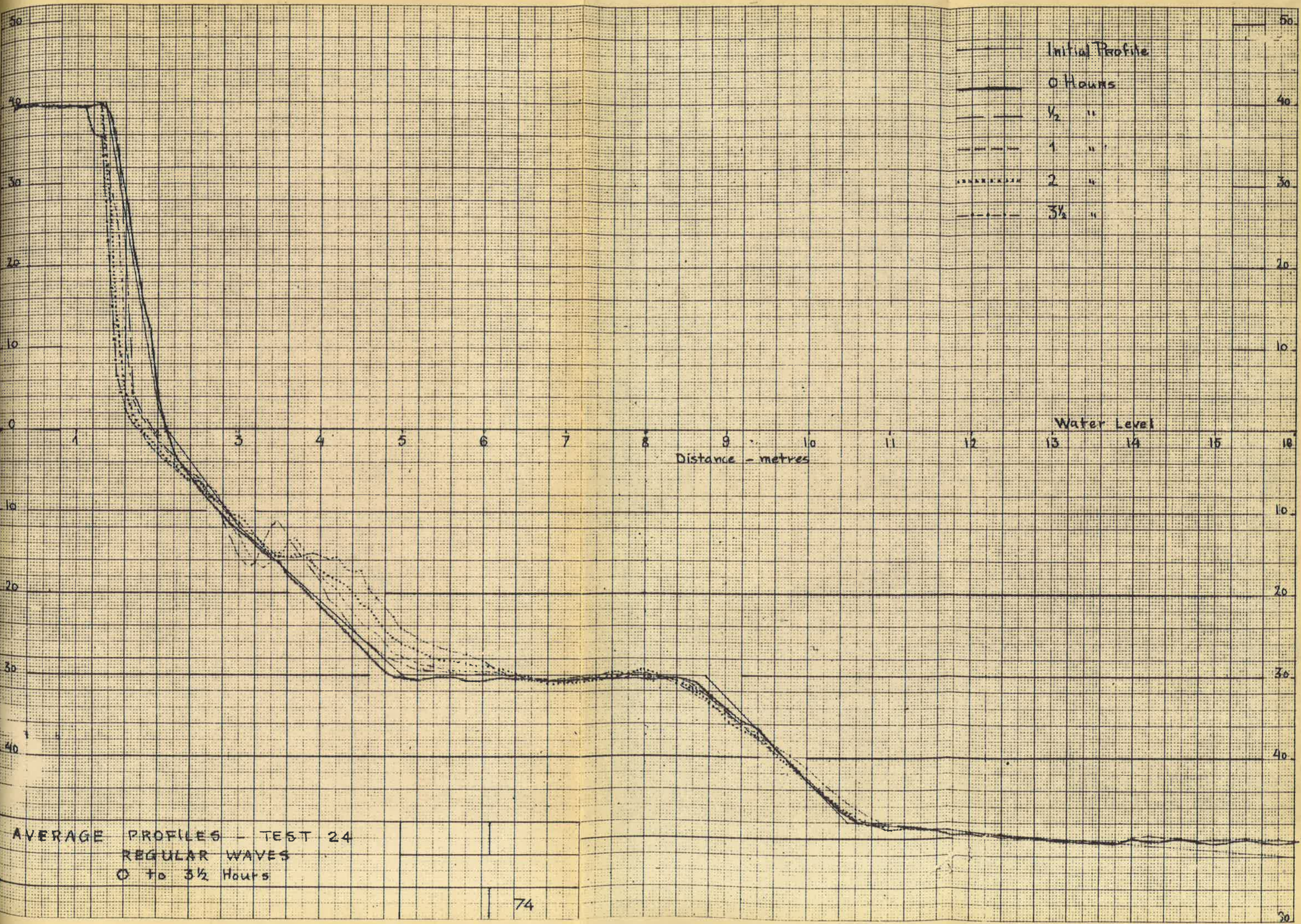
AVERAGE PROFILES — TEST 24
REGULAR WAVES
0 to 3½ Hours

Height - cm

Depth - cm

Distance - metres

Water Level

Initial Profile
0 Hours
½ "
1 "
2 "
3½ "

74
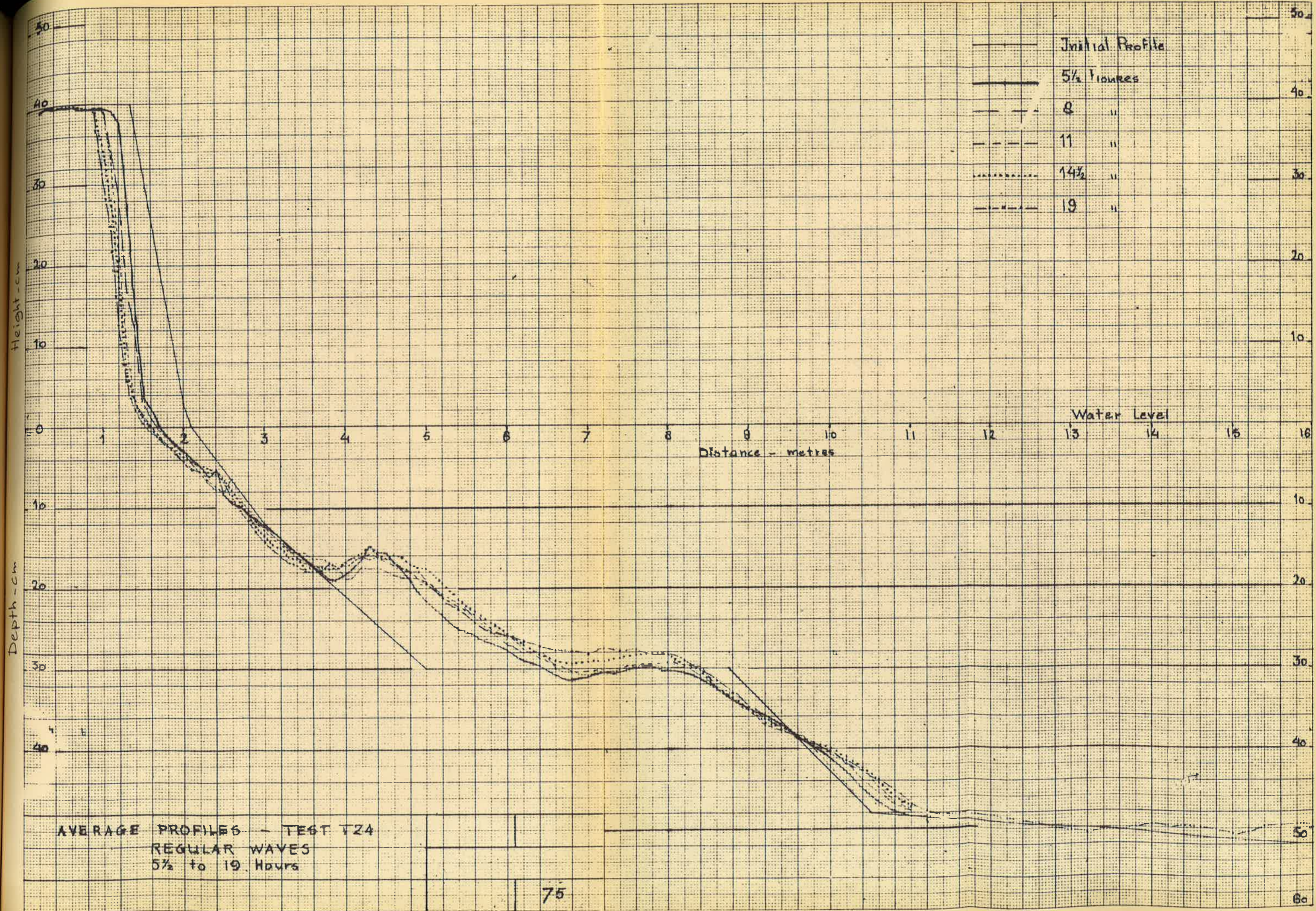
AVERAGE PROFILES — TEST T24
REGULAR WAVES
5½ to 19 Hours
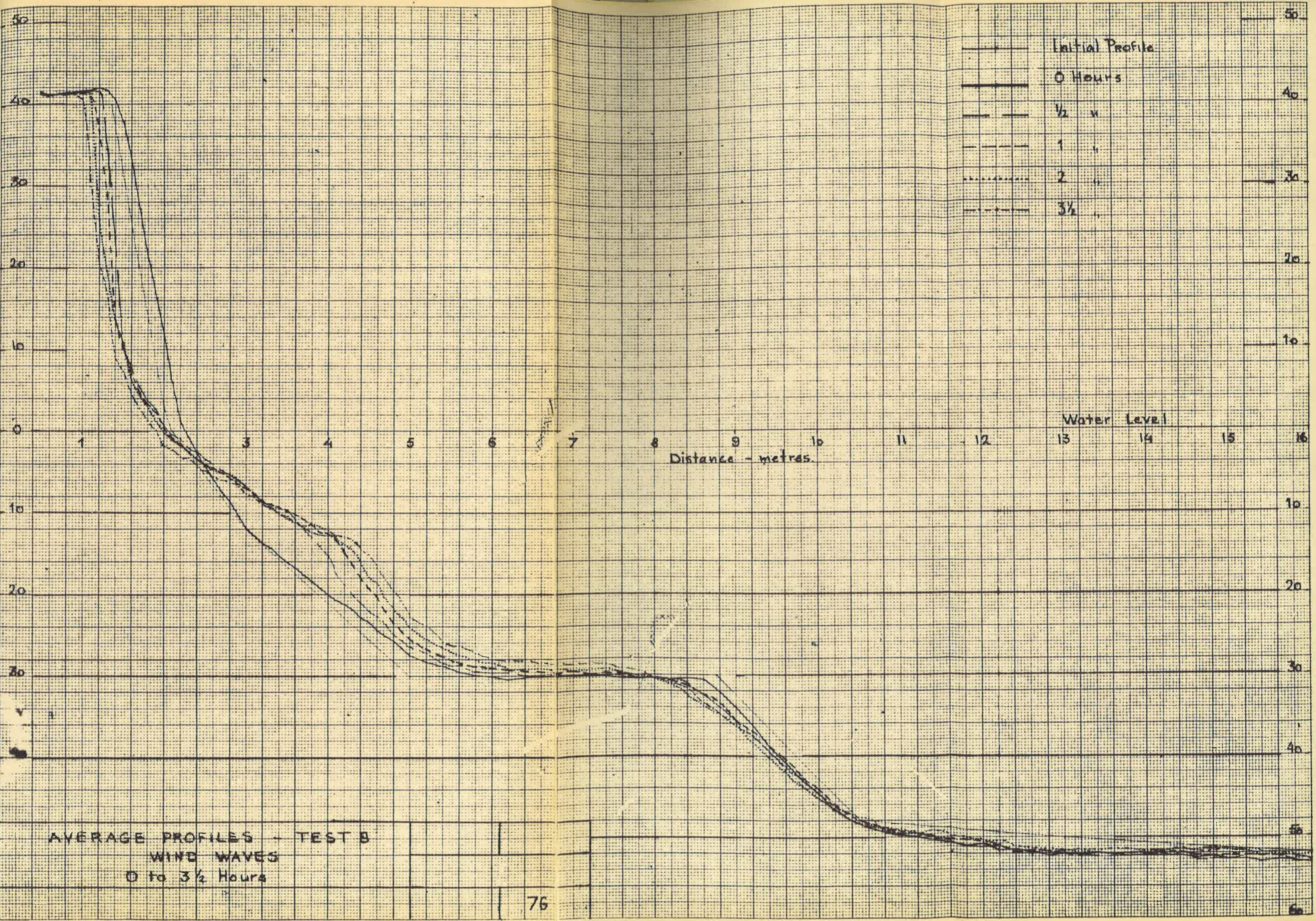
Legend:
— Initial Profile
— 5½ Hours
— · — 8 "
— · — 11 "
······· 14½ "
— · — 19 "

Height – cm
Depth – cm
Distance – metres
Water Level

75

AVERAGE PROFILES — TEST 8
WIND WAVES
0 to 3½ Hours

76

Height - cm

Depth - cm

Distance - metres
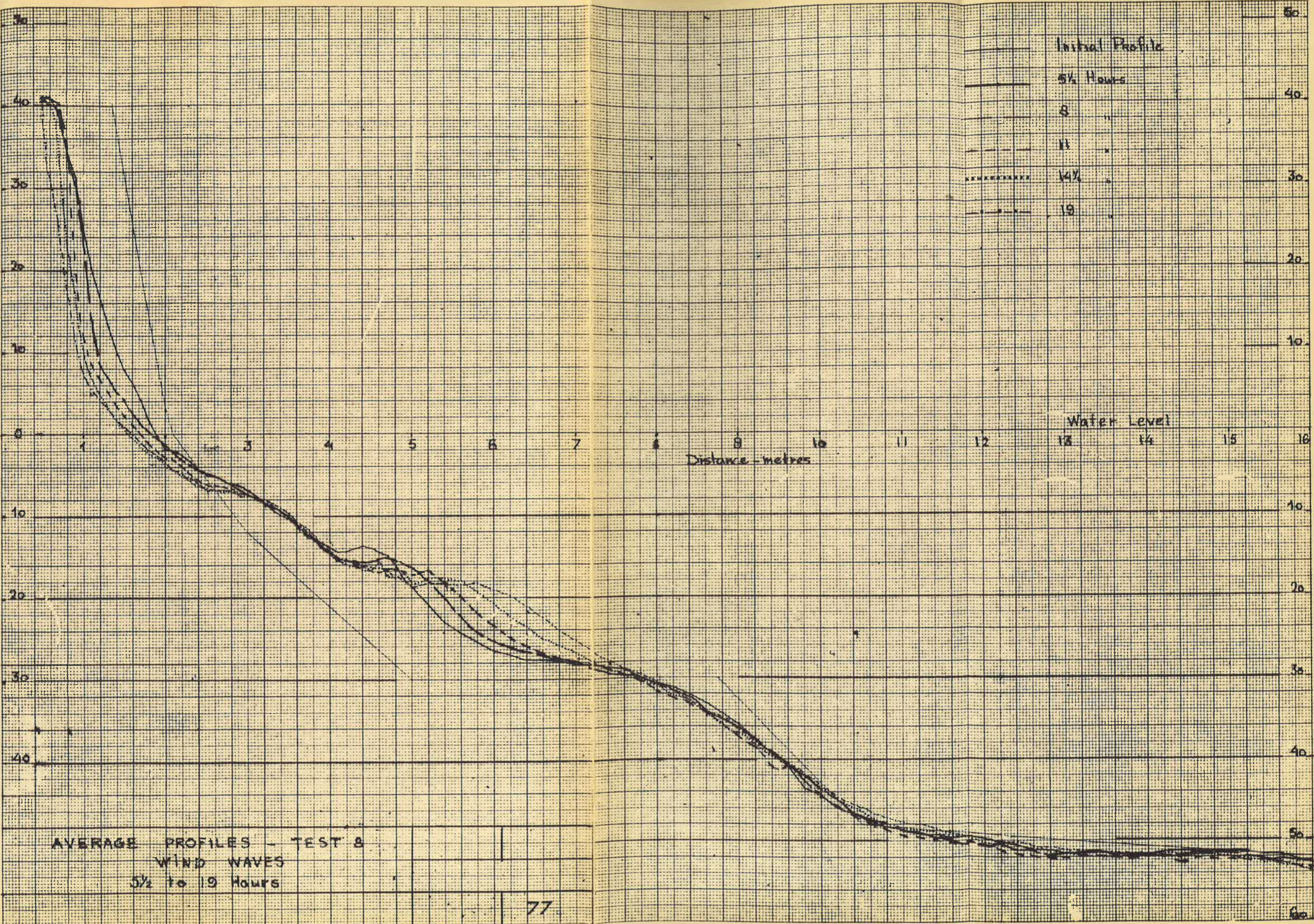
Water Level

Initial Profile
5½ Hours
8
11
14½
19

AVERAGE PROFILES — TEST 8
WIND WAVES
5½ to 19 Hours

77
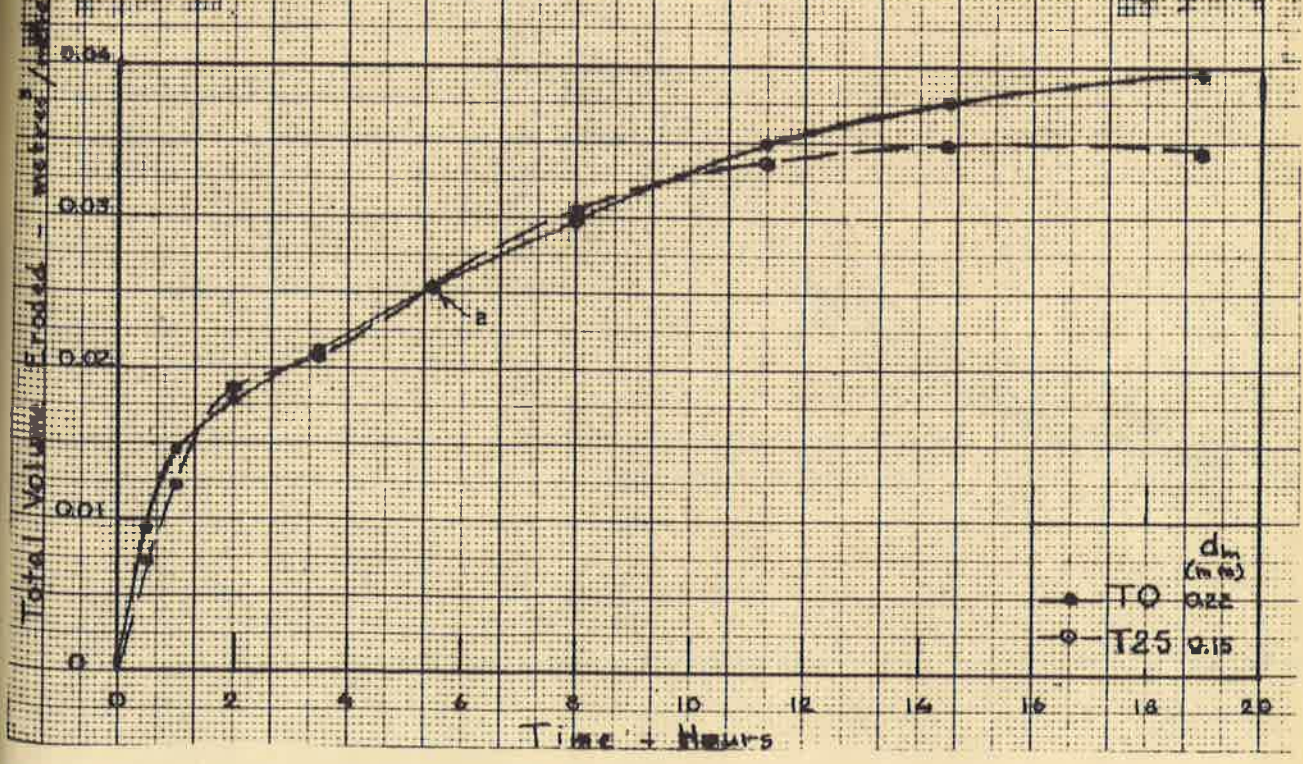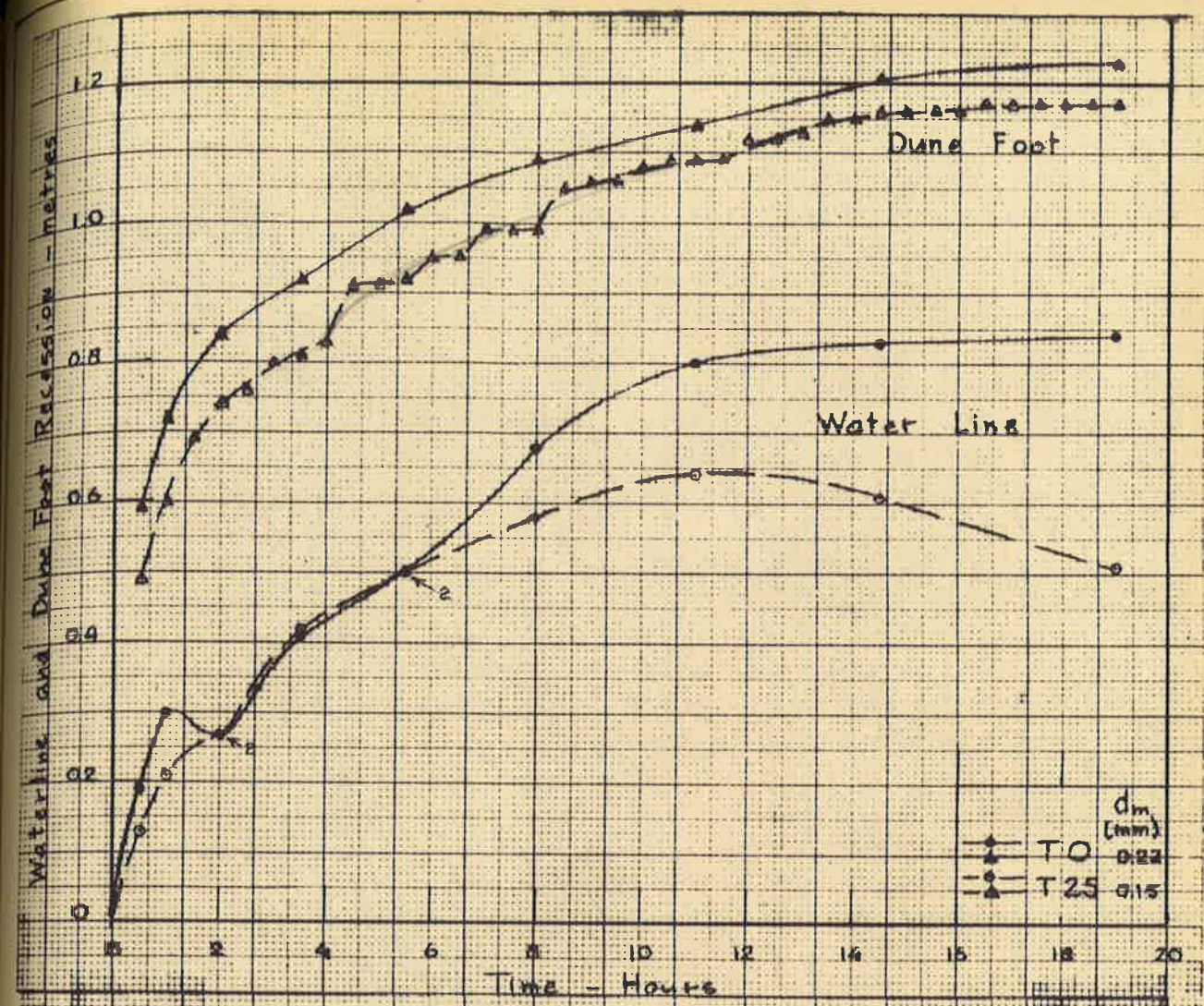
INFLUENCE OF SAND SIZE UPON
DUNE EROSION
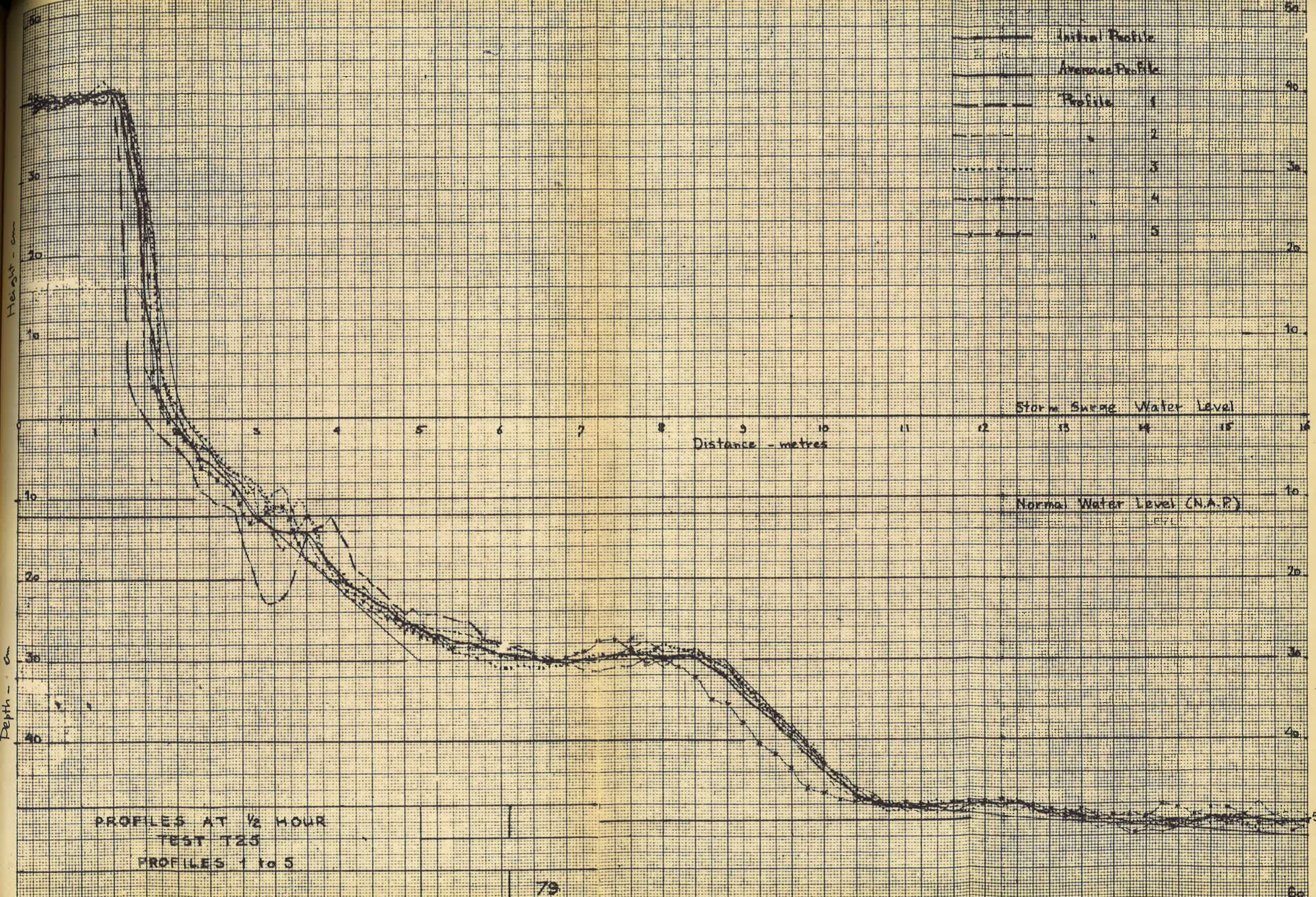
Height - cm.

Depth - cm.

Distance - metres

Storm Surge Water Level

Normal Water Level (N.A.P.)

Initial Profile
Average Profile
Profile   1
  "   2
  "   3
  "   4
  "   5

PROFILES AT ½ HOUR
TEST T25
PROFILES 1 to 5

79

Height - cm

Depth - cm

Distance - metres

Storm Surge Water Level

Normal Water Level (N.A.P.)

Initial Profile
Average Profile
Profile 1
      "   2
      "   3
      "   4
      "   5

PROFILES AT 1 HOUR
TEST T25
PROFILES 1 to 5

PROFILES AT 2 HOURS
TEST T25
PROFILES 1 to 5

Height - cm

Depth - m

Storm Surge Water Level

Distance - metres

Normal Water Level (N.A.P.)

Initial Profile
Average Profile
Profile 1
   " 2
   " 3
   " 4
   " 5

PROFILES AT 3½ HOURS
TEST T 25
PROFILES 1 to 5

82

80

Height - cm

Depth - cm

Initial Profile
Average Profile
Profile 1
" 2
" 3
" 4
" 5

Storm Surge Water Level

Distance - metres

Normal Water Level (N.A.P.)
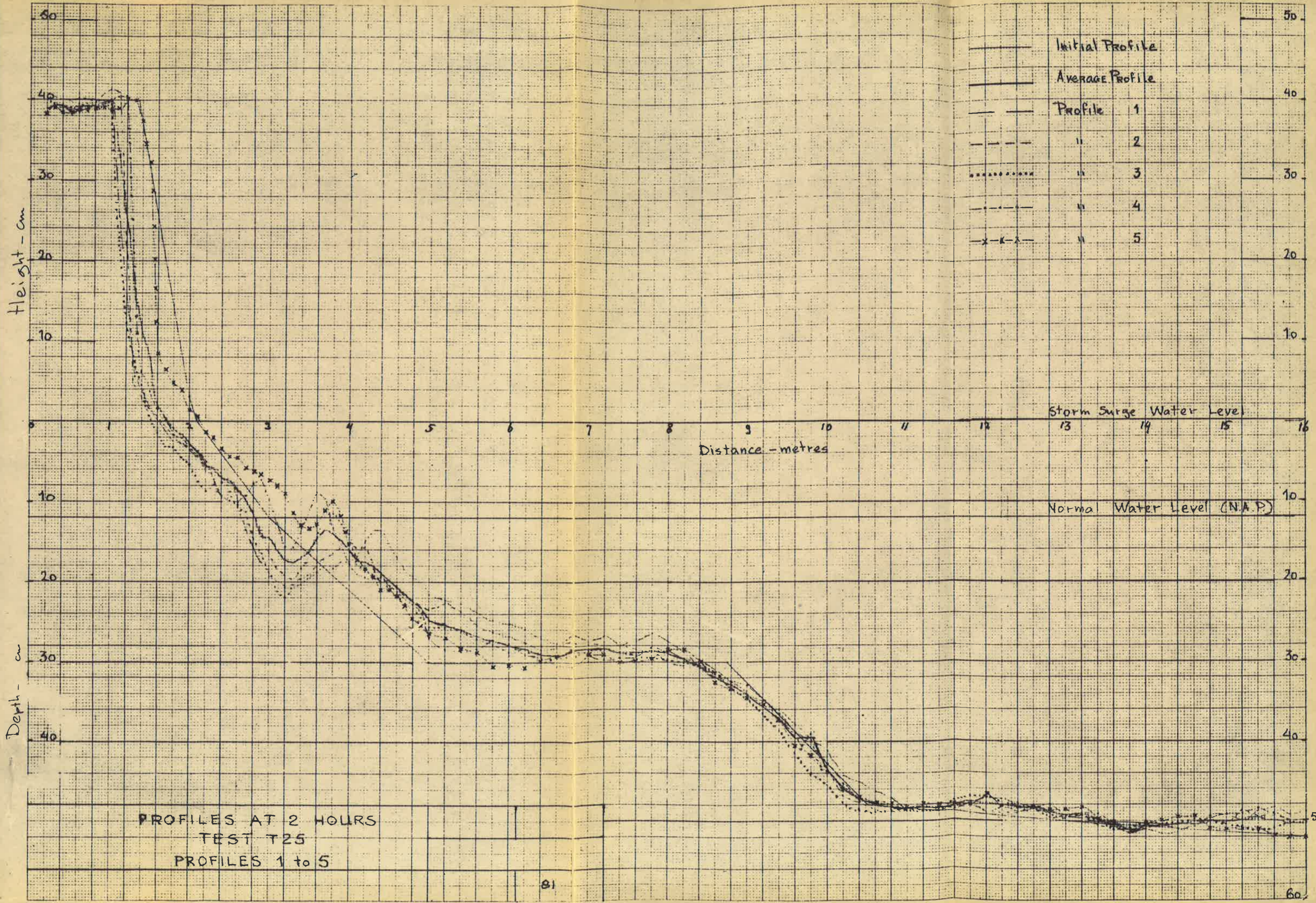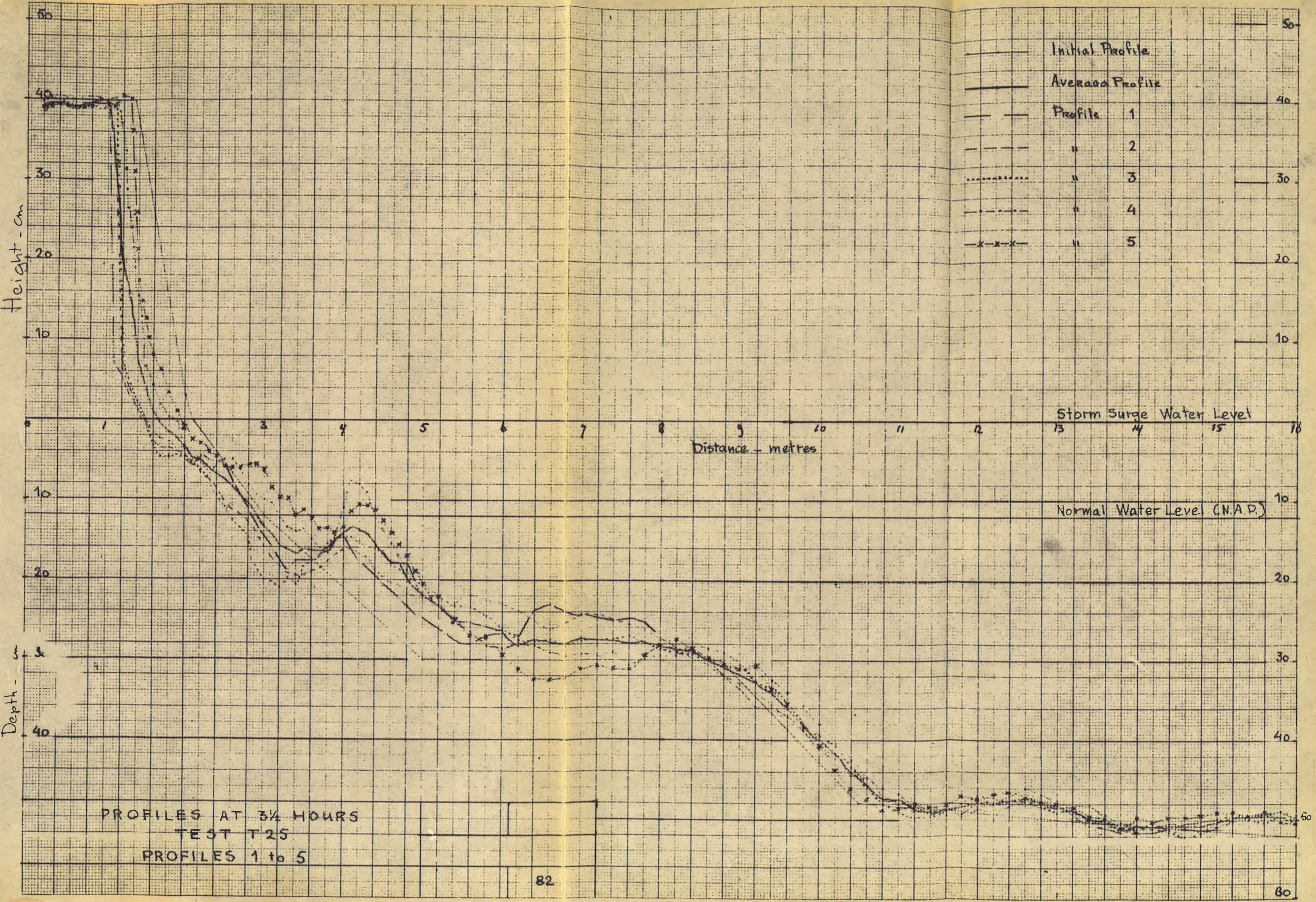
PROFILES AT 5½ HOURS
TEST T25
PROFILES 1 to 5

83

PROFILES AT 8 HOURS
TEST 25
PROFILES 1 to 5

Legend (top right):

Initial Profile
Average Profile
Profile 1
" 2
" 3
" 4
" 5

Storm Surge Water Level

Normal Water Level (N.A.P.)

Axis labels:

Height – cm
Depth – cm
Distance – metres

Title (bottom left):

PROFILES AT 11 HOURS
TEST T28
PROFILES 1 to 5

85

Height – cm

Depth – cm

Distance –metres

Initial Profile
Average Profile
Profile 1
" 2
" 3
" 4
" 5

Storm Surge Water Level

Normal Water Level (N.A.P)

PROFILES AT 14½ HOURS
TEST T28
PROFILES 1 to 5

PROFILES AT 19 HOURS
TEST T25
PROFILES 1 to 5

Initial Profile

T0 $d_m = 0.22$ mm

T25 $d_m = 0.15$ mm

Storm Surge Water Level

Normal Water Level (N.A.P)

Distance - metres

Height - cm

Depth - cm

AVERAGE PROFILES AT 19 HOURS
FOR DIFFERENT SAND SIZES
TESTS T0 and T25
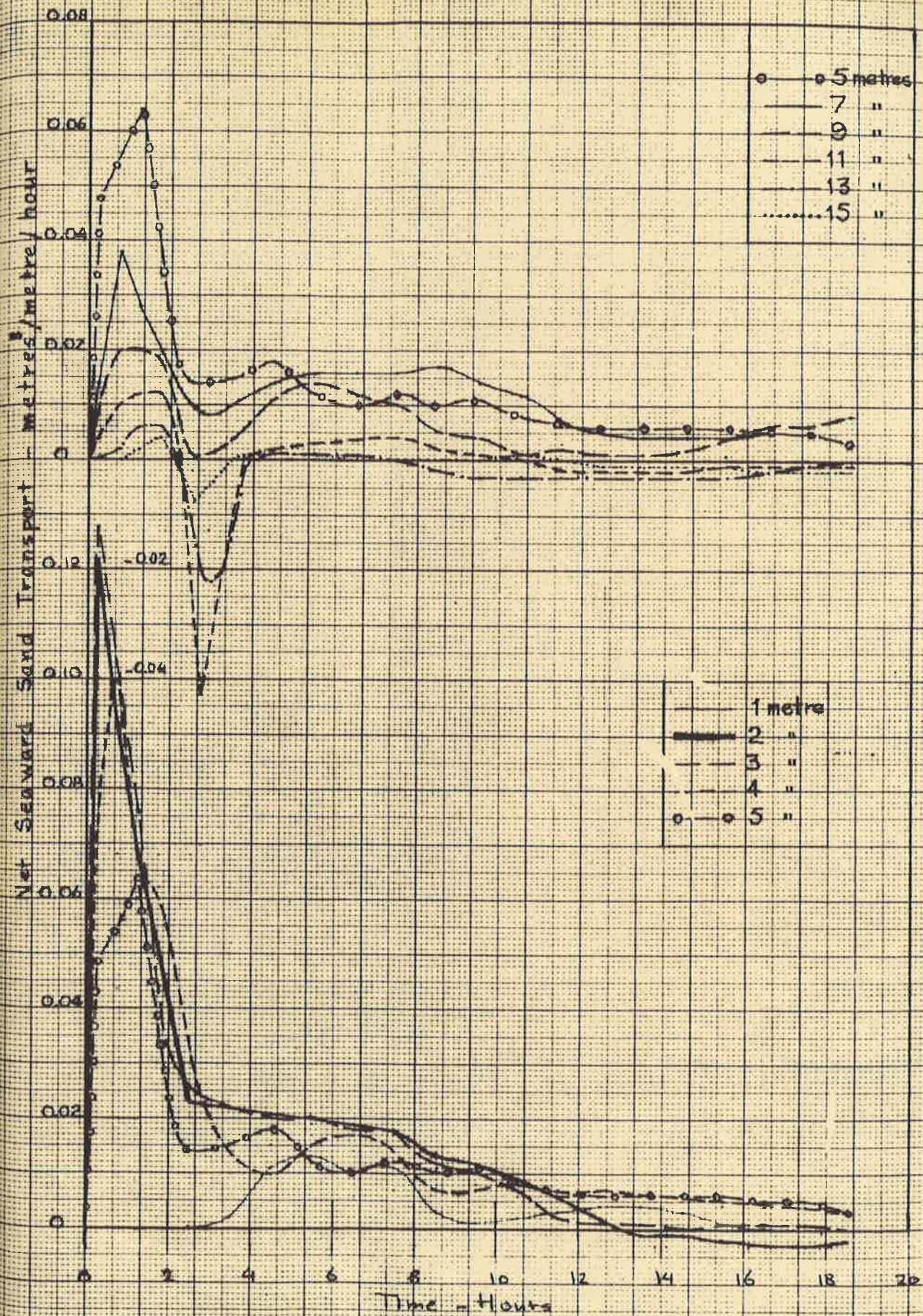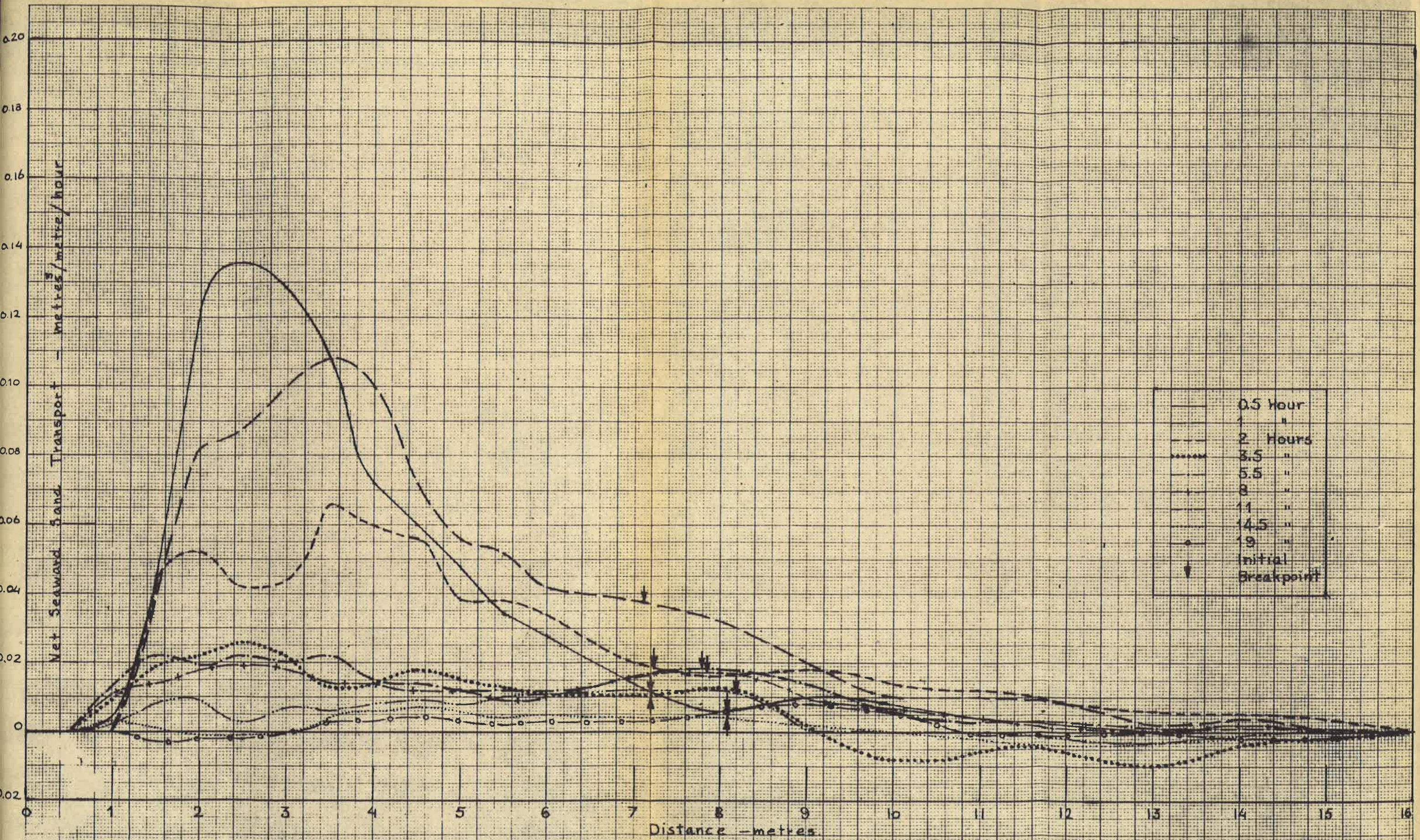
88

NET SEAWARD SAND TRANSPORT AS
FUNCTION OF TIME — TEST T25

NET SEAWARD SAND TRANSPORT OVER
BEACH PROFILES AT VARIOUS TIMES
TEST T25

90
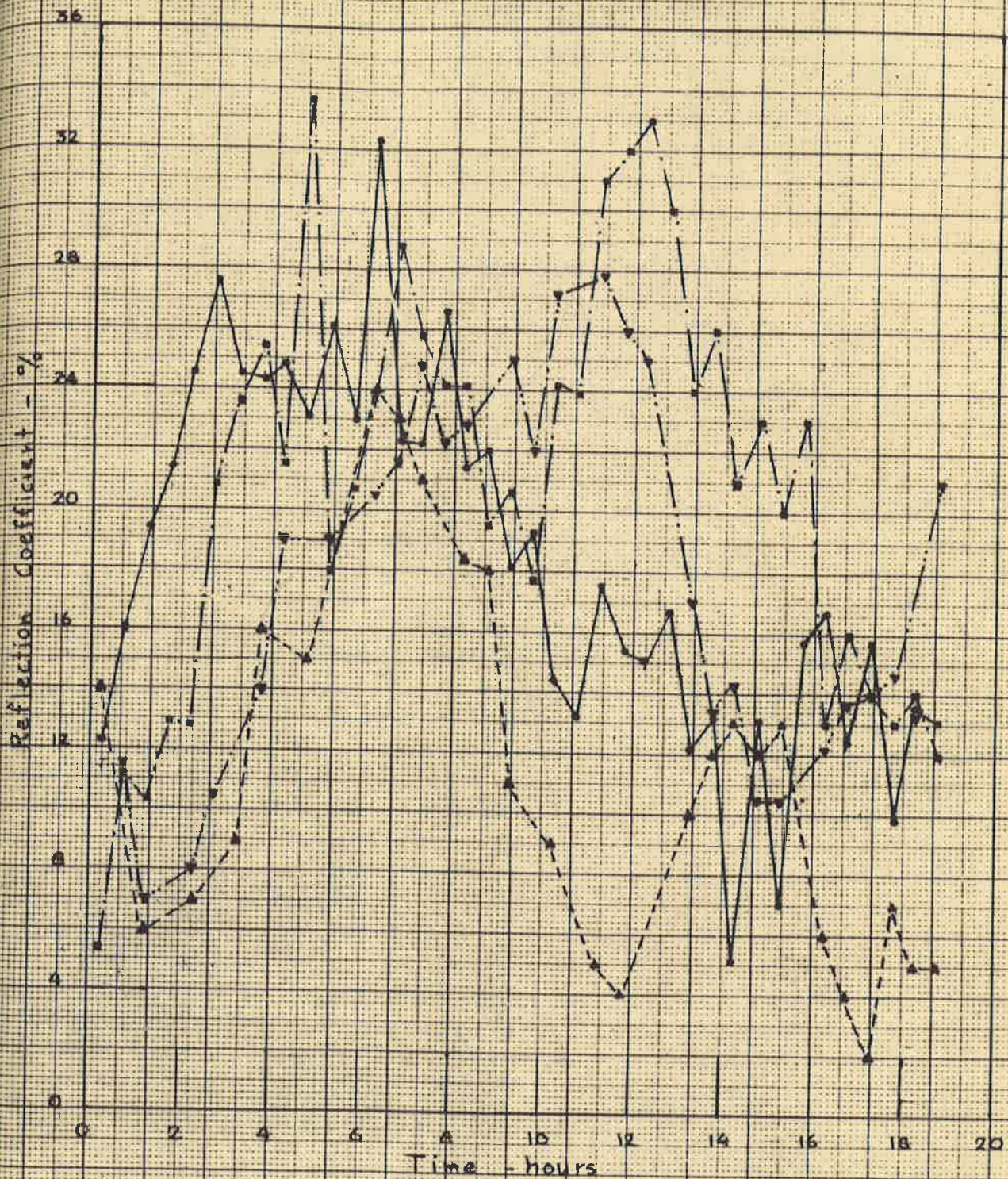
VARIATION OF REFLECTION COEFFICIENT
WITH TIME FOR DIFFERENT WAVE HEIGHTS
T = 1.56 to 1.63 sec

91
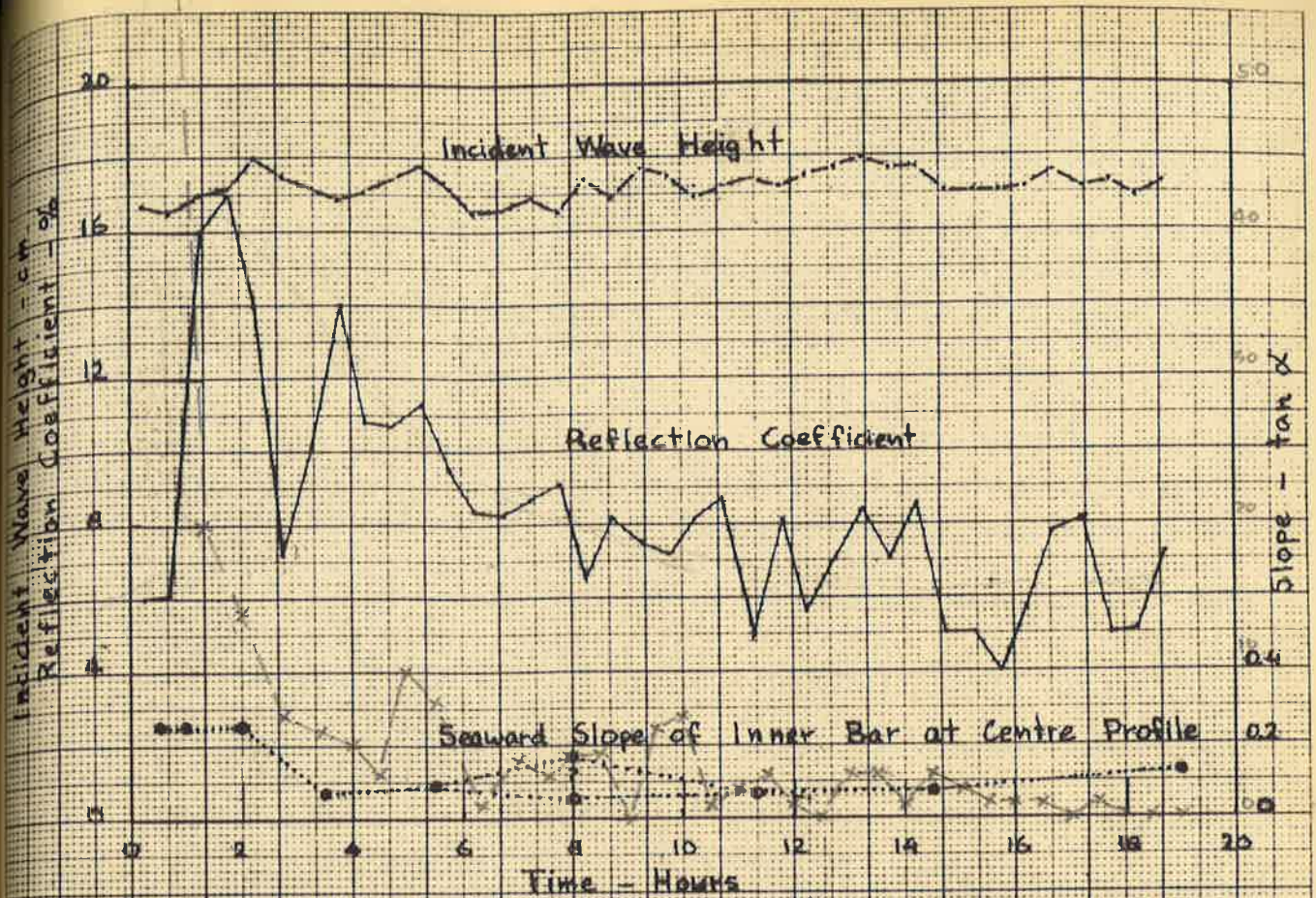
(a) Wave Height, Reflection Coefficient and Inner Bar Seaward Slope
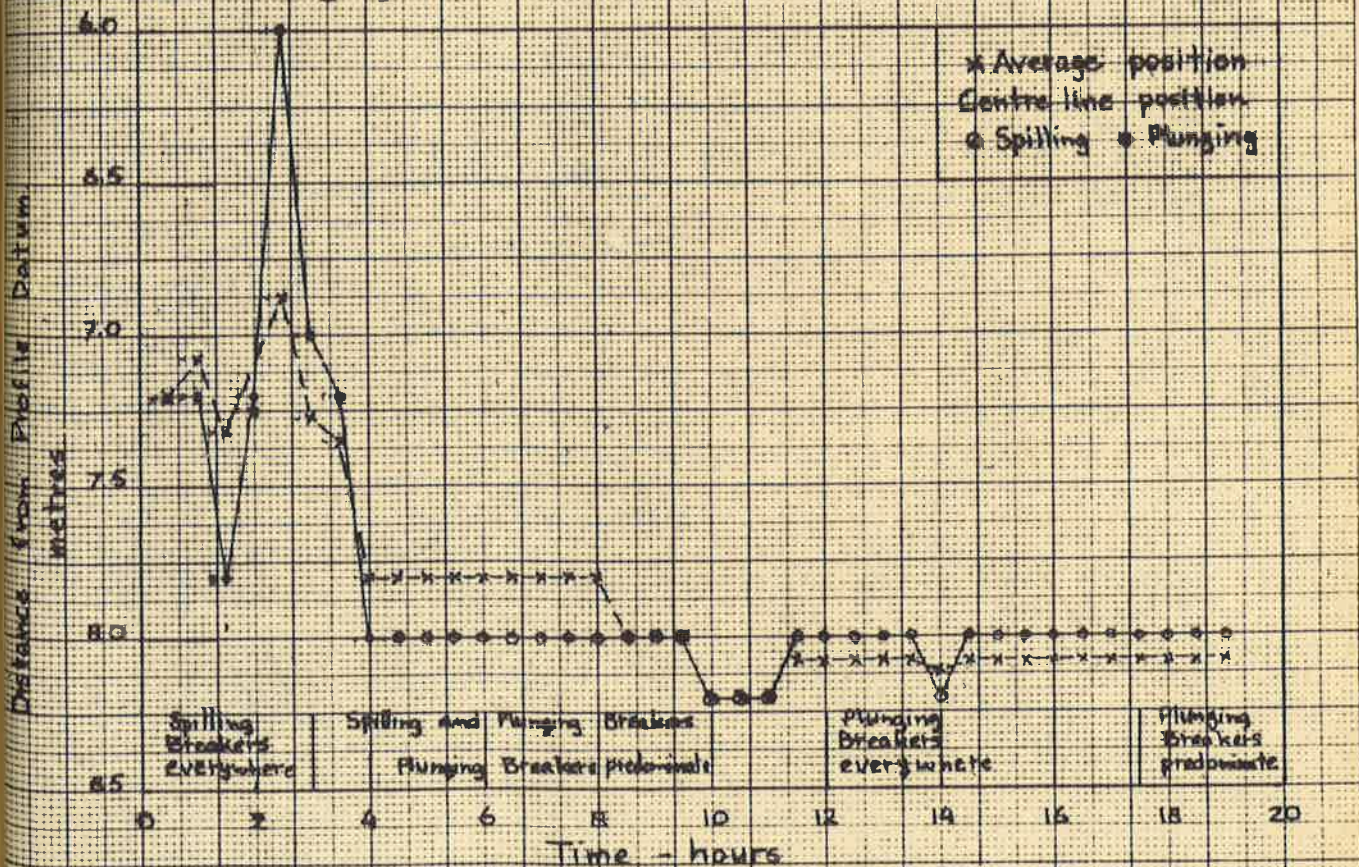
(b) Initial Break point Position.

REFLECTION COEFFICIENT, INNER BAR
SEAWARD SLOPE AND INITIAL BREAK POINT POSITION.
TEST T25

92

REFLECTION COEFFICIENT, INITIAL BREAK
NT POSITION AND DUNE EROSION
TEST T 22

93
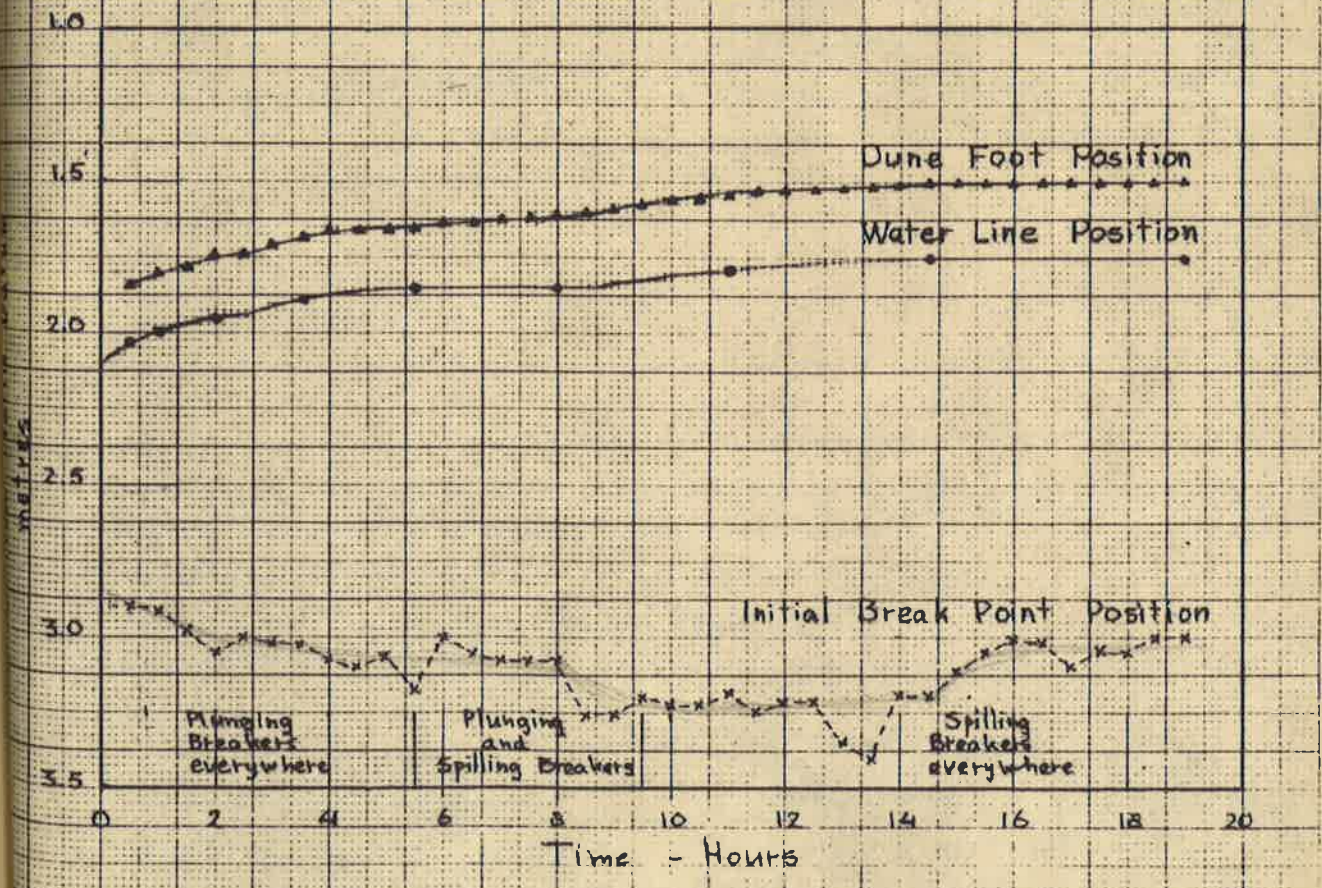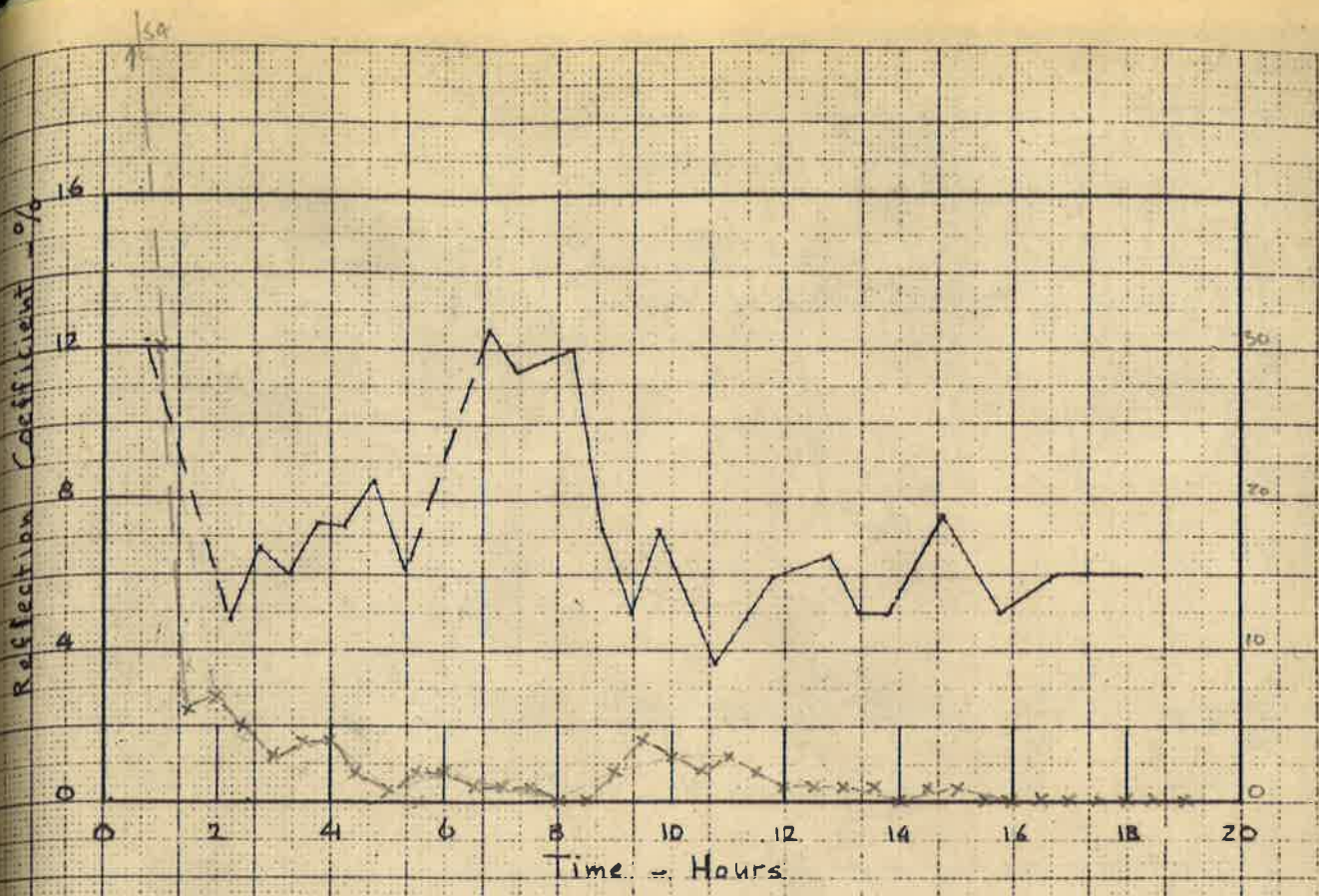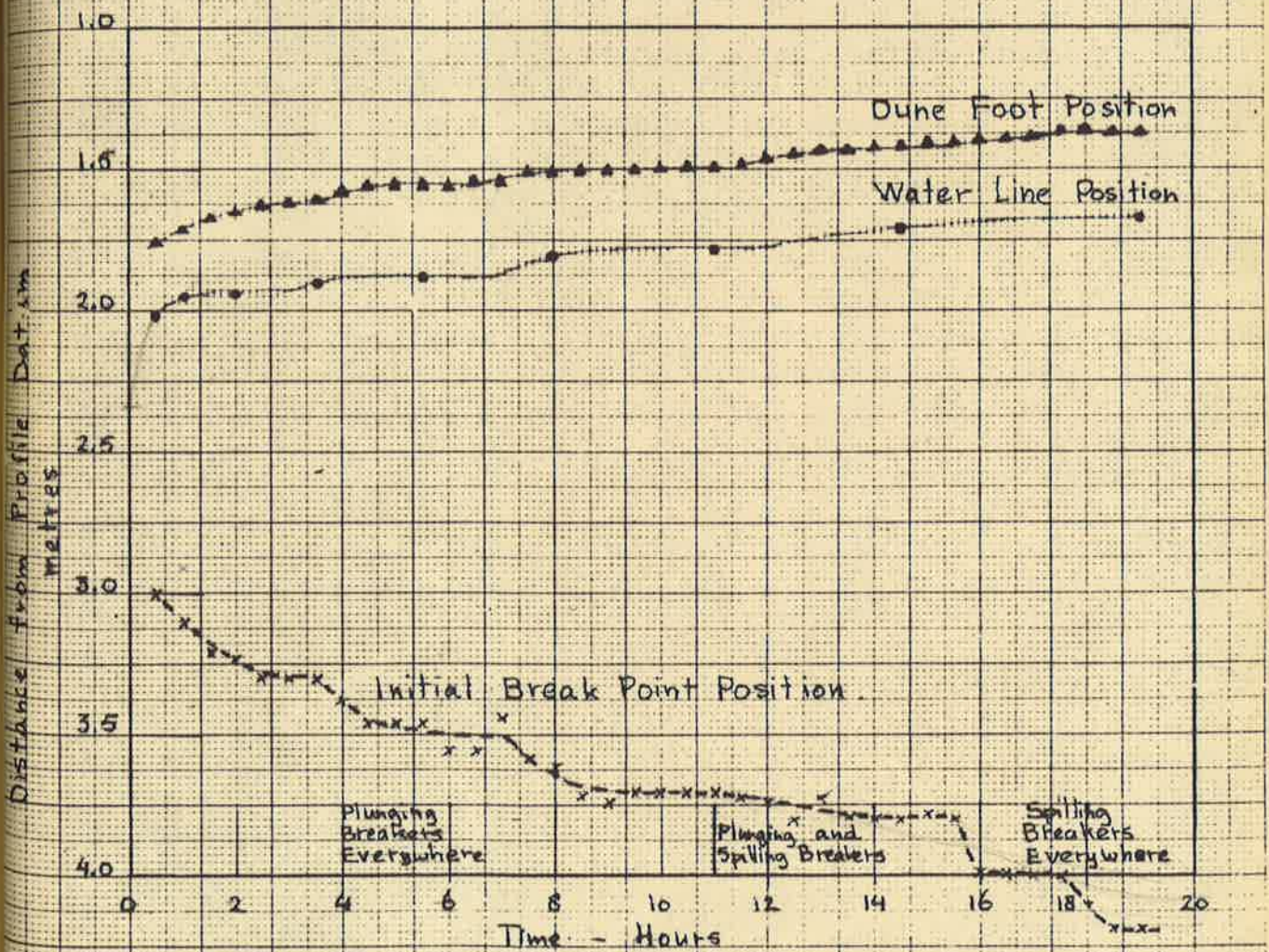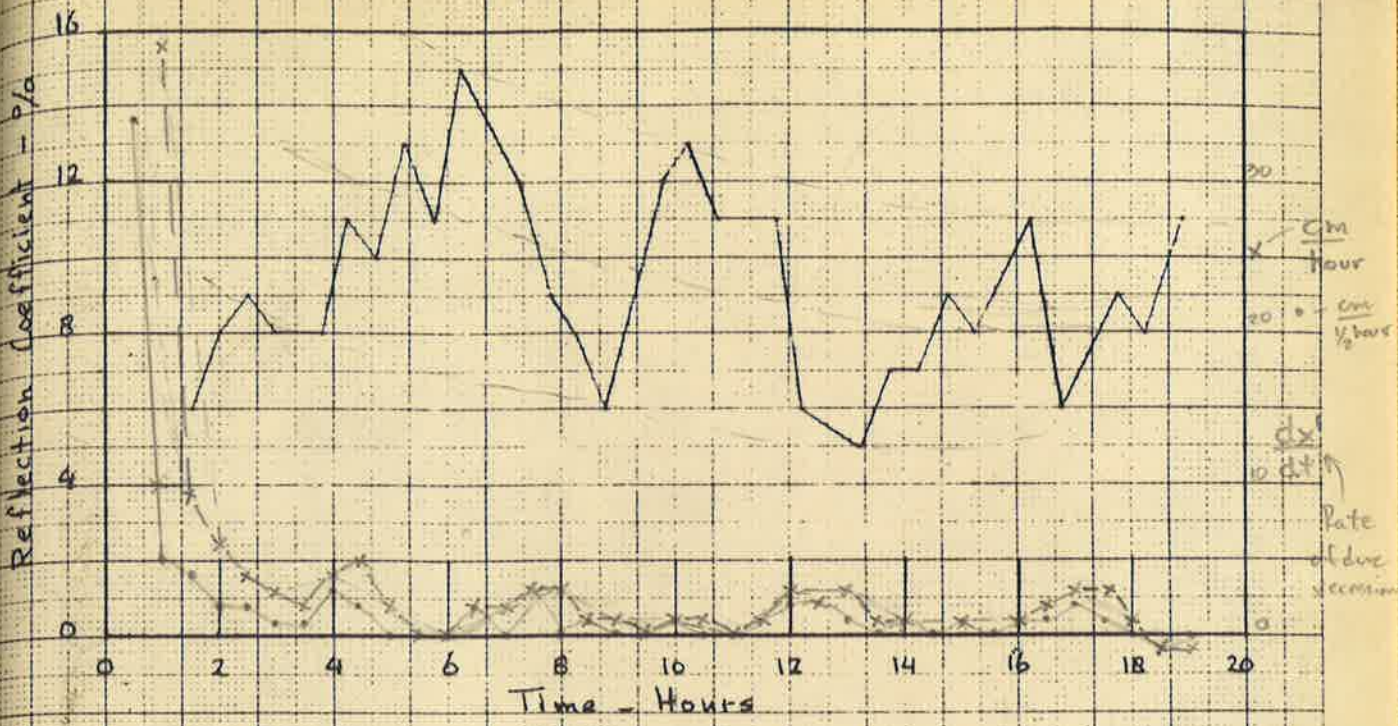
REFLECTION COEFFICIENT, INITIAL BREAK
POINT POSITION AND DUNE EROSION
TEST T23

T = 1.16   Hₐ = 11.8   94

Incident Wave Height 18·5 cm
Reflection Coefficient 75%
(Measured at 50 cm depth)

Wave Height

Equivalent Deep Water Level

Model Water Level

Distance — metres

Mean Water Level
calculated from measured
wave heights using equation 5.6.2.1.f

Mean Water Level
assuming no energy losses

Bottom Profile

Dune and Wave Height — cm

Depth — cm

Mean Water Level Relative to Deep Water — mm

WAVE HEIGHTS IN SURF ZONE AND
MEAN WATER LEVEL CHANGES
PROFILE 1

95

Incident Wave Height 57.0cm
Reflection Coefficient 72%
(Measured at 50cm depth)

Wave Height

Equivalent Deep Water Level

Mean Water Level

Distance metres

Mean Water Level
calculated from measured
wave heights using equation 3.42.14

Mean Water Level
assuming no energy losses

Mean Water Level
assuming 72% reflection
at bar crest

Bottom Profile

WAVE HEIGHTS IN SURF ZONE AND
MEAN WATER LEVEL CHANGES
PROFILE 3

96

Incident Wave Height 185cm
Reflection Coefficient 64%
(Measured at 50 cm depth)

Wave Height

Equivalent Deep Water Level

Model Water Level

Distance — metres

Mean Water Level
calculated from measured
wave heights using equation 5.62.1 f.

Mean Water Level
assuming no energy losses.

Bottom Profile

WAVE HEIGHTS IN SURF ZONE AND
MEAN WATER LEVEL CHANGES
PROFILE 5

97

PROFILE 1

PROFILE 3

Numbers on figure represent profile distances in metres

WAVE HEIGHT, WAVE LENGTH AND WATER DEPTH
RELATIONSHIPS FOR REGULAR WAVES
IN SURF ZONE - PROFILES 1 and 3

98
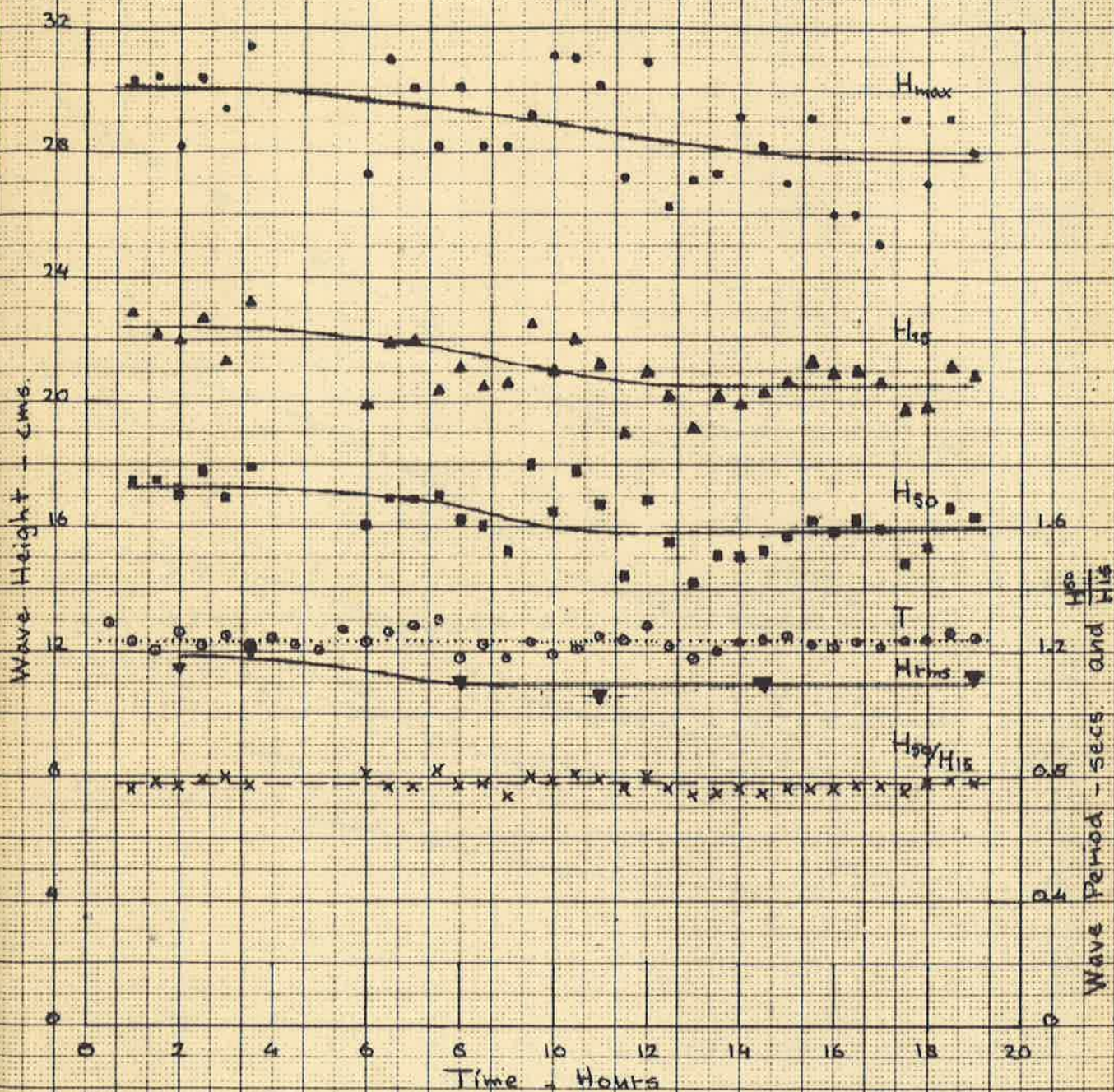
WAVE HEIGHT, WAVE LENGTH AND WATER DEPTH
RELATIONSHIPS FOR REGULAR WAVES
IN SURF ZONE – PROFILE 5

WAVE CHARACTERISTICS DURING
WIND WAVE TEST T8
OFFSHORE POSITION
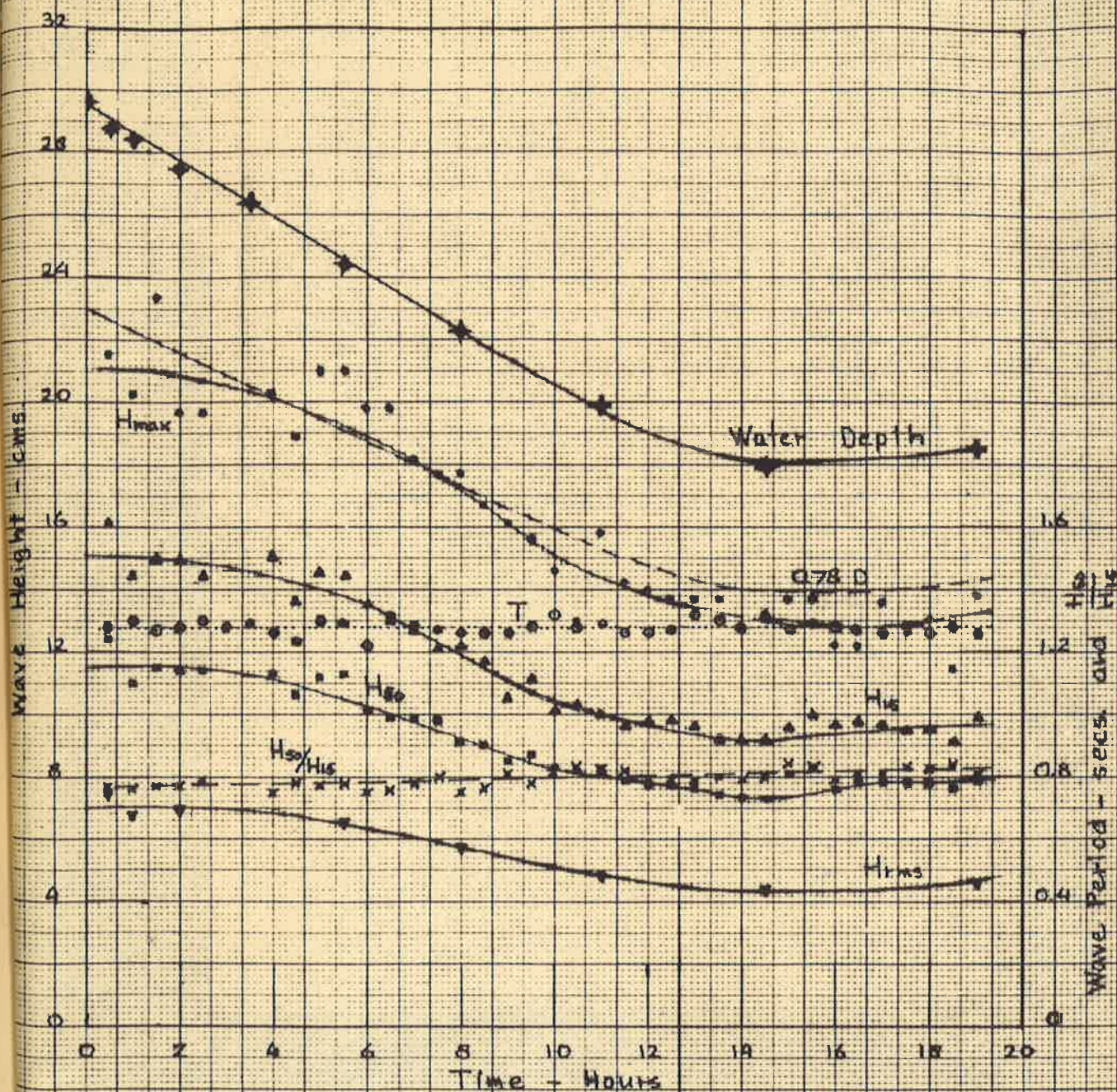
100

WAVE CHARACTERISTICS DURING
WIND WAVE TEST T6
INSHORE POSITION
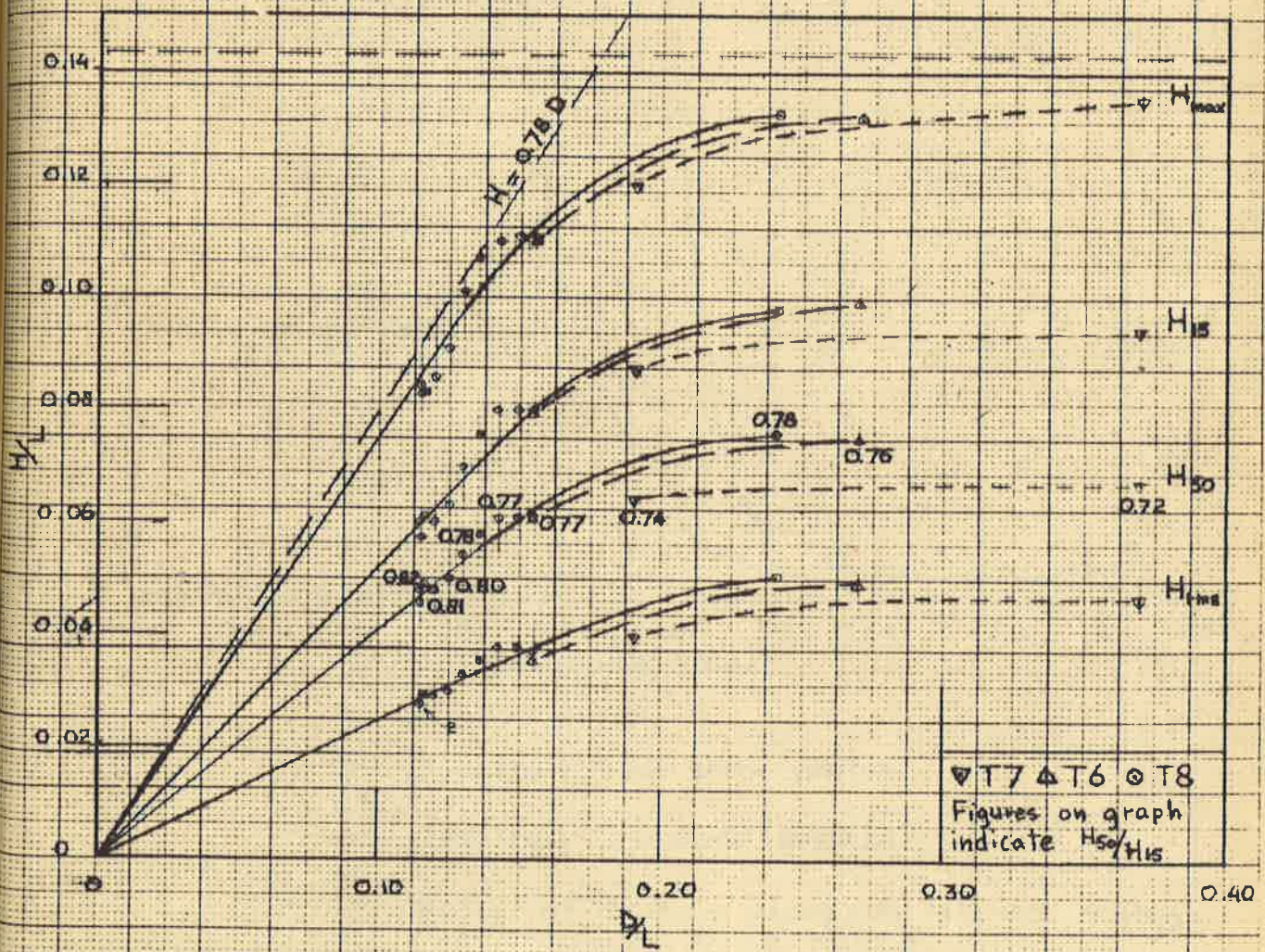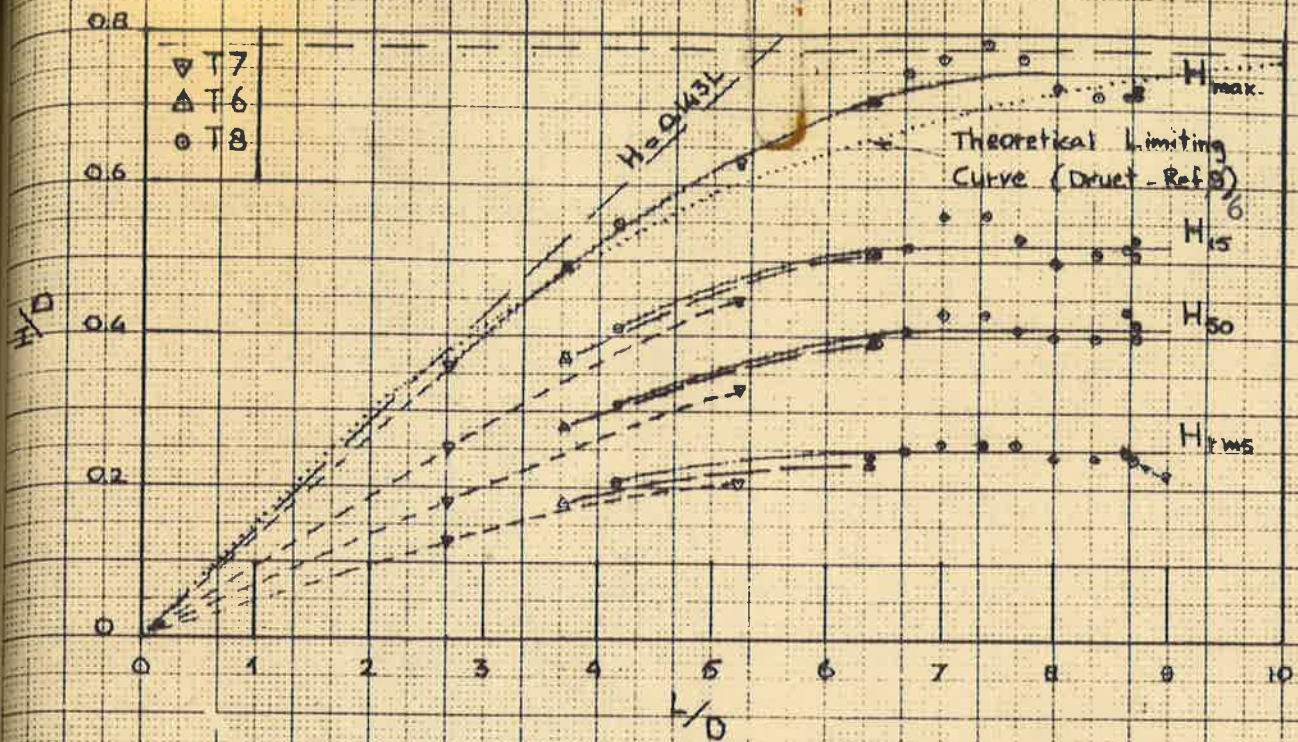
WAVE HEIGHT, WAVE LENGTH AND WATER DEPTH
RELATIONSHIPS FOR WIND WAVES IN
SHOALING WATER
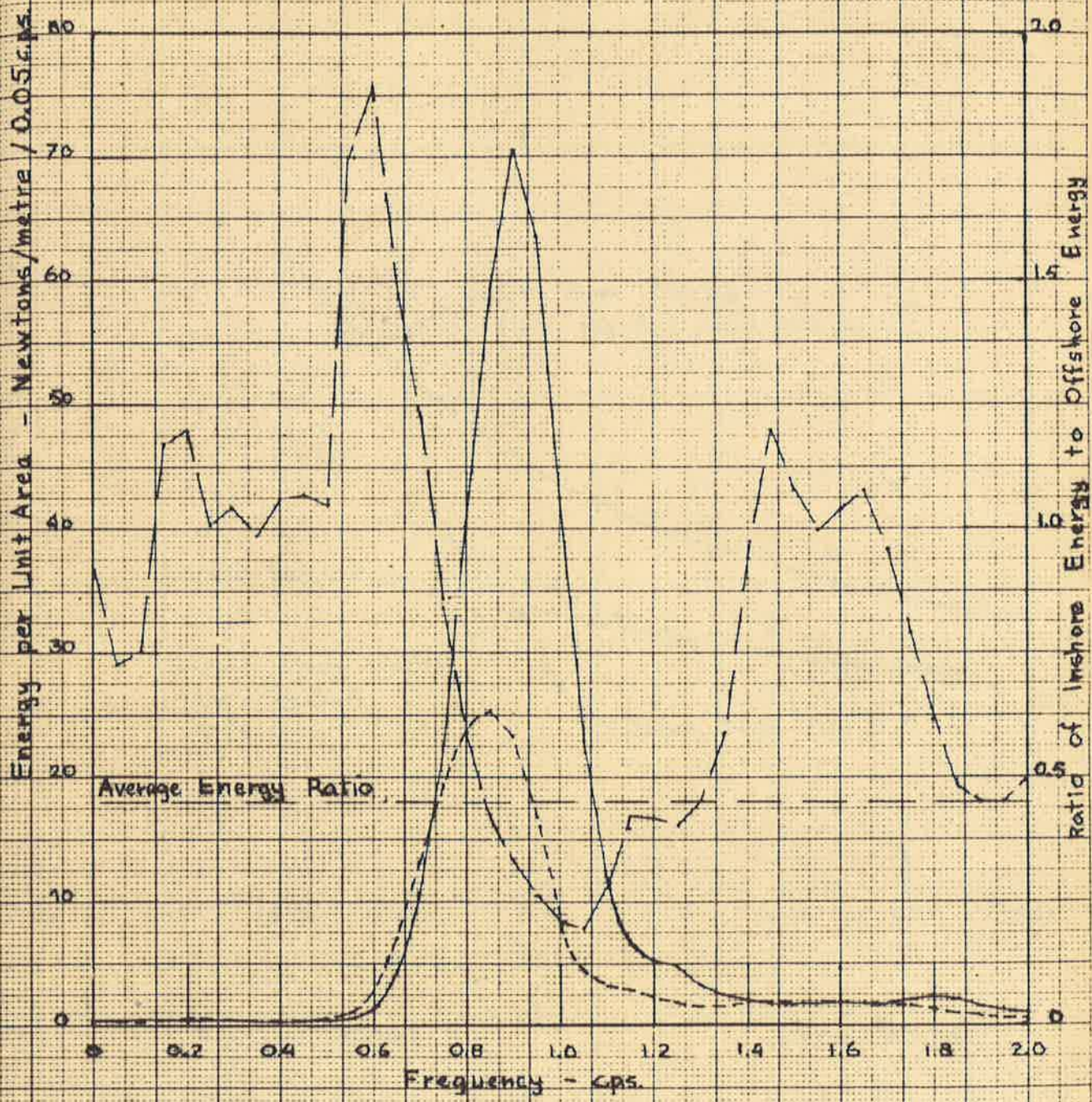
102

CHANGES IN WIND WAVE SPECTRA IN
SHOALING WATER
TEST T6 — 11 Hours

RELATIVE RUN-UP HEIGHT AS FUNCTION OF WAVE STEEPNESS FOR SAND BEACHES

The chart plots R/H_o (vertical axis, 0 to 1.2) against H_o/L_o (horizontal axis, 0 to 0.08).

Curve labels:
- Smooth Slope 1 in 5½ from Fig 3-3 reference 21·47
- Average Beach Slope 1 in 5½
- Smooth Slope 1 in 10 from Fig 3-3 reference 21·47
- Beach Slope 1 in 9.7
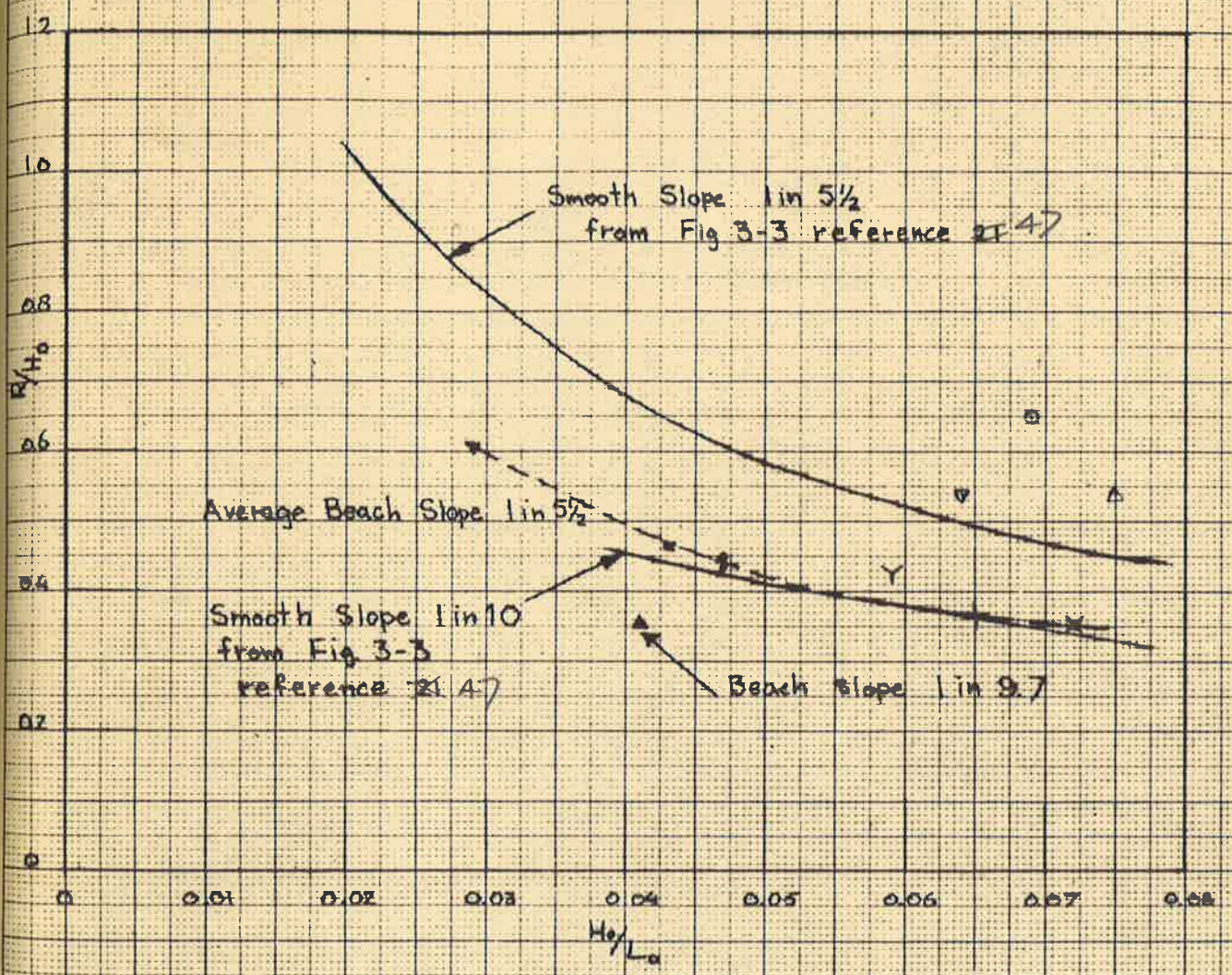
Regular Waves						Wind Waves		
♦	T0 and T0'	1 in 5.3	Y	T 22	1 in 5.9	▽	T 7	1 in 4.8
■	T 4	5.3	+	T 23	5.2	△	T 6	5.0
▲	T 19	9.7	✱	T 24	5.6	⊙	T 8	5.8
▼	T 20	5.8						

104
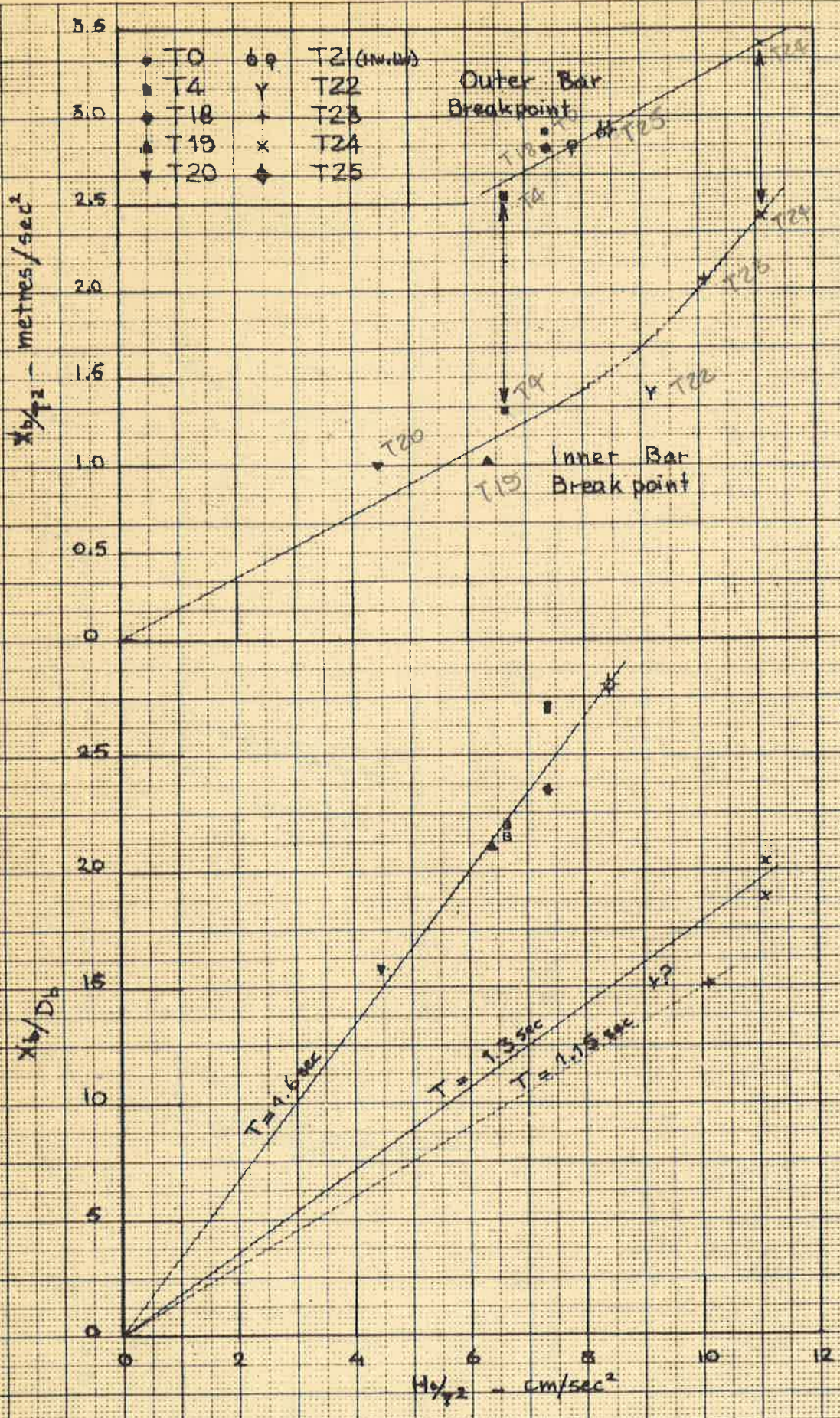
DIMENSIONLESS BREAKER DISTANCE
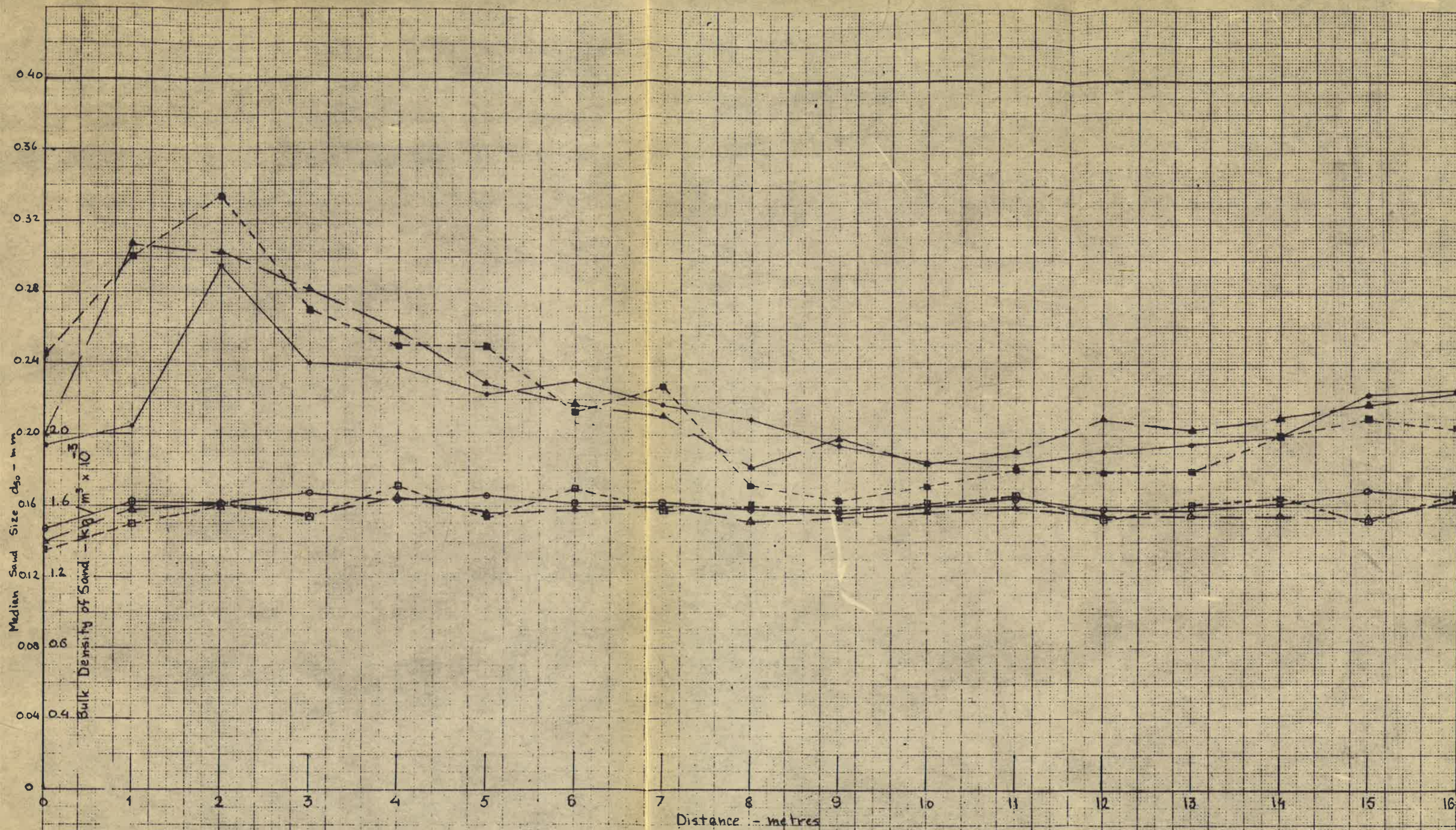AS FUNCTION OF WAVE STEEPNESS
FOR REGULAR WAVES

VARIATION OF MAXIMUN ORBITAL VELOCITIES WITHIN SURFZONE
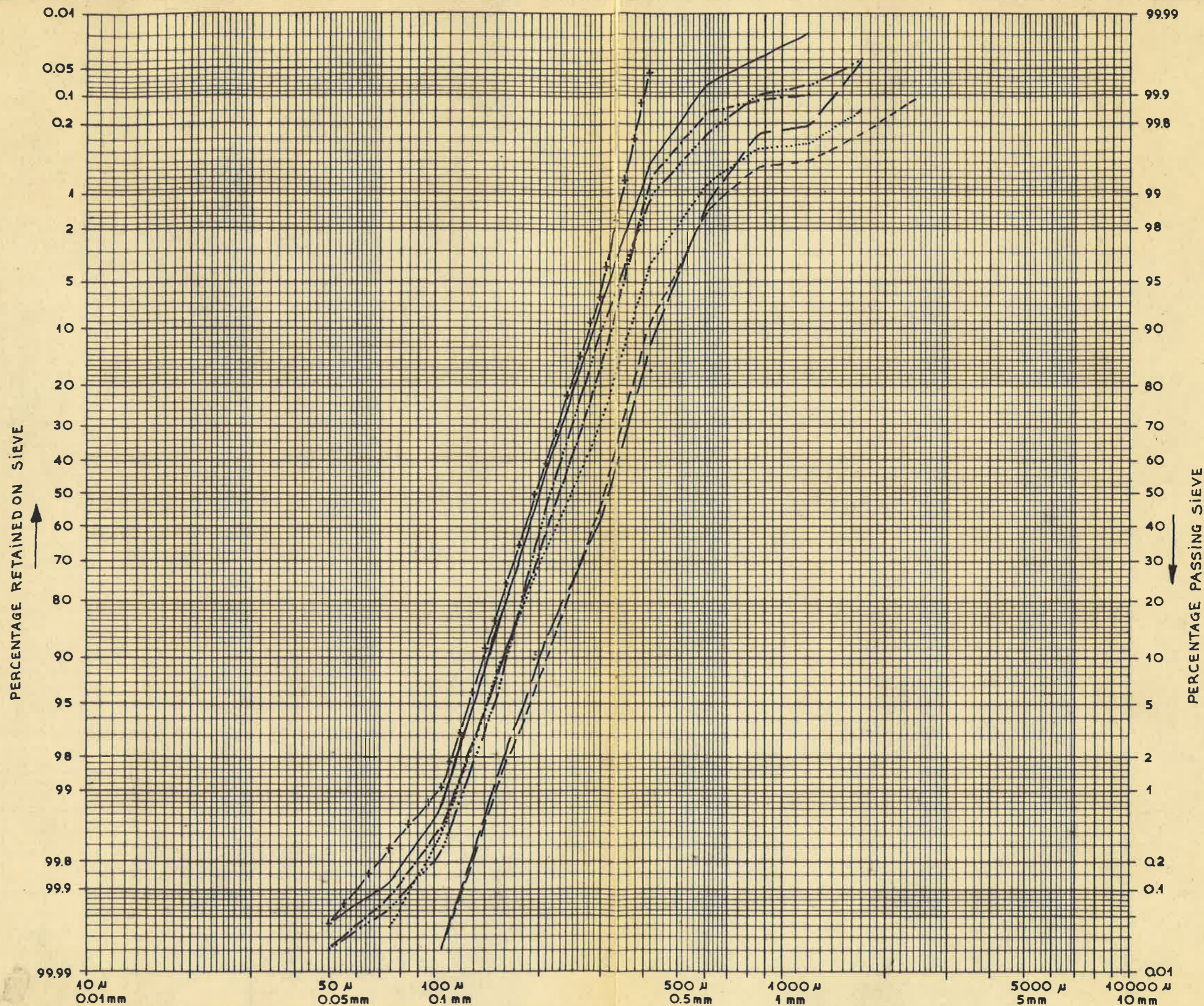
$H_o = 19.5$ $T = 1.56$

106
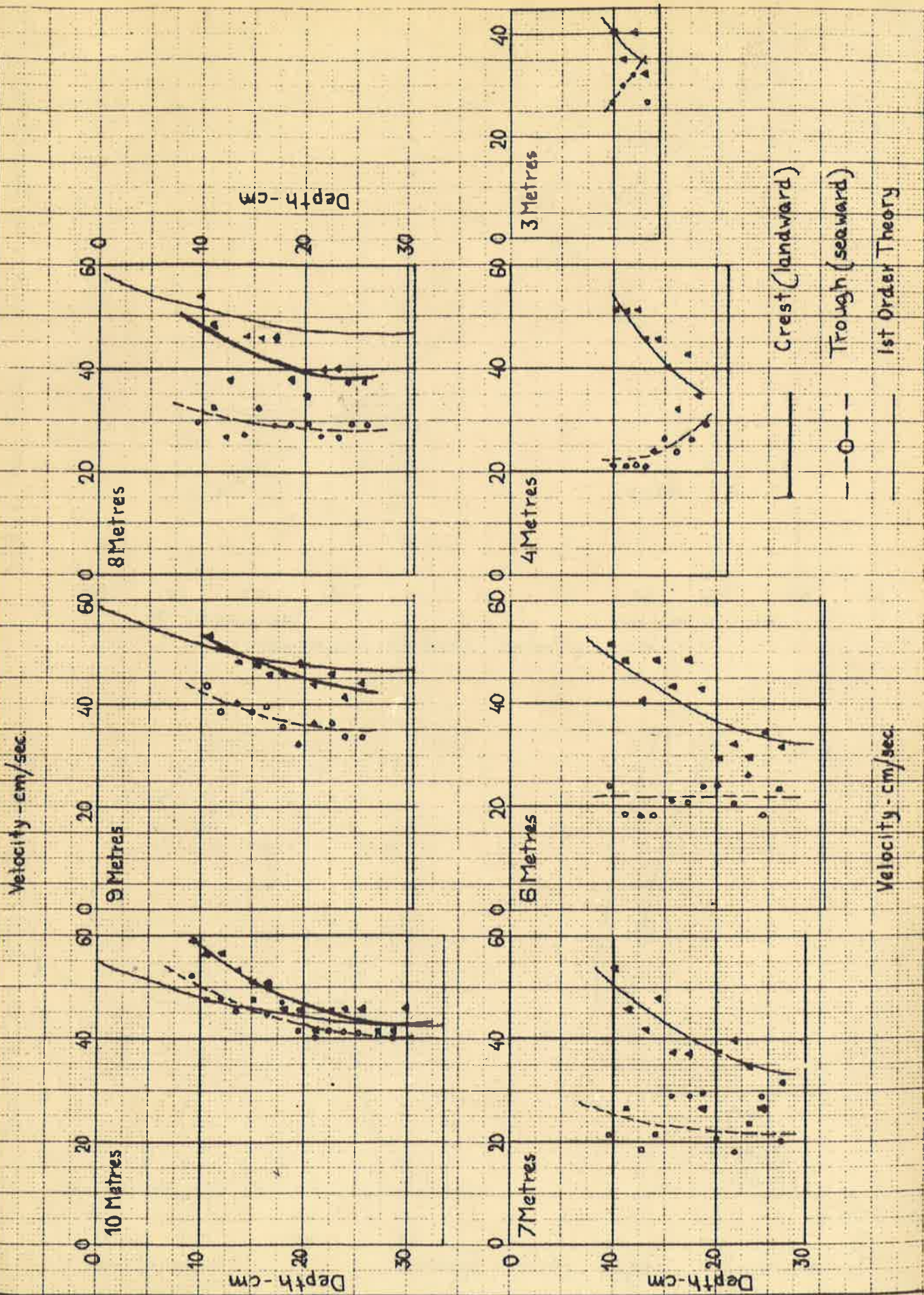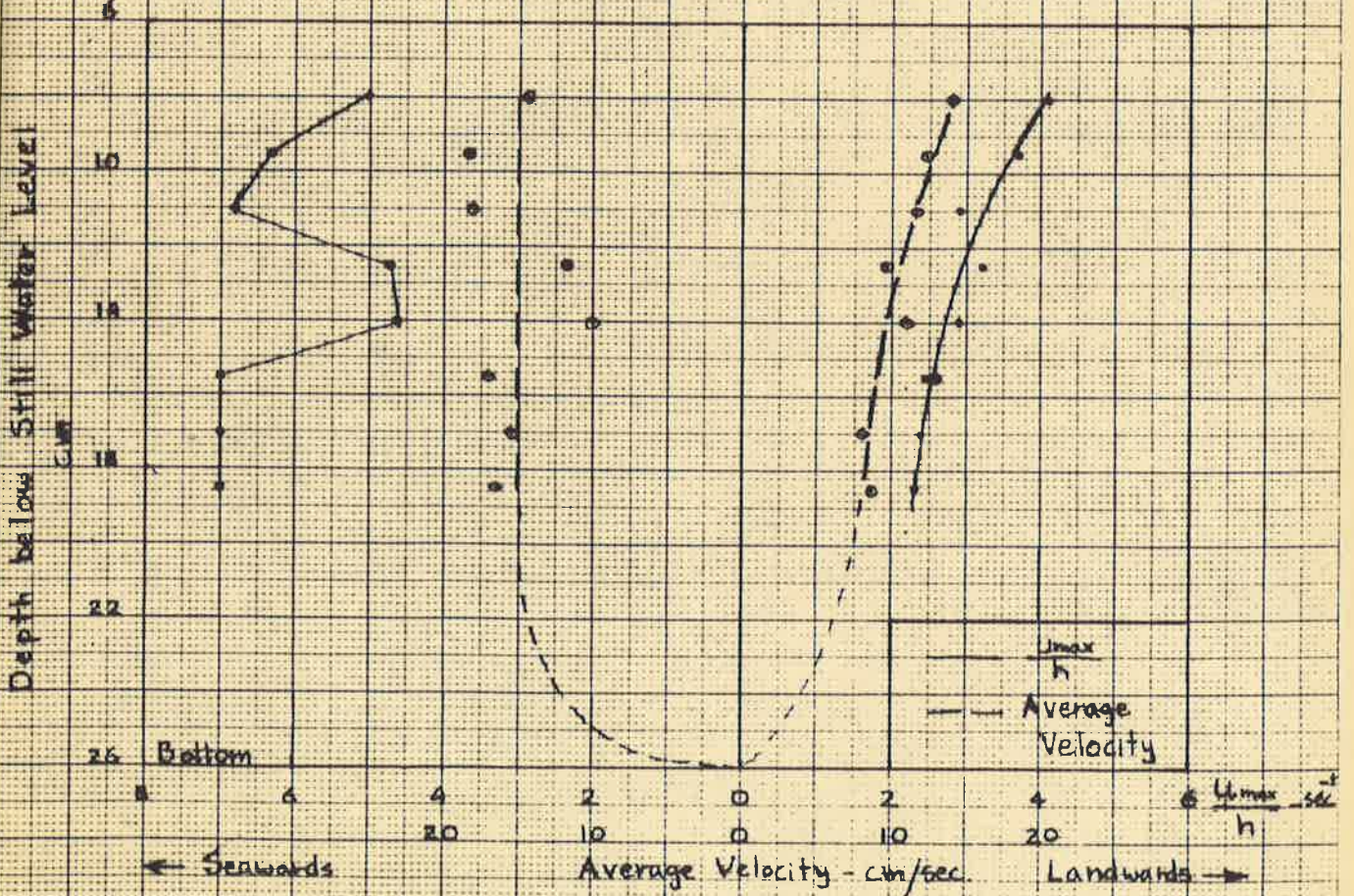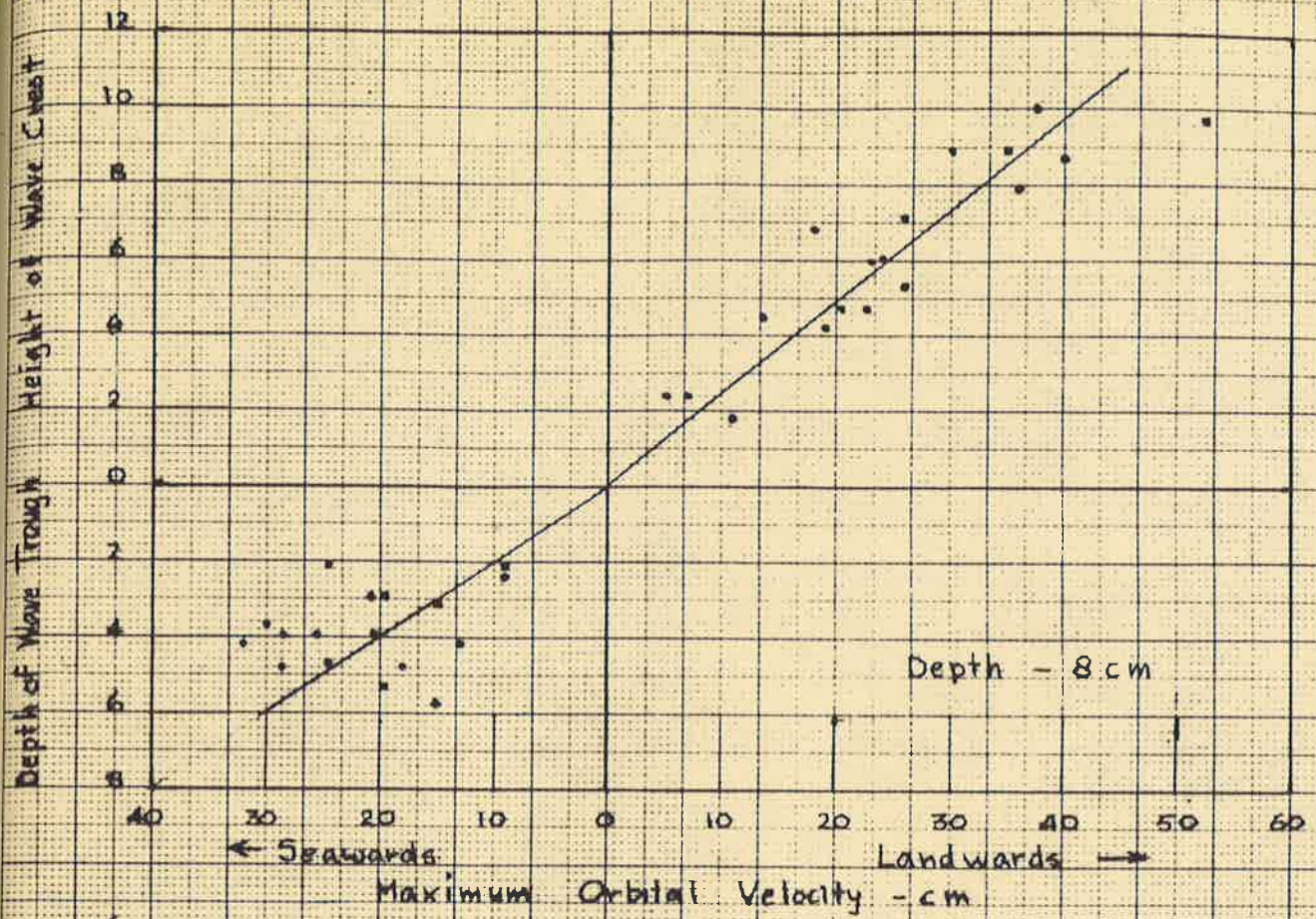
ORBITAL VELOCITY MEASUREMENTS IN WIND WAVES

T6 — ½ hour

VARIATION OF MEDIAN SAND SIZE AND BULK DENSITY ALONG BEACH PROFILES TEST T17 at 19 Hours

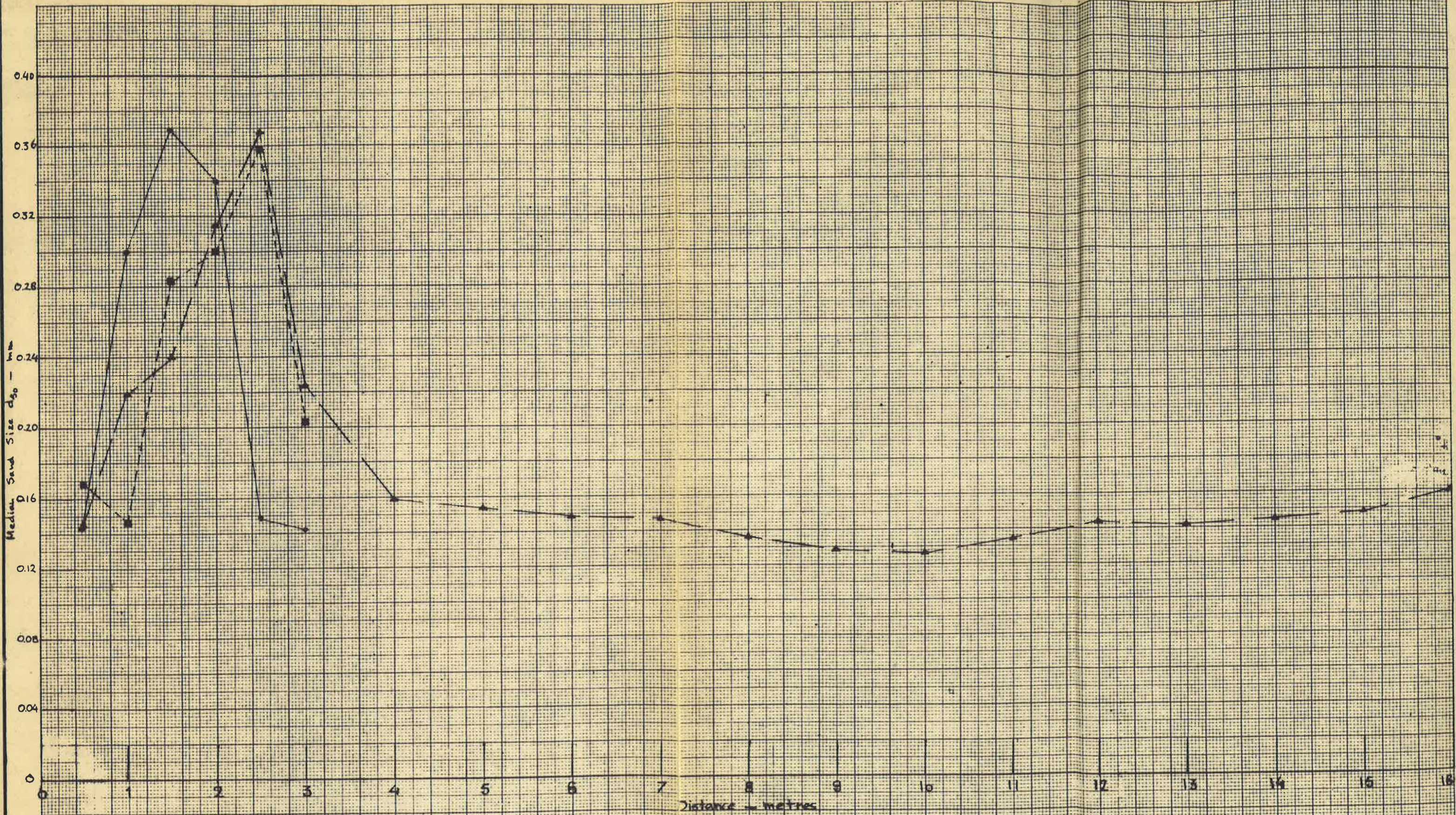Median Sand Size d_{50}
- Profile 1
▲ " 3
■ " 5

Bulk Density of Sand
⊕ Profile 1
△ " 3
⊡ " 5

108

SAND GRADING CURVES ALONG BEACH PROFILE
TEST T17 AT 19 HOURS
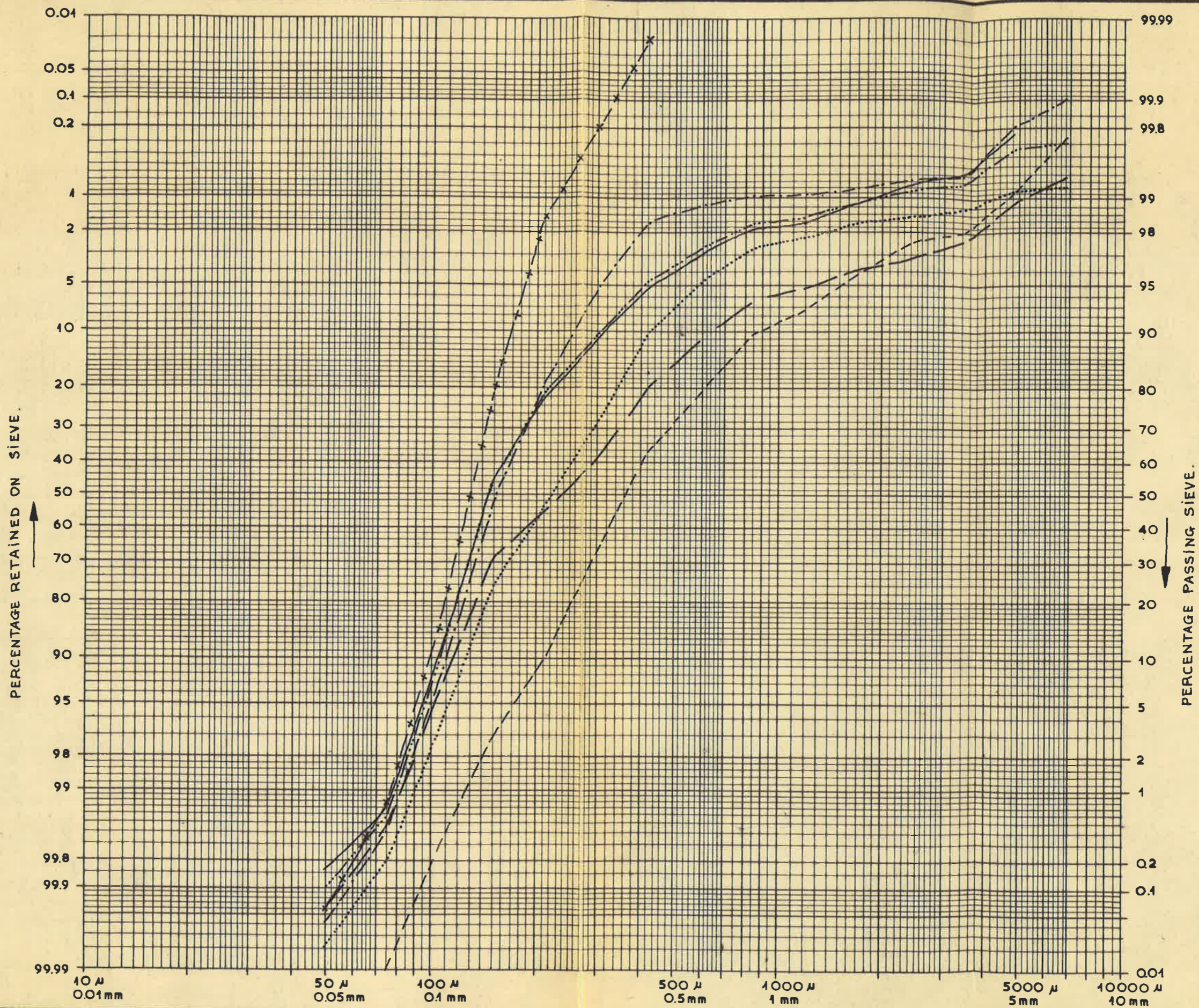BETWEEN PROFILES 5 AND 6 (BASIN CENTREline)

GET.: T.S.

DATUM: 2-2-'68

WATERLOOPKUNDIG LABORATORIUM

M.936   FIG. 109

PERCENTAGE RETAINED ON SiEVE

PERCENTAGE PASSING SiEVE

Legend:
——————   0 metres
— —   1 "
— — —   2 "
········· 3 "
—·—   5 metres.
—+—   9 "
—··—   15 "

VARIATION OF MEDIAN SAND SIZE
ALONG BEACH PROFILES
TEST T25 at 19 Hours

Profile 1
,, 3
,, 5

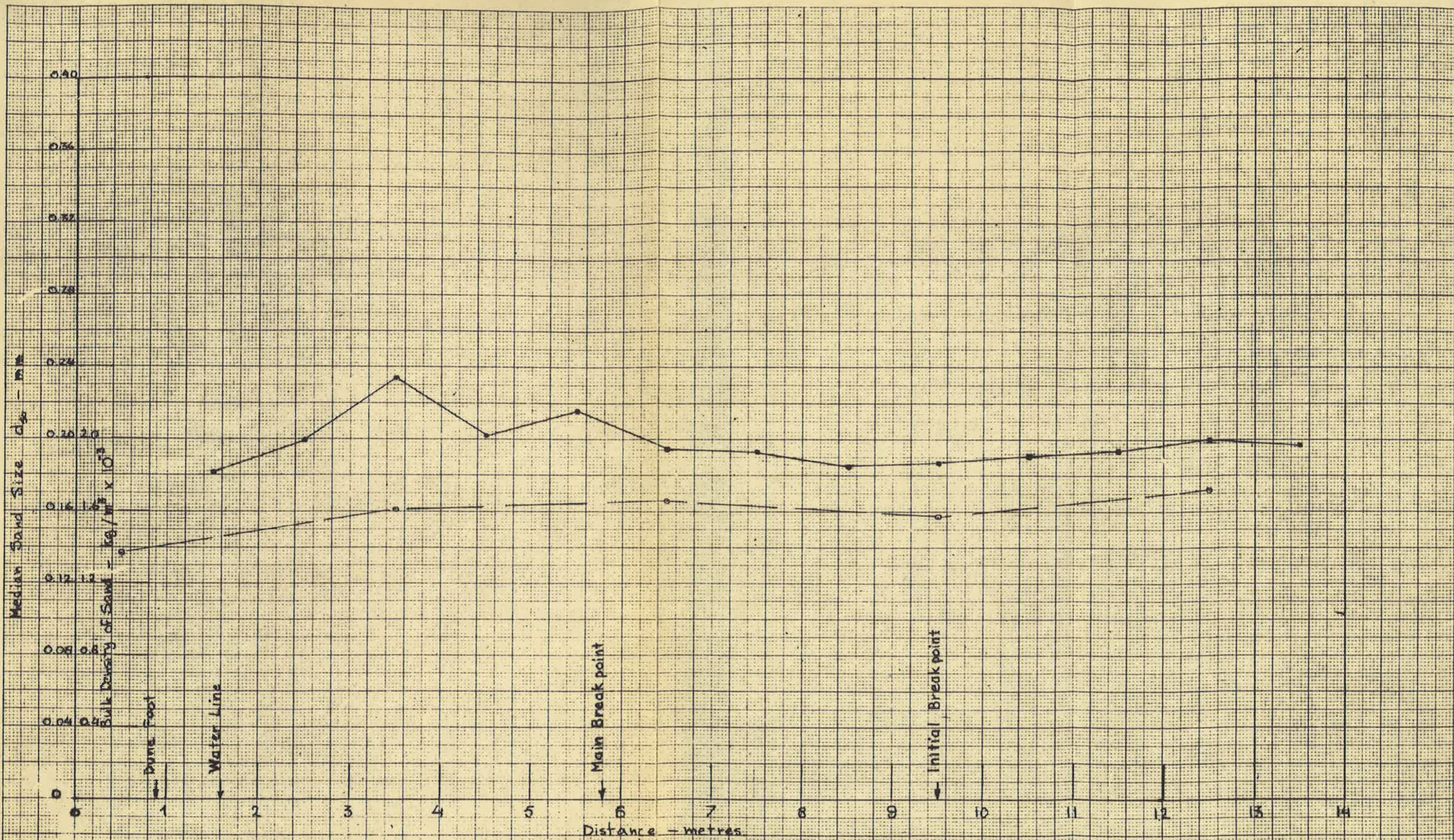Median Sand Size d_{50} — mm

Distance — metres

110

SAND GRADING CURVES ALONG BEACH PROFILE
TEST T 25 AT 19 HOURS
PROFILE 3 (BASIN CENTRELINE)

WATERLOOPKUNDIG LABORATORIUM

GET.: T.S.

DATUM : 2-2-'68

M. 936   FIG. 111

——— 0.5 metres.   —..— 5.0 metres.
— — 1.5 "   —+— 9.0 "
— — — 2.5 "   —...— 15.0 "
.... 3.0 "

68-47

VARIATION OF MEDIAN SAND SIZE
ALONG CENTRE PROFILE
TEST T8 at 19 Hours

- Median Diameter d_{50}
- Bulk Density