RAPPORT No: M 935/M 936

BEACH AND DUNE EROSION TESTS I

AUTEUR: M.R. Gourlay

DATUM: May 1968

CODE No:
# LIST OF CONTENTS

1. **Introduction**
   - 1.1. The Problems ......................................................... 1
   - 1.2. Acknowledgements .................................................. 2

2. **Review of present knowledge**
   - 2.1. Dune erosion and design of artificial dunes ......................... 3
   - 2.2. Rate of erosion and rate of profile adjustment ..................... 5
   - 2.3. Equilibrium profiles ............................................... 8

3. **Model investigation**
   - 3.1. Outside model (M 936) ............................................. 11
     - 3.1.1. General layout .................................................. 11
     - 3.1.2. Measurements ................................................... 11
   - 3.2. Wind flume model (M 935) .......................................... 13
     - 3.2.1. General layout .................................................. 13
     - 3.2.2. Measurements ................................................... 13
   - 3.3. Model scales ........................................................ 15
     - 3.3.1. General considerations .......................................... 15
     - 3.3.2. Scales for present investigation ................................ 20

4. **Model tests**
   - 4.1. Outside model - large basin ....................................... 22
     - 4.1.1. Preliminary tests for initial profile .......................... 22
     - 4.1.2. Initial tests in wide basin .................................... 23
     - 4.1.3. Varying dune height tests in large basin ...................... 24
   - 4.2. Wind flume .......................................................... 26
     - 4.2.1. Regular waves for comparison with outside model ........... 26
     - 4.2.2. Mixed irregular waves .......................................... 27
     - 4.2.3. Wind waves ...................................................... 30
   - 4.3. Outside model - small basin or flume ................................ 35
     - 4.3.1. Wave filter tests ............................................... 35
     - 4.3.2. Tests with different wave height and constant period ........ 37
     - 4.3.3. Tests with changing water level ................................ 38
     - 4.3.4. Tests with same $H_{rms}$ and $T_o$ as wind wave tests ........ 38
5. Model Results

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

5.1.1. Water line and dune foot recession

5.1.2. Sand volumes eroded

5.1.3. Profile changes and development of equilibrium profile

5.1.4. Transport rates during profile development

5.1.4.1. Method of calculation

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

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

5.1.5. Summary

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

5.2.1. Water line and dune foot recession

5.2.2. Sand volumes eroded

5.2.3. Profile changes and development of equilibrium profile

5.2.4. Summary

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

5.3.1. Water line and dune foot recession

5.3.2. Profile changes and development of equilibrium profile

5.3.3. Summary

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

5.4.1. Water line and dune foot recession

5.4.2. Sand volumes eroded

5.4.3. Profile changes and development of equilibrium profile

5.4.4. Transport rates during profile development

5.4.5. Summary
5.5. Influence of sand size upon erosion and profile development...
   5.5.1. Water line and dune foot recession.......................... 81
   5.5.2. Sand volumes eroded............................................. 81
   5.5.3. Profile changes and development of equilibrium profile...
   5.5.4. Transport rates during profile development............... 84
   5.5.5. Summary.......................................................... 85
5.6. Other factors influencing erosion and profile development....
   5.6.1. Wave reflection and bar development......................... 85
   5.6.2. Wave characteristics in the surf zone..................... 90
      5.6.2.1. Regular waves............................................. 90
      5.6.2.2. Wind waves............................................... 97
   5.6.3. Wave runup height, beach slope and breaker distance...... 101
   5.6.4. Orbital velocities within the surf zone.................... 105
   5.6.5. Sediment density and grain size distribution variations 108
   5.6.6. Summary........................................................ 111

References......................................................................... 113
LIST OF FIGURES

1. General layout of outside model.
2. Comparison of prototype beach profiles with model initial profile.
3. Profiles at normal water level (N.A.P.).
4. Sand dune profiles for various tests.
5. Average profiles at 19 hours for similar wave conditions wind flume and large basin.
6. Average profiles at 19 hours for similar wave conditions wind flume and small basin, test T4 and T18.
7. Wave spectra for tests T3, T1 and T2.
8. Effect of wave reflection on wave height measurements of regular and irregular waves.
9. Effect of measurement position on wind wave height and relationship between $H$ and $H_{rms}$ for regular waves.
10. Wave characteristics wind wave tests and wave measurement positions.
11. Variation of waterline and dune foot positions - tests T14, T15 and T16.
12. Recession of waterline for various dune heights.
13. Recession of dune foot for various dune heights.
14. Waterline recession as function of dune height.
15. Dune foot recession as function of dune height.
16. Waterline recession as function of dune height - logarithmic scales.
17. Relation between waterline position, dune height and time.
18. Dune foot recession as function of dune height - logarithmic scales.
20. Dune foot recession ($x' - 0,5$) as function of dune height and time.
21. Volumes of sand eroded as function of time for different sand dunes.
22. Total volume of sand eroded from beach and dune as function of dune height and time.
23. Volume of sand eroded above storm surge level as function of dune height.
24. Waterline recession as function of volume eroded from sand dune.
25. Dune foot recession as function of volume eroded from sand dune.
26. Position of centroid of volumes eroded above storm surge level for various sand dunes.
27. Profiles at 19 hours - Test T14.
28. Profiles at centre of basin - Test T14, 0 to $\frac{3}{2}$ hours.
29. Profiles at centre of basin - Test T14, $\frac{1}{2}$ to 19 hours.
30. Average profiles at 19 hours for different sand dunes.
31. Profiles at 19 hours - Test T26, Profiles 1 to 5.
32. Profiles at 19 hours - Test T26, Profiles 6 to 10.
33. Average profiles - 0 to $\frac{3}{2}$ hours, 40 oms. dune.
34. Average profiles - $\frac{1}{2}$ to 19 hours, 40 oms dune.
35. Sand volumes eroded and deposited as function of time - Test T14.
36. Average profiles - 0 to $\frac{1}{2}$ hours - Test T26, 80 oms dune.
37. Average profiles - $\frac{1}{2}$ to 19 hours - Test T26, 80 oms dune.
38. Average profiles - 0 to $\frac{1}{2}$ hours - Test T17, 10 oms dune.
39. Average profiles - $\frac{1}{2}$ to 19 hours - Test T17, 10 oms dune.
40. Logarithmic plot of average profile at 19 hours - Test T14.
41. Schematic outline of net transport rate calculation.
42. Net seaward sand transport as function of time - Test T26, 1 to 5 metres.
43. Net seaward sand transport as function of time - Test T17, 1 to 5 metres.
44. Net seaward sand transport as function of time - Test T17 and T26, 5 to 15 metres.
45. Net seaward sand transport over beach profiles at various times - Test T26.
46. Net seaward sand transport over beach profiles at various times - Test T17.
47. Dune foot and dune crest recession - Test T26.
48. Recession of waterline for various wave heights - $T = 1.56$ to 1.63 sec.
49. Recession of dune foot for various wave heights - $T = 1.56$ to 1.63 sec.
50. Dune foot recession as function of wave height.
51. Relative dune foot recession $\frac{X}{T^2}$ as function of number of waves $\frac{1}{T}$. $H_o$.
52. Relative dune foot recession $\frac{X}{T^2}$ as function of wave steepness $\frac{T}{2}$.
53. Relative dune erosion volume $\frac{V}{T^2}$ as function of number of waves for different wave steepness $\frac{H_o T}{2}$.
54. Relative dune erosion volume $\frac{V}{T^2}$ as function of number of waves for different wave steepness.
55. Dune erosion volume as function of time and wave characteristics.
56. Final average profiles for different wave heights. $T = 1.56$ to 1.63 sec.
57. Recession of waterline and dune foot for changing and constant level test (T21 and T0).
58. Average profiles during test T21 changing water level.
59. Recession of waterline and dune foot for wind waves and regular waves.
60. Recession of waterline and dune foot for wind waves and regular waves.

61. Relative erosion volume \( \frac{V}{H_0^2} \) as function of number of waves for wind waves and regular waves.

62. Relative erosion volume \( \frac{V}{T^2} \) as function of number of waves for wind waves and regular waves.

63. Average profiles at 19 hours for wind waves. Tests T7, T6 and T8.

64. Average profiles at 19 hours. Wind waves and regular waves. Tests T7 and T22.

65. Average profiles at 19 hours. Wind waves and regular waves. Tests T6 and T23.


67. Profiles at 19 hours. Test T24 - Regular waves.

68. Profiles at 19 hours. Test T6 - Wind waves.

69. Net seaward sand transport as function of time - Test T24, 1 to 11 metres.

70. Net seaward sand transport as function of time - Test T6, 1 to 9 metres.

71. Net seaward sand transport as function of time - Test T8, 5 to 15 metres.

72. Net seaward sand transport over beach profiles at various times - Test T24.

73. Net seaward sand transport over beach profiles at various times - Test T8.

74. Average profiles - Test T24. Regular waves. 0 to 3\( \frac{1}{2} \) hours.

75. Average profiles - Test T24. Regular waves. 3\( \frac{1}{2} \) to 19 hours.

76. Average profiles - Test T6. Wind waves. 0 to 3\( \frac{1}{2} \) hours.

77. Average profiles - Test T8. Wind waves. 3\( \frac{1}{2} \) to 19 hours.

78. Influence of sand size upon dune erosion.

79. Profiles at 1\( \frac{1}{2} \) hour - Test T25. Profiles 1 to 5.

80. Profiles at 1 hour - Test T25. Profiles 1 to 5.

81. Profiles at 2 hours - Test T25. Profiles 1 to 5.

82. Profiles at 3\( \frac{1}{2} \) hours - Test T25. Profiles 1 to 5.

83. Profiles at 5\( \frac{1}{2} \) hours - Test T25. Profiles 1 to 5.

84. Profiles at 8 hours - Test T25. Profiles 1 to 5.

85. Profiles at 11 hours - Test T25. Profiles 1 to 5.

86. Profiles at 14\( \frac{1}{2} \) hours - Test T25. Profiles 1 to 5.

87. Profiles at 19 hours - Test T25. Profiles 1 to 5.

88. Average profiles at 19 hours for different sand sizes - Tests T0 and T25.

89. Net seaward sand transport as function of time - Test T25.
90. Net seaward sand transport over beach profiles at various times. Test T25.
91. Variation of reflection coefficient with time for different wave heights. \( T = 1.56 \) to \( 1.63 \) sec.
92. Reflection coefficient, inner bar, seaward slope and initial breakpoint position – Test T25.
93. Reflection coefficient, initial breakpoint position and dune erosion – Test T22.
94. Reflection coefficient, initial breakpoint position and dune erosion – Test T23.
95. Wave heights in surf zone and mean water level changes. Profile 1.
96. Wave heights in surf zone and mean water level changes. Profile 3.
97. Wave heights in surf zone and mean water level changes. Profile 5.
98. Wave height, wave length and water depth relationships for regular waves in surf zone – Profiles 1 and 3.
99. Wave height, wave length and water depth relationships for regular waves in surf zone – Profile 5.
100. Wave characteristics during wind wave test T6. Offshore position.
102. Wave height, wave length and water depth relationships for wind waves in shoaling water.
103. Changes in wind wave spectra in shoaling water. Test T6 – 11 hours.
104. Relative run-up height as function of wave steepness for sand beaches.
105. Dimensionless breaker distance as function of wave steepness for regular waves.
106. Variation of maximum orbital velocities within surf zone. \( H_o = 19.5 \).
          \( T = 1.56 \).
108. Variation of median sand size and bulk density along beach profiles. Test T17 at 19 hours.
109. Sand grading curves along beach profile. Test T17 at 19 hours. Between profiles 5 and 6 (basin centreline).
110. Variation of median sand size along beach profiles. Test T25 at 19 hours.
111. Sand grading curves along beach profile. Test T25 at 19 hours. Profile 3 (basin centreline).
112. Variation of median sand size along centre profile. Test T6 at 19 hours.
LIST OF SYMBOLS

\( \delta \) wave celerity

\( C_{o3} \) celerity of wave with frequency \( \omega \)

\( G \) group velocity

\( D \) water depth

\( D_b \) breaker depth

\( D' = \frac{2 \pi D}{L} \) depth

\( D_s \) 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 \( H \))

\( H_D \) deepwater wave height

\( H_0 \) theoretical wave height (i.e. shallow water height calculated from \( H_0 \)).

\( H_{\text{max}} \) maximum wave height (usually from record of 500 wind waves)

\( H_{\text{rms}} \) root mean square wave height (based on water surface elevation relative to mean level not individual waves)

\( H_{1/3} \) significant wave height (average of the highest 1/3 of the waves in a particular recording)

\( H_{15}, H_{50} \) 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

\( L_D \) 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

\( T_{\text{mean}} \) average period of wind wave recording calculated from number of waves and duration of record
central period of wave spectrum (i.e. period with greatest amount of energy)

Maximum orbital velocity at bottom

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

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

breaker distance (measured from initial break point to runup limit)
a constant in dune height - water line recession relationship

a constant in dune height - dune foot recession relationship

a constant in dune height - dune foot recession relationship

median sand diameter

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

wave friction factor

gravitational constant

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

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

a constant in dune height-erosion volume relationship

either an exponent or the ratio of group velocity to wave celerity

\( \frac{C}{C} \)
time

maximum horizontal orbital velocity at a given depth

shear velocity \( = \sqrt{\frac{T}{\rho}} \)

fall velocity of sand or other sediment

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

recession of dune foot relative to initial still water line

recession of dune foot relative to initial still water line - 0.5 metres

position of centroid of volume eroded above storm surge level relative to initial still water line

vertical distance usually with respect to water level

wave energy level (equal to deep water level)

distance below water level (+ upwards)
\( \alpha \)  
beach slope angle

\( \rho \)  
density

\( \rho' \)  
submerged density

\( \tau_c \)  
shear stress at bottom

\( \omega \)  
frequency

\( \omega_0 \)  
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 oceanographical conditions.

In certain parts of the world such as Florida, U.S.A. and southern Queensland, 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 asset 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. Bijkar, deputy director of Delft Hydraulics Laboratory, were commenced
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
irs. 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 cut 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 problem of protecting the country against inundation from the sea. Several such methods are described in reference 13 and are summarised below.

a) Vlissingen 1953 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 composed 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 (M.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 on 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 surf zone 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.

Implicit 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 steepness 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 (Hc/Lc = 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 = 1.26 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 colder 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 \( \Delta d \over H_c \) as a function of \( t \over T \) where \( \Delta d \) 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 \( x \over L_o \) and \( \Delta z \over L_o \) as a function of the number of waves \( n \over T \) gave similar curves of logarithmic form for two different waves. Somewhat similar curves were also found for the dimensionless erosion volume \( V \over L_o \mu_o^2 \) as
a function of $\frac{1}{T}$. 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 $\frac{H_o}{L_0}$ was logarithmically related to $\frac{1}{T}$ 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 $\frac{H_o}{d_{50}}$ (where $d_{50}$ is median sand size) exceeded a certain value.

For a fairly steep initial slope of 1 in 10 this critical value of $\frac{H_o}{d_{50}}$ is rather variable but tends to decrease as the steepness increases. This variation of the critical value of $\frac{H_o}{d_{50}}$ with $\frac{H_o}{L_o}$ 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 $\frac{H_o}{d_{50}}$ and step profiles, the latter with large values of $\frac{H_o}{d_{50}}$ 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, Inubaki 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 $\frac{V}{L_0 H_o^2}$ 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 steepness. 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 Savilles 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:

\[ \frac{y}{L_0} = k \left( \frac{x}{L_0} \right)^m \]

in which \( x \) is the distance referred to the still water line,
\( y \) is the depth below still water level,
\( L_0 \) is the deep water wave length,
\[ K = \frac{H_0}{L_o} + 0.039 \sqrt[3]{\frac{d_m}{\rho}} , \]

\[ m = 11.5 \frac{H_0}{L_o} + 0.275 \frac{1}{\sqrt[3]{\rho}} - 0.05 , \]

Where \( H_0 \) is the deep water wave height,
\( d_m \) is the mean sand diameter,
\( \rho' \) 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. Ono and Inoue have 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 11 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 develop 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 \( \frac{H_0}{L_o} \) and the parameter \( \frac{\frac{H_0}{L_o}}{d_{50}} \) indicating the relative size of the bottom material.
Large values of $\frac{H_o}{d_{50}}$ 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 surf zone, 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 reflection 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 outside 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 observations 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 cm). From the envelope of these wave records, 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 resembles 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 \( \frac{H_0}{L_0} \), 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 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 \( H_0 \), i.e. the deepwater wave height and the median sand size, and the deep water wave steepness \( H_0 \). 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 in 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:

\[
\frac{H}{T_W} \gg 1
\]

In a given situation where \( \frac{H}{T_W} \) 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 lighter 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 \( \frac{H_0}{L} > 0.04 \). 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 criteria for suspension conditions within the surf zone can be related to the usual parameter influencing suspended sediment distribution in a unidirectional flow, \( \frac{v_\star}{w} \), where \( v_\star \) is the shear velocity which is defined as \( \sqrt{\frac{T_\sigma}{\rho}} \) where \( T_\sigma \) is the shear stress on the channel bottom and \( \rho \) the fluid density. This is seen from the following relationship:

\[
v_\star = \sqrt{\frac{T_\sigma}{\rho}} = \frac{U_\circ}{U_{\max}} \approx \sqrt{\frac{f_w}{c}}
\]

where \( f_w \) is the friction factor due to wave action

and \( U_{\max} \) is the maximum orbital velocity at the bottom given by the following equation:

\[
U_{\max} = \frac{\pi H}{T \sinh \frac{2 \pi D}{L}}
\]

Whence

\[
\frac{v_\star}{w} = \frac{\pi H}{wT \sinh \frac{2 \pi D}{L}} \approx \frac{H}{T_w}
\]

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 3.11-1 below, that in all cases the ratio \( \frac{H_0}{T_w} \) 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 $\frac{H_o}{T_w}$ the bar is located further seaward and/or is higher than those with lower values of this parameter.

**TABLE 3.31-1**

<table>
<thead>
<tr>
<th>Test number</th>
<th>Wave height $H_o$ - cm</th>
<th>Wave period $T$ - sec</th>
<th>Sand size $d_{50}$ - mm</th>
<th>Fall velocity* $w$ - cm/sec</th>
<th>$\frac{H_o}{T_w}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T14-T17 T26, T0</td>
<td>19.5</td>
<td>1.6</td>
<td>0.22</td>
<td>2.5</td>
<td>4.9</td>
</tr>
<tr>
<td>T25</td>
<td>19.5</td>
<td>1.6</td>
<td>0.15</td>
<td>1.4</td>
<td>3.7</td>
</tr>
<tr>
<td>T24</td>
<td>18.2</td>
<td>1.3</td>
<td>0.22</td>
<td>2.5</td>
<td>5.6</td>
</tr>
<tr>
<td>T22</td>
<td>9.8</td>
<td>1.0</td>
<td>0.22</td>
<td>2.5</td>
<td>3.9</td>
</tr>
<tr>
<td>T20</td>
<td>10.7</td>
<td>1.6</td>
<td>0.22</td>
<td>2.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Prototype</td>
<td>450</td>
<td>8.0</td>
<td>0.22</td>
<td>2.5</td>
<td>22.5</td>
</tr>
</tbody>
</table>

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 $\frac{H}{T_w}$. When this is comparatively small as in test T20 (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 $60^\circ F (13^\circ C)$ 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 Bonneville and Pernecker (reference 3) while an estimate of the time scale for bed movement can be obtained from an empirical equation of Larraza (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 undistorted form to the vertical scale. Scale effect due to incorrect reproduction 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 \( \frac{H}{T_w} > 1 \). 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 horizontal 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 cm, 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 \(l/n\), 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 omission 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 preceded 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 storm surge level. 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 cm 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 central line 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>
<thead>
<tr>
<th>Test Number</th>
<th>Model</th>
<th>Dune Height-cm</th>
<th>Dune Slope</th>
<th>Type of Waves</th>
<th>Wave Height (50 cm)</th>
<th>Deepwater Wave Height</th>
<th>Wave Period - sec</th>
<th>Sand Size-mm</th>
<th>Water Level</th>
<th>Duration of Test-hours</th>
<th>Beach Profiles</th>
<th>No. of Profiles</th>
<th>No. of Times</th>
<th>Wave Height</th>
<th>Reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>Wind Flume</td>
<td>40</td>
<td>1 to 1 1/4</td>
<td>Regular Waves</td>
<td>17.9</td>
<td>-</td>
<td>-</td>
<td>19.5</td>
<td>1.65</td>
<td>0.22</td>
<td>Constant</td>
<td>2 + 19</td>
<td>5</td>
<td>10</td>
<td>Every 1/2 hour</td>
</tr>
<tr>
<td>T0'</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>18.0</td>
<td>16.5</td>
<td>8.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T1</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>17.7</td>
<td>18.5</td>
<td>9.8</td>
<td>17.2</td>
<td>1.12</td>
<td>2 1/2</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2 + 19</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>T2</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>19.0</td>
<td>19.0</td>
<td>9.4</td>
<td>17.2</td>
<td>1.11</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>19</td>
<td>5</td>
</tr>
<tr>
<td>T3</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>21.0</td>
<td>21.0</td>
<td>11.2</td>
<td>17.2</td>
<td>1.29</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T4</td>
<td>Original Basin Outside</td>
<td>24</td>
<td>1 to 3</td>
<td>Regular Waves</td>
<td>18</td>
<td>-</td>
<td>-</td>
<td>19.7</td>
<td>1.56</td>
<td>0.22</td>
<td>&quot;</td>
<td>2 + 14 1/2</td>
<td>5</td>
<td>9</td>
<td>Occasionally</td>
</tr>
<tr>
<td>T12</td>
<td>&quot;</td>
<td>15</td>
<td>1 to 10</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T13</td>
<td>&quot;</td>
<td>35 to 40</td>
<td>1 to 2</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T14</td>
<td>Large basin Outside</td>
<td>40</td>
<td>1 to 1 1/4</td>
<td>Regular Waves</td>
<td>18</td>
<td>-</td>
<td>-</td>
<td>19.7</td>
<td>1.56</td>
<td>0.22</td>
<td>&quot;</td>
<td>2 + 19</td>
<td>7</td>
<td>10</td>
<td>Occasionally</td>
</tr>
<tr>
<td>T15</td>
<td>&quot;</td>
<td>30</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>7</td>
</tr>
<tr>
<td>T16</td>
<td>&quot;</td>
<td>20</td>
<td>&quot;</td>
<td>&quot;</td>
<td>18.0</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T17</td>
<td>&quot;</td>
<td>10</td>
<td>&quot;</td>
<td>&quot;</td>
<td>18.3</td>
<td>-</td>
<td>-</td>
<td>20.0</td>
<td>1.15</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T18</td>
<td>Small basin Outside</td>
<td>40</td>
<td>1 to 1 1/4</td>
<td>Regular Waves</td>
<td>16.3</td>
<td>-</td>
<td>-</td>
<td>17.8</td>
<td>1.56</td>
<td>0.22</td>
<td>&quot;</td>
<td>2 + 19</td>
<td>5</td>
<td>2</td>
<td>Occasionally every 1/4 hour</td>
</tr>
<tr>
<td>T19</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>14.1</td>
<td>-</td>
<td>-</td>
<td>15.4</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2 + 26 1/2</td>
</tr>
<tr>
<td>T20</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>9.8</td>
<td>-</td>
<td>-</td>
<td>10.7</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T21</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>18.4 L.W.</td>
<td>-</td>
<td>-</td>
<td>20.1 L.W.</td>
<td>18.2 L.W.</td>
<td>1.04</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>19</td>
</tr>
<tr>
<td>T22</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>17.3 L.W.</td>
<td>9.3</td>
<td>6.6</td>
<td>9.8</td>
<td>1.04</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Constant</td>
<td>19</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T23</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>12.5</td>
<td>12.5</td>
<td>8.9</td>
<td>15.4</td>
<td>1.16</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T24</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>16.7</td>
<td>-</td>
<td>10.9</td>
<td>18.2</td>
<td>1.29</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T25</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>18.6</td>
<td>-</td>
<td>20.3</td>
<td>1.56</td>
<td>0.15</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>T26</td>
<td>Large basin Outside</td>
<td>80</td>
<td>1 to 1</td>
<td>Regular Waves</td>
<td>19.9</td>
<td>-</td>
<td>-</td>
<td>21.7</td>
<td>1.56</td>
<td>0.22</td>
<td>&quot;</td>
<td>2 + 19</td>
<td>10</td>
<td>10</td>
<td>After test</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------</td>
<td>------------------</td>
<td>--------------</td>
<td>------------------------</td>
<td>---------------------</td>
<td>---------------</td>
<td>-------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inshore</td>
<td>Offshore</td>
<td>Inshore</td>
<td>Offshore</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>After test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>Every 1/2 hour</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot; several times</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>&quot;</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot; several times</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>&quot;</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot; several times</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>Every 1/2 hour</td>
<td>16 Points at 22 cm</td>
<td>Every 1/2 hour at inshore point</td>
<td>After test</td>
<td>After test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>Every 1/2 hour</td>
<td>3 times</td>
<td>After test</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>1/2 hour</td>
<td>3 times</td>
<td>After test</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>&quot;</td>
<td>-</td>
<td>After test</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>Before After test</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>Before After test</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>Before After test</td>
<td>at each level-ling</td>
<td>Every 1/2 hour</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Thrice Daily
- Occasion -ally
- Approx. 2 hours
- At each leveling
- Occasion -ally
- Every 1/2 hour
- Every 1/2 hour
- Every 1/2 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 irregular 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 $1\frac{1}{4}$ 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 1 on 2 which would have made test T14 almost identical with test T13 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 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, $\frac{3}{2}$, $\frac{5}{2}$, 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

4.2.1. 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 T0 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 6.75 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, $\frac{3}{2}$, $\frac{5}{2}$, 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 T0 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 T0' agreed reasonably well with test T0 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 T0 and T0' 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 identical with T0 and T0' 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 irregular 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 indeed 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 cm 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 eccentricity 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 $\frac{H_{1/3}}{H_{20}}$ 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 T0 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 spectre for the regular wave tests were made in a separate measurement from the original tests T0 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 preceding 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 procedure 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 flumes 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 particular the initial beach profile. If this were to have the same physical 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 exception 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, i.e 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 H40 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 \( \omega \) 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, \( H_{rms} \). If the regular wave is a sine wave or closely approximates to one then it can be shown theoretically that

\[ H_{rms} = 0.707 \, H \]

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 \( H_{rms} \) was measured. If the wave is not a sine wave, it has relatively sharper crests as is the case for most waves in practice, then the actual value of \( H_{rms} \) 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 toward the shore the same for both regular and irregular waves. This may indeed be so but its computation is more difficult since

\[ P = \frac{n \cdot E}{T} \]

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

\( n \) is the ratio of group velocity \( C_g \) to phase velocity \( C \),

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

Now \( E = \frac{P \cdot g \cdot H^2 \cdot L}{8} \)

whence \( P = \frac{H^2 \cdot n \cdot C}{C \cdot T} \), since \( L = C \cdot T \).

where both \( C \) and \( n \) are functions of the relative depth \( \frac{D}{L} \).

*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

\[ P \propto \sum_{w=0}^{\infty} \left[ E^i (w) n_w C_w \right] \Delta w \]

where \( n_w \) and \( C_w \) are the values of \( n \) and \( C \) at a given frequency \( w \).

If the spectrum is measured in deep water \( n_w \) is constant and equal to 0.5 while \( C_w \) is proportional to \( \frac{1}{w} \) 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 \( H_{rms} \) 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 \( w_0 \), 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, i.e., 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 tests in terms of the conditions imposed is thus T7, T6, T8.
4.3. Outside model - small basin

4.3.1. 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**

\[ T = 1.56 \text{ sec} \]

<table>
<thead>
<tr>
<th>Type of filter</th>
<th>Number of layers</th>
<th>Avg. wave-height after filter ( H_{av-co} )</th>
<th>Transmission coefficient ( H_{av}/H_{avo} )</th>
<th>Wave-height variation ( H_{max}-H_{min} ) (cm)</th>
<th>Variability coefficient ( H_{max}-H_{min}/H_{av} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>No filter</td>
<td>-</td>
<td>27.7</td>
<td>100%</td>
<td>2.8</td>
<td>10%</td>
</tr>
<tr>
<td>Original &quot;Steengaas&quot;</td>
<td></td>
<td>18.0</td>
<td>65</td>
<td>3.5</td>
<td>20%</td>
</tr>
<tr>
<td>&quot;Steengaas&quot;</td>
<td>1</td>
<td>18.0</td>
<td>72</td>
<td>3.5</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>18.2</td>
<td>66</td>
<td>1.6</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>16.2</td>
<td>59</td>
<td>1.4</td>
<td>9%</td>
</tr>
<tr>
<td>&quot;Steengaas&quot; (new mat.)</td>
<td></td>
<td>18.2</td>
<td>66</td>
<td>1.6</td>
<td>1%</td>
</tr>
<tr>
<td>Plastic mesh</td>
<td>1</td>
<td>26.4</td>
<td>95</td>
<td>3.5</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>24.7</td>
<td>89</td>
<td>2.0</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>23.5</td>
<td>85</td>
<td>2.0</td>
<td>9%</td>
</tr>
<tr>
<td>Nylon mesh</td>
<td>1</td>
<td>25.7</td>
<td>93</td>
<td>2.2</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>23.8</td>
<td>86</td>
<td>3.7</td>
<td>16%</td>
</tr>
<tr>
<td>Expanded metal mesh</td>
<td>1</td>
<td>26.0</td>
<td>94</td>
<td>2.6</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>24.0</td>
<td>87</td>
<td>3.5</td>
<td>15%</td>
</tr>
</tbody>
</table>

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 outside tests*.

4.32. Tests with different wave heights and constant period.

The first test T16 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 ± 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 $T_o$ 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. These 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, $\frac{3}{2}$, $\frac{5}{2}$, 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 test, 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 T16 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

5.1.1. 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 identifiable 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 5.1.1. 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)

<table>
<thead>
<tr>
<th>Waterline recession m</th>
<th>Test Number</th>
<th>Dune height</th>
<th>( \frac{1}{2} )</th>
<th>1</th>
<th>2</th>
<th>( \frac{3}{2} )</th>
<th>( \frac{5}{2} )</th>
<th>8</th>
<th>11</th>
<th>( \frac{14}{2} )</th>
<th>19</th>
<th>( \frac{27}{2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T14</td>
<td>40 cm</td>
<td>0.20</td>
<td>0.27</td>
<td>0.39</td>
<td>0.42</td>
<td>0.51</td>
<td>0.59</td>
<td>0.61</td>
<td>0.63</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T15</td>
<td>30</td>
<td>0.22</td>
<td>0.33</td>
<td>0.45</td>
<td>0.54</td>
<td>0.61</td>
<td>0.66</td>
<td>0.71</td>
<td>0.72</td>
<td>0.74</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>T16</td>
<td>20</td>
<td>0.25</td>
<td>0.36</td>
<td>0.49</td>
<td>0.58</td>
<td>0.64</td>
<td>0.72</td>
<td>0.76</td>
<td>0.86</td>
<td>0.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T17</td>
<td>10</td>
<td>0.43</td>
<td>0.53</td>
<td>0.68</td>
<td>0.81</td>
<td>0.96</td>
<td>1.09</td>
<td>1.12</td>
<td>1.22</td>
<td>1.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T26</td>
<td>80</td>
<td>0.18</td>
<td>0.07</td>
<td>0.13</td>
<td>0.21</td>
<td>0.24</td>
<td>0.24</td>
<td>0.23</td>
<td>0.24</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dune foot recession m</th>
<th>Test Number</th>
<th>Dune height</th>
<th>( \frac{1}{2} )</th>
<th>1</th>
<th>2</th>
<th>( \frac{3}{2} )</th>
<th>( \frac{5}{2} )</th>
<th>8</th>
<th>11</th>
<th>( \frac{14}{2} )</th>
<th>19</th>
<th>( \frac{27}{2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T14</td>
<td>40</td>
<td>0.61</td>
<td>0.68</td>
<td>0.79</td>
<td>0.86</td>
<td>0.93</td>
<td>1.02</td>
<td>1.05</td>
<td>1.10</td>
<td>1.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T15</td>
<td>30</td>
<td>0.71</td>
<td>0.78</td>
<td>0.88</td>
<td>0.97</td>
<td>1.04</td>
<td>1.11</td>
<td>1.19</td>
<td>1.23</td>
<td>1.24</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>T16</td>
<td>20</td>
<td>0.70</td>
<td>0.79</td>
<td>0.90</td>
<td>1.01</td>
<td>1.11</td>
<td>1.21</td>
<td>1.28</td>
<td>1.34</td>
<td>1.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T17</td>
<td>10</td>
<td>0.91</td>
<td>1.03</td>
<td>1.15</td>
<td>1.30</td>
<td>1.44</td>
<td>1.56</td>
<td>1.64</td>
<td>1.79</td>
<td>1.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T26</td>
<td>80</td>
<td>0.42</td>
<td>0.58</td>
<td>0.60</td>
<td>0.61</td>
<td>0.68</td>
<td>0.73</td>
<td>0.74</td>
<td>0.79</td>
<td>0.82</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 logarithmic 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 \( x^0.5 \) and \( x^0.3 \) 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 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:

\[
x'' = \frac{1.51 + 0.37}{h^{0.5}}
\]

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**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Dune height cm</th>
<th>Dune slope</th>
<th>( \frac{1}{2} )</th>
<th>1</th>
<th>2</th>
<th>( \frac{3}{2} )</th>
<th>( \frac{5}{2} )</th>
<th>8</th>
<th>11</th>
<th>( \frac{15}{2} )</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>T14</td>
<td>40</td>
<td>1:1 3/4</td>
<td>0.113</td>
<td>0.154</td>
<td>0.197</td>
<td>0.243</td>
<td>0.271</td>
<td>0.311</td>
<td>0.333</td>
<td>0.342</td>
<td>0.376</td>
</tr>
<tr>
<td>T15</td>
<td>30</td>
<td>&quot;</td>
<td>0.131</td>
<td>0.148</td>
<td>0.186</td>
<td>0.218</td>
<td>0.242</td>
<td>0.284</td>
<td>0.303</td>
<td>0.309</td>
<td>0.316</td>
</tr>
<tr>
<td>T16</td>
<td>20</td>
<td>&quot;</td>
<td>0.091</td>
<td>0.123</td>
<td>0.157</td>
<td>0.180</td>
<td>0.213</td>
<td>0.228</td>
<td>0.245</td>
<td>0.268</td>
<td>0.282</td>
</tr>
<tr>
<td>T17</td>
<td>10</td>
<td>&quot;</td>
<td>0.082</td>
<td>0.096</td>
<td>0.114</td>
<td>0.143</td>
<td>0.180</td>
<td>0.191</td>
<td>0.209</td>
<td>0.224</td>
<td>0.229</td>
</tr>
<tr>
<td>T26</td>
<td>80</td>
<td>1:1</td>
<td>0.117</td>
<td>0.164</td>
<td>0.202</td>
<td>0.249</td>
<td>0.306</td>
<td>0.323</td>
<td>0.377</td>
<td>0.400</td>
<td>0.467</td>
</tr>
</tbody>
</table>

Consideration of these figures which are plotted as a function of time on figure 20 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:

\[
V = \frac{(h + 41)^{0.3}}{0.62}
\]
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**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Dune height cm</th>
<th>Dune Slope</th>
<th>Time - hours</th>
<th>1/2</th>
<th>1</th>
<th>2</th>
<th>1/2</th>
<th>1/2</th>
<th>8</th>
<th>11</th>
<th>16/2</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>T14</td>
<td>40</td>
<td>1:1(\frac{3}{4})</td>
<td></td>
<td>0.102</td>
<td>0.137</td>
<td>0.174</td>
<td>0.211</td>
<td>0.238</td>
<td>0.267</td>
<td>0.286</td>
<td>0.301</td>
<td>0.333</td>
</tr>
<tr>
<td>T15</td>
<td>30</td>
<td>&quot;</td>
<td></td>
<td>0.120</td>
<td>0.136</td>
<td>0.164</td>
<td>0.184</td>
<td>0.206</td>
<td>0.238</td>
<td>0.254</td>
<td>0.263</td>
<td>0.274</td>
</tr>
<tr>
<td>T16</td>
<td>20</td>
<td>&quot;</td>
<td></td>
<td>0.088</td>
<td>0.111</td>
<td>0.134</td>
<td>0.150</td>
<td>0.173</td>
<td>0.190</td>
<td>0.200</td>
<td>0.217</td>
<td>0.228</td>
</tr>
<tr>
<td>T17</td>
<td>10</td>
<td>&quot;</td>
<td></td>
<td>0.068</td>
<td>0.077</td>
<td>0.089</td>
<td>0.103</td>
<td>0.119</td>
<td>0.130</td>
<td>0.133</td>
<td>0.143</td>
<td>0.145</td>
</tr>
<tr>
<td>T26</td>
<td>80</td>
<td>1:1</td>
<td></td>
<td>0.116</td>
<td>0.163</td>
<td>0.201</td>
<td>0.253</td>
<td>0.288</td>
<td>0.314</td>
<td>0.369</td>
<td>0.392</td>
<td>0.455</td>
</tr>
</tbody>
</table>

The data from table 5.12-2 are plotted on figure 21-b as a function of 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 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.

Obviously \( V^1 = K \cdot h^n \) 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 T25), 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)

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Dune height</th>
<th>Dune slope</th>
<th>Time - hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \frac{1}{2} )</td>
</tr>
<tr>
<td>T14</td>
<td>40</td>
<td>11( \frac{3}{4} )</td>
<td>0.49</td>
</tr>
<tr>
<td>T15</td>
<td>30</td>
<td>&quot;</td>
<td>0.52</td>
</tr>
<tr>
<td>T16</td>
<td>20</td>
<td>&quot;</td>
<td>0.41</td>
</tr>
<tr>
<td>T17</td>
<td>10</td>
<td>&quot;</td>
<td>0.37</td>
</tr>
<tr>
<td>T26</td>
<td>80</td>
<td>11( \frac{1}{2} )</td>
<td>0.52</td>
</tr>
</tbody>
</table>

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

\[
\frac{\bar{x}'}{t} = 4.9 t^{0.16}
\]

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/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 intertidal 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, T15 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 (e.g., 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 break point 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 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 $\frac{1}{2}$ 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 $\frac{3}{2}$ 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 recession is more rapid. An inner bar appears to be present up to $\frac{3}{2}$ 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 flatter 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 builds up. 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 receded 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.F.) for different sand dunes

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Dune height</th>
<th>Time - hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>T14</td>
<td>40 cm</td>
<td></td>
</tr>
<tr>
<td>T15</td>
<td>30</td>
<td>2.84</td>
</tr>
<tr>
<td>T16</td>
<td>20</td>
<td>2.76</td>
</tr>
<tr>
<td>T17</td>
<td>10</td>
<td>2.86</td>
</tr>
<tr>
<td>T26</td>
<td>80</td>
<td>2.83</td>
</tr>
</tbody>
</table>

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 root 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

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

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 Larrañ (reference 1) who expressed the equilibrium profile form in terms of dimensionless coordinates \( \frac{x}{L_0} \) and \( \frac{y}{L_0^2} \) where \( x \) and \( y \) are referred to the still water line position, the wave steepness \( \frac{H_0}{L_0} \) and the sediment size. For the particular sediment and wave conditions of these tests Larrañ's 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 Larrañ's 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 Larrañ 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 Larrañ.

However such parabolae 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 5.55 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 intermittent 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 undoubtedly 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 eroded 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 recession 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 $180^\circ$ 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 recede 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 $\frac{3}{2}$ 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 $\frac{3}{2}$ hours while sand accumulates offshore of the breakpoint 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 breakpoint, 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 potential 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 noticeable 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 suspension 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 within 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 proportional 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 $\frac{51}{2}$, the average slope between storm surge water level and normal water level (N.A.P.) is 1 in $\frac{131}{2}$ 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

5.2.1. 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 1.53) 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**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Wave height $H_0$</th>
<th>Time - hours</th>
<th>Water line recession metres</th>
<th>Dune foot recession metres</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{1}{2}$</td>
<td>1</td>
<td>2</td>
<td>$3\frac{1}{2}$</td>
</tr>
<tr>
<td>T0</td>
<td>19.5 cm</td>
<td>0.19</td>
<td>0.30</td>
<td>0.27</td>
</tr>
<tr>
<td>T0'</td>
<td>19.5</td>
<td>0.18</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>T4</td>
<td>17.6</td>
<td>0.05</td>
<td>0.01</td>
<td>0.15</td>
</tr>
<tr>
<td>T18</td>
<td>17.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>T19</td>
<td>15.4</td>
<td>0.04</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>T20</td>
<td>10.7</td>
<td>0.00</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>T0</td>
<td>19.5</td>
<td>0.59</td>
<td>0.72</td>
<td>0.84</td>
</tr>
<tr>
<td>T0'</td>
<td>19.5</td>
<td>0.62</td>
<td>0.73</td>
<td>0.76</td>
</tr>
<tr>
<td>T4</td>
<td>17.6</td>
<td>0.48</td>
<td>0.48</td>
<td>0.60</td>
</tr>
<tr>
<td>T18</td>
<td>17.8</td>
<td>-</td>
<td>0.56</td>
<td>0.72</td>
</tr>
<tr>
<td>T19</td>
<td>15.4</td>
<td>0.40</td>
<td>0.47</td>
<td>0.55</td>
</tr>
<tr>
<td>T20</td>
<td>10.7</td>
<td>0.40</td>
<td>0.46</td>
<td>0.46</td>
</tr>
</tbody>
</table>

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

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

physical considerations indicate that

\[ \frac{x'}{gT^2} = f \left( \frac{H_o}{gT^2}, \frac{t}{T} \right), \]

or since

\[ L_o = \frac{gT^2}{2\pi} \quad \text{where } L_o \text{ is the deepwater wave length} \]

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

These three dimensionless parameters can be easily interpreted as follows:
\( \frac{x'}{L_0} \) — a scale factor representing the known fact that model beaches are steeper than prototype ones (cf formula of Larras in section 2.3).

\( \frac{H_0}{L_0} \) — the deepwater wave steepness.

\( \frac{t}{T} \) — 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 \( \frac{x'}{L_0} \) plotted against \( \frac{t}{T} \) for various tests (i.e. constant steepness \( \frac{H_0}{L_0} \)). It is apparent that for a given value of \( \frac{t}{T} \) the parameter \( \frac{x'}{L_0} \) increases with the wave steepness, while, except for relatively small values of \( \frac{t}{T} \) and \( \frac{H_0}{L_0} \), the lines of constant steepness \( \frac{H_0}{L_0} \) have essentially the same shape, thus indicating a general functional relation between \( \frac{x'}{L_0} \) and \( \frac{t}{T} \) similar in form to that found in section 5.11 between \( r'' \) and \( t \).

However the relation between \( \frac{x'}{L_0} \) and \( \frac{H_0}{L_0} \) for constant values of \( \frac{t}{T} \) does not appear to be a simple one. Figure 52, obtained using values of \( \frac{t}{T} \) and \( \frac{x'}{L_0} \), read off the smoothed curves of figure 51 at given \( \frac{t}{T} \), indicates that there is a discontinuity in this relationship when \( \frac{H_0}{L_0} \) is approximately 7 cm/sec² (\( \frac{H_0}{L_0} = 0.047 \)). 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 \( \frac{x'}{L_0} \), \( \frac{H_0}{L_0} \) and \( \frac{t}{T} \), 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 (metres³/metre)

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Wave height H₀ cm</th>
<th>Wave period sec</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>3.5</th>
<th>5.5</th>
<th>8</th>
<th>11</th>
<th>14.5</th>
<th>19</th>
<th>26.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>19.5</td>
<td>1.63</td>
<td>0.094</td>
<td>0.146</td>
<td>0.179</td>
<td>0.212</td>
<td>0.253</td>
<td>0.296</td>
<td>0.349</td>
<td>0.375</td>
<td>0.396</td>
<td>-</td>
</tr>
<tr>
<td>T0'</td>
<td>19.5</td>
<td>1.63</td>
<td>0.101</td>
<td>0.162</td>
<td>0.148</td>
<td>0.221</td>
<td>0.221</td>
<td>0.280</td>
<td>0.341</td>
<td>0.382</td>
<td>0.369</td>
<td>-</td>
</tr>
<tr>
<td>T4</td>
<td>17.6</td>
<td>1.63</td>
<td>0.065</td>
<td>0.081</td>
<td>0.111</td>
<td>0.117</td>
<td>0.187</td>
<td>0.191</td>
<td>0.250</td>
<td>0.324</td>
<td>0.359</td>
<td>-</td>
</tr>
<tr>
<td>T20</td>
<td>10.7</td>
<td>1.56</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.193</td>
</tr>
<tr>
<td>T22</td>
<td>9.8</td>
<td>1.04</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.113</td>
<td>-</td>
</tr>
<tr>
<td>T23</td>
<td>13.4</td>
<td>1.16</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.139</td>
<td>-</td>
<td>0.150</td>
</tr>
<tr>
<td>T24</td>
<td>18.2</td>
<td>1.29</td>
<td>0.055</td>
<td>0.087</td>
<td>0.114</td>
<td>0.141</td>
<td>0.166</td>
<td>0.187</td>
<td>0.217</td>
<td>0.233</td>
<td>0.251</td>
<td>-</td>
</tr>
</tbody>
</table>

Plotting the volume eroded with respect to time (figure 55b) yields somewhat 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 systematisation of the data by dimensionless representation are considered, there appear to be two, reasonable alternatives. If it is agreed that both the wave steepness \( \frac{H}{L₀} \) or \( \frac{H}{T²} \) 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:

\[
\frac{V}{H_0 L_0} \quad \text{or} \quad \frac{V}{g H_0 T^2}
\]

and

\[
\frac{V}{L_0^2} \quad \text{or} \quad \frac{V}{g^2 T^4}
\]

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 \( \frac{H_0}{T} \), it is found that the data tend to be more clearly represented by \( \frac{V}{T} \). For instance, in the plot of \( \frac{V}{H_0 T^2} \) (figure 53) it is not possible to detect a systematic effect of the wave steepness \( \frac{H_0}{T^2} \), 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 \( \frac{H_0}{T^2} \) is greatest (11.1), fall almost exactly on the same line as TO and TO' where \( \frac{H_0}{T^2} \) 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 from the smoothed curves of figure 54 at constant \( \frac{H_0}{T^2} \). 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 \( \frac{H_0}{T^2} = 8.3 \, \text{cm/sec}^2 \) 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 TO and T14 are almost horizontal when \( \frac{H_0}{T^2} \approx 4.5 \times 10^4 \) while for test T24 (greater steepness) this does not occur until \( \frac{H_0}{T^2} \approx 6. \times 10^4 \). Test T20 (lower steepness) has not reached equilibrium at \( \frac{H_0}{T^2} \approx 6 \times 10^4 \). The reason for this difference is probably due to the fact that the initial profile is somewhat closer to the equilibrium profile for tests TO 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 relationship between the three parameters \(\frac{V}{n^4}, \frac{H_0}{T^2}, \frac{t}{T}\) 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 \((\frac{H_0}{T^2} = 11.1 \text{ cm/sec}^2)\), 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 inconstancy of the wave steepness lines on figure 53 \((\frac{V}{n^4} \text{ versus } \frac{t}{T})\). Finally it should be noted that the parameter \(\frac{V}{n^4}\) or \(\frac{L}{T^2}\) would seem to be consistent with the dimensionless representation of beach profiles in terms of \(\frac{H}{L}\) and \(\frac{W}{L}\) by Larraza (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 15.4 cm (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 $H_0 = 10.7$ 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 Larraá (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

5.3.1. 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 5.32-1**

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

<table>
<thead>
<tr>
<th>Time hours</th>
<th>L.W.L. position</th>
<th>M.W.L. position</th>
<th>H.W.L. position</th>
<th>Dune foot position</th>
<th>Time hours</th>
<th>L.W.L. position</th>
<th>M.W.L. position</th>
<th>H.W.L. position</th>
<th>Dune foot position</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>-0.07</td>
<td>-</td>
<td>0.16</td>
<td>0.33</td>
<td>1.0</td>
<td>-0.25</td>
<td>-</td>
<td>0.18</td>
<td>0.68</td>
</tr>
<tr>
<td>1.5</td>
<td>-0.06</td>
<td>-</td>
<td>0.23</td>
<td>0.68</td>
<td>2.0</td>
<td>-0.22</td>
<td>-</td>
<td>0.29</td>
<td>0.74</td>
</tr>
<tr>
<td>2.5</td>
<td>-0.03</td>
<td>-</td>
<td>0.26</td>
<td>0.78</td>
<td>3.0</td>
<td>-0.11</td>
<td>-</td>
<td>0.31</td>
<td>0.84</td>
</tr>
<tr>
<td>3.5</td>
<td>0.01</td>
<td>-</td>
<td>0.30</td>
<td>0.83</td>
<td>4.0</td>
<td>-0.09</td>
<td>0.29</td>
<td>0.44</td>
<td>0.90</td>
</tr>
<tr>
<td>4.5</td>
<td>0.04</td>
<td>0.28</td>
<td>0.36</td>
<td>0.90</td>
<td>5.0</td>
<td>0.03</td>
<td>-</td>
<td>0.49</td>
<td>0.93</td>
</tr>
<tr>
<td>5.5</td>
<td>0.12</td>
<td>-</td>
<td>0.39</td>
<td>0.94</td>
<td>6.0</td>
<td>0.01</td>
<td>-</td>
<td>0.51</td>
<td>0.99</td>
</tr>
<tr>
<td>6.5</td>
<td>0.17</td>
<td>-</td>
<td>0.43</td>
<td>1.00</td>
<td>7.0</td>
<td>0.05</td>
<td>-</td>
<td>0.61</td>
<td>1.01</td>
</tr>
<tr>
<td>7.5</td>
<td>0.15</td>
<td>-</td>
<td>0.45</td>
<td>1.01</td>
<td>8.0</td>
<td>0.13</td>
<td>-</td>
<td>0.66</td>
<td>1.06</td>
</tr>
<tr>
<td>8.5</td>
<td>0.20</td>
<td>-</td>
<td>0.53</td>
<td>1.06</td>
<td>9.0</td>
<td>0.16</td>
<td>-</td>
<td>0.67</td>
<td>1.07</td>
</tr>
<tr>
<td>9.5</td>
<td>0.18</td>
<td>-</td>
<td>0.57</td>
<td>1.07</td>
<td>10.0</td>
<td>0.08</td>
<td>-</td>
<td>0.56</td>
<td>1.08</td>
</tr>
<tr>
<td>10.5</td>
<td>0.23</td>
<td>-</td>
<td>0.54</td>
<td>1.11</td>
<td>11.0</td>
<td>0.00</td>
<td>-</td>
<td>0.67</td>
<td>1.13</td>
</tr>
<tr>
<td>11.5</td>
<td>0.23</td>
<td>-</td>
<td>0.57</td>
<td>1.11</td>
<td>12.0</td>
<td>0.09</td>
<td>-</td>
<td>0.63</td>
<td>1.14</td>
</tr>
<tr>
<td>12.5</td>
<td>0.27</td>
<td>-</td>
<td>0.57</td>
<td>1.15</td>
<td>13.0</td>
<td>0.19</td>
<td>-</td>
<td>0.67</td>
<td>1.14</td>
</tr>
<tr>
<td>13.5</td>
<td>0.26</td>
<td>-</td>
<td>0.62</td>
<td>1.13</td>
<td>14.0</td>
<td>0.23</td>
<td>-</td>
<td>0.67</td>
<td>1.15</td>
</tr>
<tr>
<td>14.5</td>
<td>0.36</td>
<td>-</td>
<td>0.65</td>
<td>1.15</td>
<td>15.0</td>
<td>0.24</td>
<td>-</td>
<td>0.72</td>
<td>1.16</td>
</tr>
<tr>
<td>15.5</td>
<td>0.36</td>
<td>-</td>
<td>0.66</td>
<td>1.17</td>
<td>16.0</td>
<td>0.18</td>
<td>-</td>
<td>0.76</td>
<td>1.18</td>
</tr>
<tr>
<td>16.5</td>
<td>0.37</td>
<td>-</td>
<td>0.70</td>
<td>1.18</td>
<td>17.0</td>
<td>0.09</td>
<td>-</td>
<td>0.68</td>
<td>1.21</td>
</tr>
<tr>
<td>17.5</td>
<td>0.27</td>
<td>-</td>
<td>0.72</td>
<td>1.21</td>
<td>18.0</td>
<td>0.22</td>
<td>-</td>
<td>0.75</td>
<td>1.21</td>
</tr>
<tr>
<td>18.5</td>
<td>0.42</td>
<td>-</td>
<td>0.67</td>
<td>1.21</td>
<td>19.0</td>
<td>0.13</td>
<td>0.66</td>
<td>0.78</td>
<td>1.22</td>
</tr>
<tr>
<td>19.5</td>
<td>0.36</td>
<td>0.56</td>
<td>0.71</td>
<td>1.22</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

When these figures are plotted (figure 57) it is 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 \(19\frac{1}{2}\) hours 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 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 receded 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)

<table>
<thead>
<tr>
<th>Test number</th>
<th>Water level</th>
<th>Volume eroded from beach and dune</th>
<th>Volume deposited in inner bar zone</th>
<th>Volume deposited in outer bar zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>constant</td>
<td>0.396</td>
<td>0.143</td>
<td>0.141</td>
</tr>
<tr>
<td>T21</td>
<td>changing</td>
<td>0.374</td>
<td>0.215</td>
<td>0.172 (?)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Portion of profile</th>
<th>After H.W. 4 hours</th>
<th>After L.W. 4.5 hours</th>
<th>After H.W. 19 hours</th>
<th>After L.W. 19.5 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between dune foot and high water-line</td>
<td>1 in 4</td>
<td>1 in 5.5</td>
<td>1 in 5.5</td>
<td>1 in 7.2</td>
</tr>
<tr>
<td>Between dune foot and mean water-line</td>
<td>1 in 4.5</td>
<td>1 in 5.5</td>
<td>1 in 5.5</td>
<td>1 in 7.5</td>
</tr>
<tr>
<td>Between high and low water-lines</td>
<td>1 in 9</td>
<td>1 in 7</td>
<td>1 in 10</td>
<td>1 in 8</td>
</tr>
<tr>
<td>Between storm surge level (N.W.L.) and Normal water-line</td>
<td>1 in 10.5</td>
<td>1 in 10.5</td>
<td>1 in 14</td>
<td>1 in 13.5</td>
</tr>
</tbody>
</table>
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 T0 (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 53). 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 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, particularly for test T6.

**TABLE 5.41-1**

Dune recession for wind waves and regular waves (metres)

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Wave height cm</th>
<th>Wave period sec</th>
<th>Time-hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>T7 w</td>
<td>6.7</td>
<td>1.00</td>
<td>0.16</td>
</tr>
<tr>
<td>T22 r</td>
<td>6.6</td>
<td>1.04</td>
<td>0.25</td>
</tr>
<tr>
<td>T6 w</td>
<td>9.4</td>
<td>1.11</td>
<td>0.25</td>
</tr>
<tr>
<td>T23 r</td>
<td>8.9</td>
<td>1.16</td>
<td>0.25</td>
</tr>
<tr>
<td>T8 w</td>
<td>11.2</td>
<td>1.29</td>
<td>0.25</td>
</tr>
<tr>
<td>T24 r</td>
<td>10.9</td>
<td>1.29</td>
<td>0.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waterline recession metres</th>
<th>1/2</th>
<th>1</th>
<th>2</th>
<th>3/2</th>
<th>4/2</th>
<th>8</th>
<th>11</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>T7 w</td>
<td>0.16</td>
<td>0.18</td>
<td>0.20</td>
<td>0.24</td>
<td>0.27</td>
<td>0.28</td>
<td>0.37</td>
<td>0.34</td>
</tr>
<tr>
<td>T22 r</td>
<td>0.07</td>
<td>0.11</td>
<td>0.15</td>
<td>0.21</td>
<td>0.25</td>
<td>0.25</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td>T6 w</td>
<td>0.14</td>
<td>0.13</td>
<td>0.27</td>
<td>0.21</td>
<td>0.36</td>
<td>0.40</td>
<td>0.32</td>
<td>0.35</td>
</tr>
<tr>
<td>T23 r</td>
<td>0.08</td>
<td>0.15</td>
<td>0.16</td>
<td>0.20</td>
<td>0.22</td>
<td>0.30</td>
<td>0.32</td>
<td>0.40</td>
</tr>
<tr>
<td>T8 w</td>
<td>0.04</td>
<td>0.05</td>
<td>0.12</td>
<td>0.21</td>
<td>0.19</td>
<td>0.23</td>
<td>0.40</td>
<td>0.57</td>
</tr>
<tr>
<td>T24 r</td>
<td>0.16</td>
<td>0.13</td>
<td>0.20</td>
<td>0.29</td>
<td>0.27</td>
<td>0.33</td>
<td>0.43</td>
<td>0.49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dune foot recession metres</th>
<th>1/2</th>
<th>1</th>
<th>2</th>
<th>3/2</th>
<th>4/2</th>
<th>8</th>
<th>11</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>T7 w</td>
<td>0.34</td>
<td>0.40</td>
<td>0.42</td>
<td>0.52</td>
<td>0.55</td>
<td>0.54</td>
<td>0.62</td>
<td>0.63</td>
</tr>
<tr>
<td>T22 r</td>
<td>0.27</td>
<td>0.31</td>
<td>0.38</td>
<td>0.42</td>
<td>0.45</td>
<td>0.48</td>
<td>0.56</td>
<td>0.59</td>
</tr>
<tr>
<td>T6 w</td>
<td>0.46</td>
<td>0.50</td>
<td>0.60</td>
<td>0.60</td>
<td>0.74</td>
<td>0.78</td>
<td>0.72</td>
<td>0.78</td>
</tr>
<tr>
<td>T23 r</td>
<td>0.34</td>
<td>0.39</td>
<td>0.45</td>
<td>0.49</td>
<td>0.54</td>
<td>0.59</td>
<td>0.61</td>
<td>0.68</td>
</tr>
<tr>
<td>T8 w</td>
<td>0.64</td>
<td>0.64</td>
<td>0.75</td>
<td>0.79</td>
<td>1.17</td>
<td>1.03</td>
<td>1.18</td>
<td>1.21</td>
</tr>
<tr>
<td>T24 r</td>
<td>0.47</td>
<td>0.49</td>
<td>0.60</td>
<td>0.63</td>
<td>0.70</td>
<td>0.75</td>
<td>0.80</td>
<td>0.84</td>
</tr>
</tbody>
</table>

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 1 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 T6, 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 1/2 and 5 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. T6
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 T6 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 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
\( \frac{H_c}{T} \) was obtained in a similar way. The deepwater wave steepness parameter \( \frac{H_c}{T} \)
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 \( H_{\text{rms}} \) 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 T6 before the dune was
disturbed as mentioned above.
The relative dune erosion is however significantly greater during most of the remainder of test T6. It is evident however that this difference is not a function of wave steepness since T6 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 parameter 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 T6 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 runup 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 preceding 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  
(metres$^3$/metre)

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Wave height H$_{rms}$ (cm)</th>
<th>Wave period T (sec)</th>
<th>Time-hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>T6</td>
<td>9.4</td>
<td>1.11</td>
<td>0.034</td>
</tr>
<tr>
<td>T7</td>
<td>6.7</td>
<td>1.00</td>
<td>0.049</td>
</tr>
<tr>
<td>T8</td>
<td>11.2</td>
<td>1.29</td>
<td>0.152</td>
</tr>
</tbody>
</table>

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, $\frac{V}{H_0 T^2}$ or $\frac{V}{T^4}$, 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 $\frac{1}{T}$ 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 irregularity. 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

<table>
<thead>
<tr>
<th>Test number</th>
<th>Relative erosion volume ( \frac{V}{T^4} ) at ( \frac{t}{T} = 5 \times 10^4 )</th>
<th>Wave steepness ( \frac{H_0}{T^2} )</th>
<th>Wave irregularity ( \frac{H_{50}}{H_{15}} )</th>
<th>Wind velocity metres/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6</td>
<td>0.113</td>
<td>11.6</td>
<td>0.71</td>
<td>16.1</td>
</tr>
<tr>
<td>T7</td>
<td>0.126</td>
<td>9.9</td>
<td>0.76</td>
<td>11.6</td>
</tr>
<tr>
<td>T8</td>
<td>0.166</td>
<td>10.5</td>
<td>0.77</td>
<td>21.6</td>
</tr>
</tbody>
</table>

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 redresses 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 presumably 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 T6 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 T6 (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 T6 (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 T6 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 landward between the initial breakpoint at 7 to 7.5 metres and the main breakpoint 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 T3. Between 2 and 1.5 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 breakpoint 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 1.5 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 receding 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. **Influence of Sand Size upon Erosion and Profile Development**

5.51 **Waterline and Dune foot recession**

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 T0 (where the median sand size was 0.22 mm.) on the upper part of figure 78.

**TABLE 5.51-1**

<table>
<thead>
<tr>
<th>Sand Size</th>
<th>Dune Height</th>
<th>Time-hours</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>mm.</strong></td>
<td><strong>cm</strong></td>
<td><strong>1</strong></td>
</tr>
<tr>
<td>Dune Line</td>
<td>Recession</td>
<td>0.15</td>
</tr>
<tr>
<td>Dune Foot</td>
<td>Recession</td>
<td>n</td>
</tr>
</tbody>
</table>

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 5½ 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 T0 is considered instead of test T0 (see table 5.21-1).

5.52 **Sand Volumes eroded**

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 T0 (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

<table>
<thead>
<tr>
<th>Sand Size mm.</th>
<th>Dune Height cm</th>
<th>Time-hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>40</td>
<td>3/4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.073</td>
</tr>
</tbody>
</table>

5.53 Profile Changes and Development of Equilibrium Profile

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 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, i.e., 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 T25 (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, i.e., 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, i.e., 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 metres indicating increased sand movement between the inner and outer bars (figure 89). The curves showing the transport along the profile at 5½ and 8 hours (figure 90) also clearly indicate that the transport rate increases significantly from about 5½ 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\(\frac{3}{4}\)) with fine sand than with coarse sand (1 in 5\(\frac{3}{4}\)). 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 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 available. The relevant data are presented on figures 92 and 79 to 87.

At the commencement 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 \( \tan \alpha = 0.25, \text{ ie, } 1 \text{ in } 4 \), 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 (\(\tan \alpha = 0.067\)). 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 39). 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 3½ 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 3½ 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 steadily 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 %, i.e., 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 14½ 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 T0, T0', 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 T0 (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 T28 this process is followed by the development of spilling breakers with a relatively constant reflection of the order of 64 at 9½ 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 1/2 metres at all times and a main breakpoint further inshore whose position shifts seaward from 3 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.

5.6.2 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 T16 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 Daniel (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 0.65, and it appears that the destruction 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 30%. These are somewhat high when compared with experimental reflection coefficients for similar slopes and wave conditions (e.g. those of Crealou 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 investigators (references 16 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 $H = 0.78D$ does not express the wave height within the surf zone. Thus should it be desired to use the theoretical calculation of wave runup 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)

\[
Y_E = D + \frac{H^2}{16D} \frac{2D'}{\sinh 2D'}
\]  

(5.621 a)

where \( D' = \frac{2 \pi D}{L} \)

In deep water

\[
Y_E = D
\]  

(5.621 b)

and in shallow water

\[
Y_E = D + \frac{H^2}{16D}
\]  

(5.621 c)

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

\[
h = - (Y_E - D)
\]  

(5.621 d)

where \( h \) is positive upwards from the deepwater still water level.

Whence

\[
h = - \frac{H^2}{16D} \frac{2D'}{\sinh 2D'}
\]  

(5.621 e)

In the surf zone we have

\[
h = - Y_E + D + h_L = - \frac{H_M^2}{16D} \frac{2D'}{\sinh 2D'}
\]  

(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 landward 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 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 headlands (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 T0, T mean, Hmax, H_15, H_50, Hrms and \( \frac{H_{50}}{H_{15}} \) 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 \( \frac{H}{L} \), \( \frac{H}{D} \), \( \frac{H}{D} \) and \( \frac{H}{L} \) were calculated. The data are plotted on figure 102 in two different graphs. In the upper one \( \frac{H}{D} \) is plotted as a function of \( \frac{L}{D} \) while on the lower \( \frac{H}{L} \) is plotted as a function of \( \frac{D}{L} \).
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 \( H_{\text{max}}, \text{etc.} \)) both the shallow water parameter \( H/D \) and the deep water one \( H/L \) tend to a constant value depending upon the \( L/D \) or \( D/L \). In shallow water \( L/D > 7 \) 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

<table>
<thead>
<tr>
<th>Wave height</th>
<th>( H/D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_{\text{max}} )</td>
<td>0.75</td>
</tr>
<tr>
<td>( H_{15} )</td>
<td>0.52</td>
</tr>
<tr>
<td>( H_{50} )</td>
<td>0.41</td>
</tr>
<tr>
<td>( H_{\text{rms}} )</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The value of \( H/D \) for \( H_{\text{max}} \) approaches 0.78, the theoretical value for a solitary wave on a level bottom. Individual values of \( H_{\text{max}} \) give somewhat higher values of \( H/D \) which are none the less reasonable when the effects of both refraction 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

<table>
<thead>
<tr>
<th>Wave Height</th>
<th>H/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{max}$</td>
<td>0.135</td>
</tr>
<tr>
<td>$H_{15}$</td>
<td>0.094</td>
</tr>
<tr>
<td>$H_{50}$</td>
<td>0.067</td>
</tr>
<tr>
<td>$H_{rms}$</td>
<td>0.047</td>
</tr>
</tbody>
</table>

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 concerned 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 variation in the limiting steepness. It is obvious that this perfectly reasonable result is not without significance when comparisons are made between model and prototype situations and the values given in table 5.62.2-2 above which are true for $\frac{H_{50}}{H_{15}} = 0.72$ should be interpreted with care.

For instance data given by Wiegel (reference 50) indicate that when the significant wave height $H_{1/3}$ ($\approx H_{13}$) and the mean deep water wave length are used to define the steepness, the latter has a value of the order of $\frac{1}{11.4}$ or 0.088, i.e. 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 56). In this case $H_{1/3} \approx 0.38 D$ 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 5.62.1-1. 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 ratio $\frac{H}{D}$ 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, i.e., 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 bevel. 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 $H_o/L$ (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. $H_o/H = 0$). 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

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Number of observations</th>
<th>Wave-height $H_o$ - cm</th>
<th>Wave period $T$ - sec</th>
<th>Runup height $R$ - cm</th>
<th>Beach slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>5 x 9</td>
<td>19.5</td>
<td>1.63</td>
<td>8.5</td>
<td>1 in 5.1</td>
</tr>
<tr>
<td>T0’</td>
<td>9</td>
<td>19.5</td>
<td>1.63</td>
<td>8.8</td>
<td>5.4</td>
</tr>
<tr>
<td>T4</td>
<td>9</td>
<td>17.6</td>
<td>1.63</td>
<td>8.2</td>
<td>5.3</td>
</tr>
<tr>
<td>T19</td>
<td>1</td>
<td>15.4</td>
<td>1.56</td>
<td>5.5</td>
<td>9.7</td>
</tr>
<tr>
<td>T20</td>
<td>2</td>
<td>10.7</td>
<td>1.56</td>
<td>6.5</td>
<td>5.8</td>
</tr>
<tr>
<td>T22</td>
<td>2</td>
<td>9.8</td>
<td>1.04</td>
<td>4.2</td>
<td>5.9</td>
</tr>
<tr>
<td>T23</td>
<td>2</td>
<td>13.4</td>
<td>1.16</td>
<td>4.9</td>
<td>5.2</td>
</tr>
<tr>
<td>T24</td>
<td>9</td>
<td>18.2</td>
<td>1.29</td>
<td>6.4</td>
<td>5.6</td>
</tr>
<tr>
<td>T7</td>
<td>9</td>
<td>9.9</td>
<td>1.00</td>
<td>5.3</td>
<td>4.8</td>
</tr>
<tr>
<td>T6</td>
<td>9</td>
<td>14.3</td>
<td>1.11</td>
<td>7.7</td>
<td>5.0</td>
</tr>
<tr>
<td>T8</td>
<td>8</td>
<td>17.3</td>
<td>1.29</td>
<td>11.2</td>
<td>5.8</td>
</tr>
</tbody>
</table>

**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 $H_{rms}^{0.707}$. 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 $\frac{R}{H_0}$ 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

<table>
<thead>
<tr>
<th>Test Number</th>
<th>$\frac{R}{H_0}$</th>
<th>$\frac{(\frac{R}{H_0})_W}{(\frac{R}{H_0})_R}$</th>
<th>$\frac{0.707}{\frac{H_{15}}{H_{rms}}}$</th>
<th>Inshore $H_1$</th>
<th>Offshore $H_2$</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>T7</td>
<td>0.54</td>
<td>1.26</td>
<td>1.52</td>
<td>1.42</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td>T22</td>
<td>0.43</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>0.54</td>
<td>1.47</td>
<td>1.54</td>
<td>1.43</td>
<td>1.45</td>
<td></td>
</tr>
<tr>
<td>T23</td>
<td>0.37</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T8</td>
<td>0.65</td>
<td>1.85</td>
<td>1.50</td>
<td>1.33</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>T24</td>
<td>0.35</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Consideration of the parameters which influence wave breaking suggested that either of the parameters $\frac{X_b}{D_b}$, $\frac{X_b}{T^2}$, or $\frac{X_b}{D_b}$ might vary in a systematic manner with the wave steepness $\frac{H_0}{T^2}$. 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 $\frac{H_0}{T^2}$, 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 (micromolen) 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 break point 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 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 as those near the bottom.

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 shorward 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 correlation 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:

\[
\text{u}_{\text{max}} \frac{H}{T} = \frac{\cosh \frac{2 \pi}{L} (D + z)}{\sinh \frac{2 \pi D}{L}}
\]

where \(\text{u}_{\text{max}}\) 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 \(\frac{\text{u}_{\text{max}}}{H}\) 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 \(\frac{\text{u}_{\text{max}}}{H}\) 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 \(\frac{\text{u}_{\text{max}}}{H}\) 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 T6 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 T6 (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 steadily 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 \( \frac{H_0}{T_w} \) (see section 3.31). They will of course then be more readily moved in suspension cut 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 T6 (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 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 seaward 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 this 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 ($H_0 = 1.2$ 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 breakpoint, 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 distribution (e.g. $H_{15}$, $H_{50}$ and $H_{rms}$) also approach similar but lower constant limiting values in deep and shallow water. The magnitude of the latter limiting 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 rundown $\frac{H}{H_0}$ at a given wave steepness $\frac{H_0}{L_0}$ is less than for a similar smooth slope due primarily to increased energy dissipation within the surf zone. The relative wave rundown 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


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.


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).


