CHAPTER 122

MOVABLE BED MODEL TESTS ON DUNE EROSION

by

P. Vellinga*

1 Introduction

The primary sea defence system of the Netherlands consists for a large part of sandy beaches and dunes. The row of dunes, however, is rather narrow in some places, due to long-term erosion, and reinforcement has become necessary (Figure 1 and 2). In this connection a special governmental committee requested the co-operation of the Delft Hydraulics Laboratory to developed a design criterion for a dune sea defence system that could withstand a storm surge with a frequency of occurrence of once in 10,000 years (Figure 3). For that purpose all available field observations on dune erosion were analysed and a provisional, empirical, guide-line was developed in 1972 [1], but because of the limited amount of field data and the complexity of a theoretical approach it was decided to check the validity of this guide-line by means of a model investigation.

As no adequate scaling relationships are available for movable bed models with waves, the tests were set up in the form of a scale series. A large number of two-dimensional tests with various geometric scales using two types of sand (D_{50} = 225 µm and D_{50} = 150 µm) was carried out in 1975. Simple relations were assumed for the model distortion n_l/n_d (length scale over depth scale) and for the morphological time scale n_t, namely:

$$n_l/n_d = n_d^{\alpha}; \; n_t = n_d^{\beta},$$

in which α and β are constants, while n represents prototype value over model value. The values of α and β were determined by a correlation analysis and the following relations were found for $n_D = 1$: $n_l/n_d = n_d^{0,28}$; $n_t = 1$. Consequently the scale of the dune erosion quantity per unit length of coast is

$$n_A = n_l \, n_d = (n_d)^{2.28}.$$

On the assumption that these relations are also valid outside the scale range used, a prototype value for the dune erosion was found [1]. The model tests, however, produced a number of scale effects especially as prototype sands were used leading to profiles that were steeper than in the field. Although these scale effects have been implied by the scaling relations, the prototype result was very sensitive to minor changes in the empirically determined distortion relation. Therefore additional tests were carried out with finer sands to reduce the distortion of the model and consequently to increase the reliability of the prototype result. It is the results of these tests which are described in this paper.

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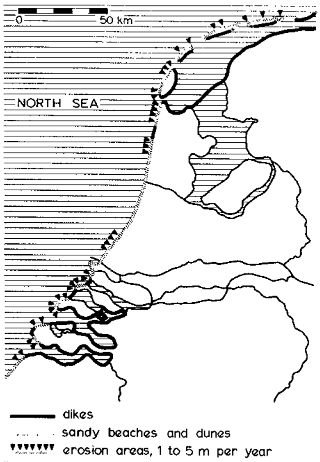


Fig. 1 Dutch coast, erosional areas

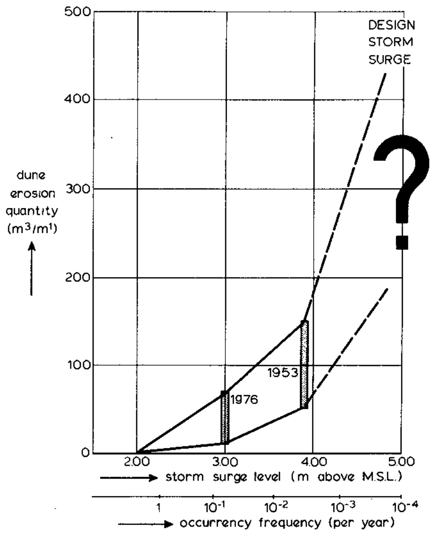


Fig 3 field measurements of dune erosion
how much erosion will occur under design storm surge conditions ?

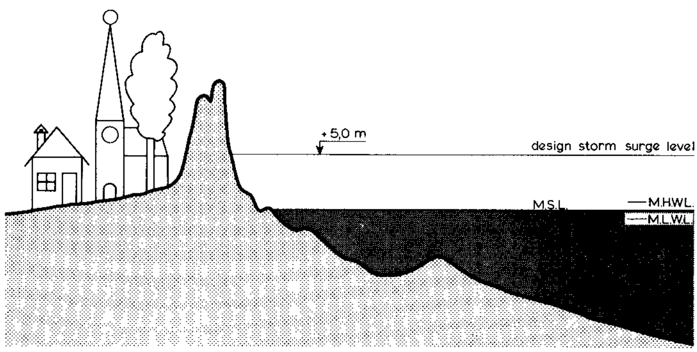


Fig 2 typical Dutch coastal profile

2 Scaling relations

The problems of scale effects in beach process modelling are not new, and especially geometric similarity in beach profile development has been given much attention. Kemp [2] suggested a distortion relation of the form $n_l/n_d = (n_d)^{\alpha}$ with $0.45 < \alpha < 0.65$, while Noda [3] found from his experiments with various materials: $n_l/n_d = (n_d)^{0.32} (n_\gamma)^{-0.386}$ in combination with $n_D(n_\gamma)^{1.85} = (n_d)^{0.55}$; ($\gamma$ is the specific weight of sediment and D is the sediment size D_{50}). Saville [4], Saville and Watts [5], Kohler and Galvin [6] and Dean [7] stress the importance of the dimensionless fall velocity parameter H/Tw for the description of beach profile development, while theoretical and practical considerations lead Dalrymple and Thompson [8] to recommend n(H/Tw) = 1 as most promising scaling relation for the modelling of beach processes.
(H = wave height, T = wave period, w = fall velocity of sediment particles).

From the earlier tests on dune erosion with two types of sand Van de Graaff found indeed that the results from different sands compared very well using the H/Tw concept. Therefore the present tests have been carried out with the finer sands, assuming that equal H/Tw values imply geometrically similar profile development.

In fact, the condition n(H/Tw) = 1 could not be entirely satisfied for the design storm surge in view of the grainsize of the available fine sand and the possible model scales. Consequently a distortion of the model could not be prevented, the value of which can in the first instance be deduced from the requirement of kinematical similarity $n_l/n_d = n_u/n_w$ [9] (u = horizontal orbital velocity). Since the waves are reproduced according to Froude's Law, this relation can be written as $n_l/n_d = (n_d/n_w^2)^{0.5}$. In case $n_w = 1$ the relation $n_l/n_d = n_d^{0.5}$ follows, which agrees again with Kemp [2]. However, from the previous series it was found that $n_l/n_d = n_d^{0.28}$ is more realistic. Thus for different types of sand the relation $n_l/n_d = (n_d/n_w^2)^{\alpha}$ with α = 0.28 would follow. The empirical exponent α incorporates any scale effect in sediment entrainment, wave breaking, wave run-up, etc.

3 Model tests

To check the suggested scaling relations for the finer sands a total of 24 tests was made, covering four types of sand and three different depth scales. The tests were carried out in the wind-wave flume of the Laboratory De Voorst (see Figures 4 and 5). Hydraulic prototype conditions as shown in Figure 6 were reproduced in all tests. The Pierson Moscowitch spectrum was used for the description of the wave field. The water level was kept constant at the maximum storm surge level because the time-scale of the morphological process is not fully understood. For each depth scale and each type of sand two tests were run with different initial profile steepness (see Table 1).

4 Test Results

During the tests the erosion profile was recorded at various times, and the results are shown in Figures 7 to 30, for the part of the profile that shows major changes and for the length of time with heaviest erosion. As can be seen from these plots, the profile-changes at a water depth greater than ½ H_{0s} are relatively small; bars and troughs are formed at a later stage. An portant phenomenon to be noticed from these recordings is that for tests with equal sand and depth scale, the form of the eroded coastal profile is independent of the initial profile. The erosion quantity above storm

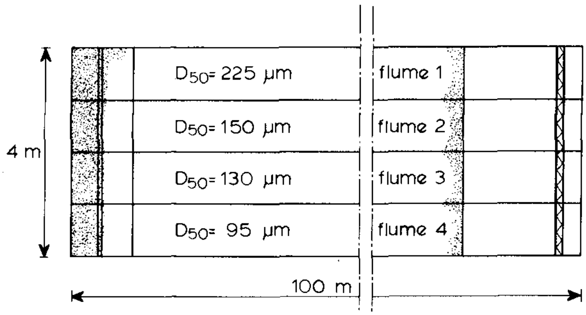


Fig. 4 plan view of model

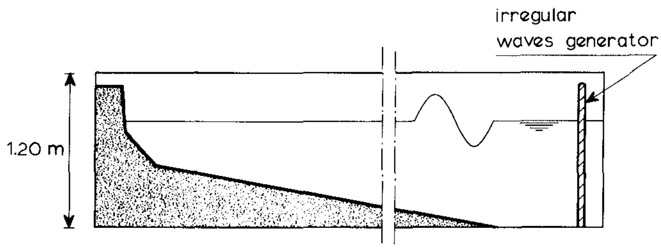


Fig. 5 cross-section of model

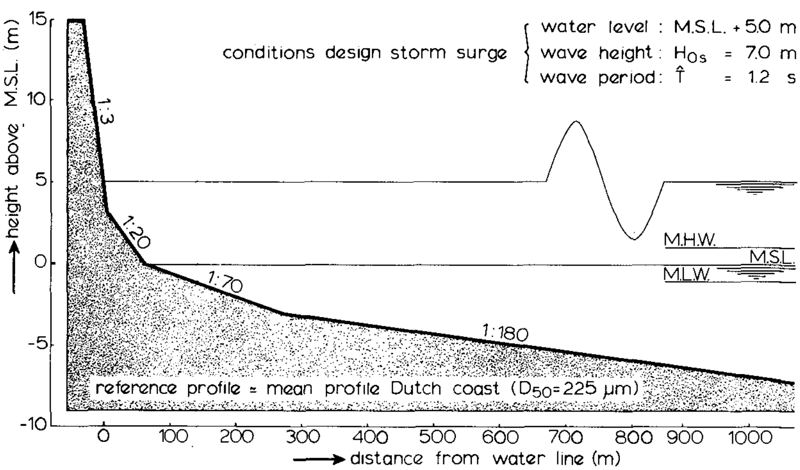


Fig. 6 reference profile and design storm surge conditions

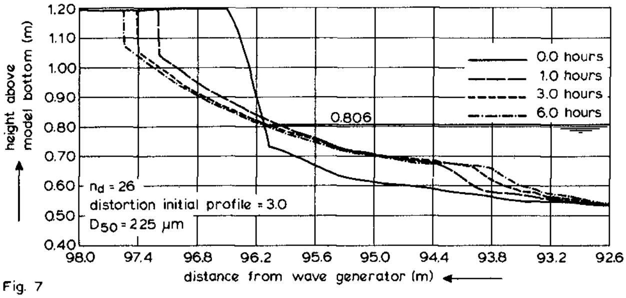


Fig. 7

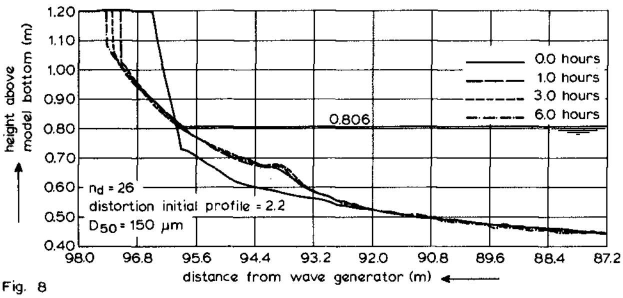


Fig. 8

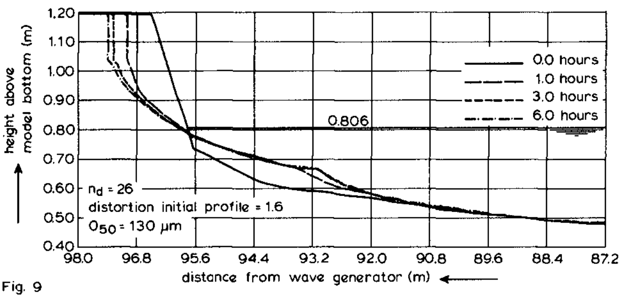


Fig. 9

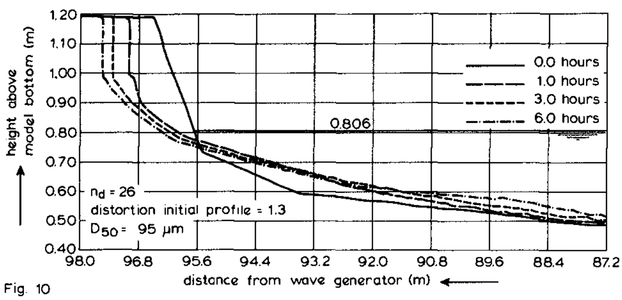


Fig. 10

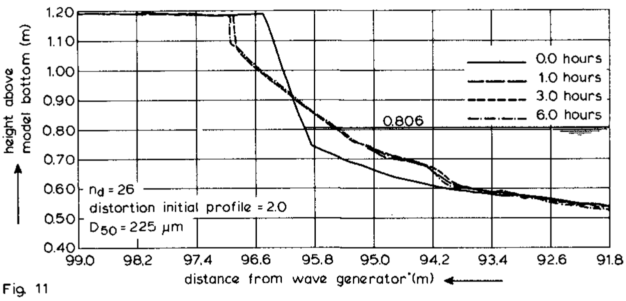


Fig. 11

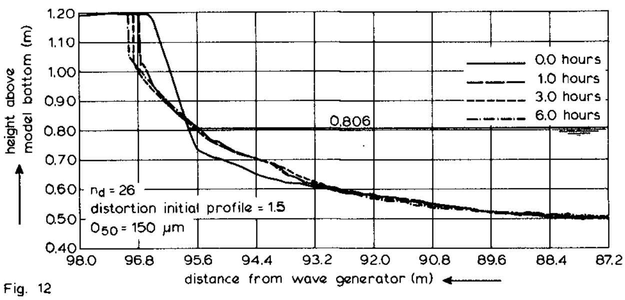


Fig. 12

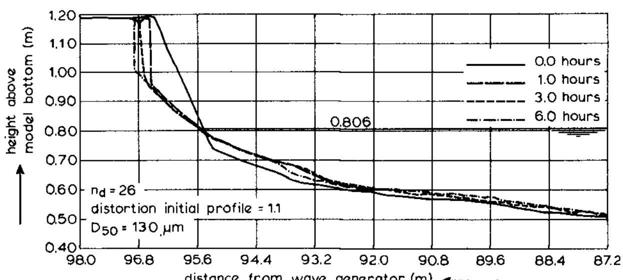


Fig. 13

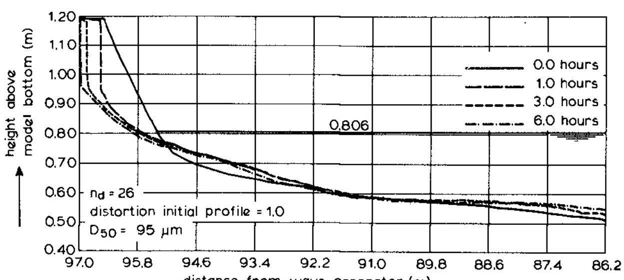


Fig. 14

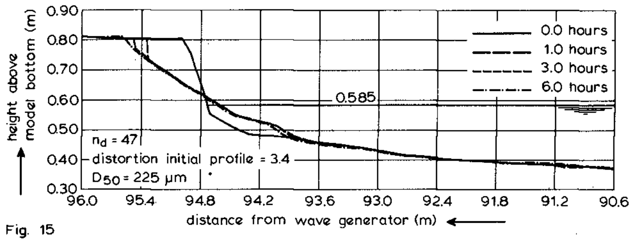


Fig. 15

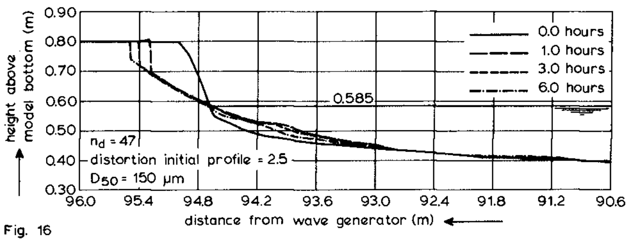
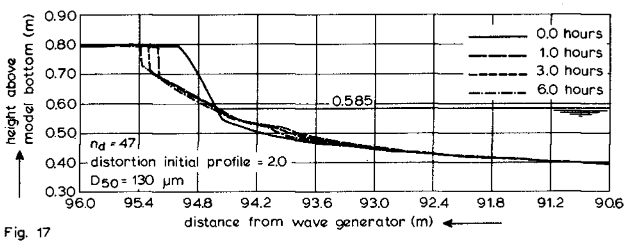


Fig. 16



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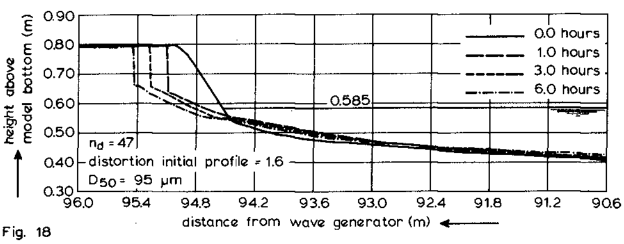

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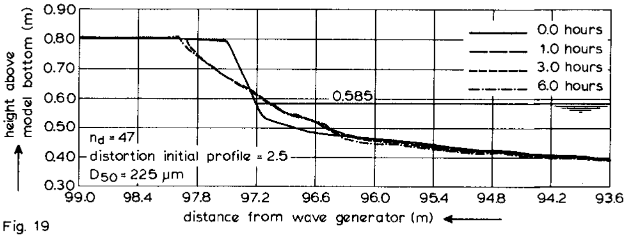

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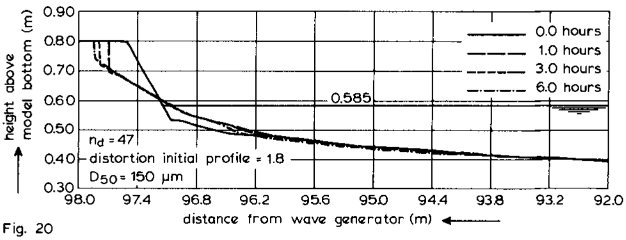

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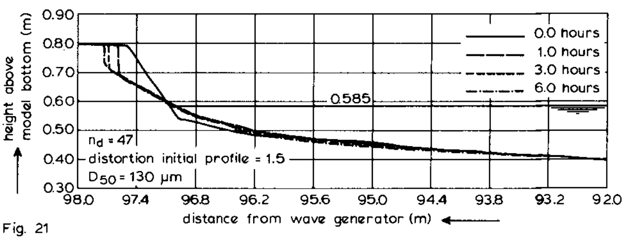

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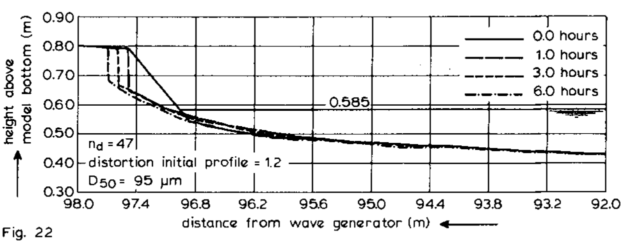

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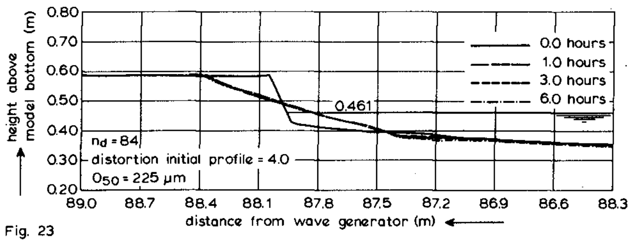

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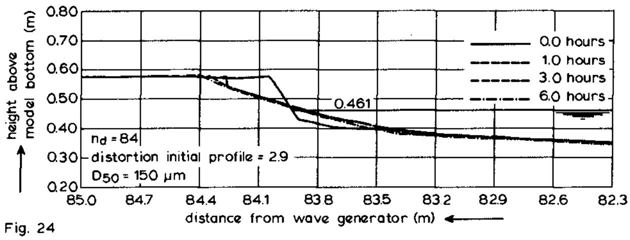

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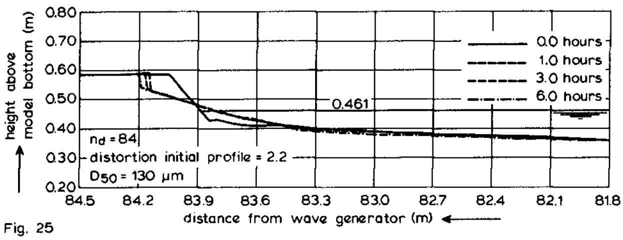

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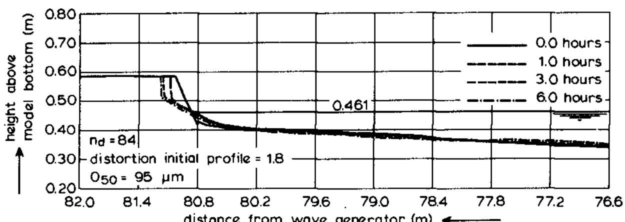

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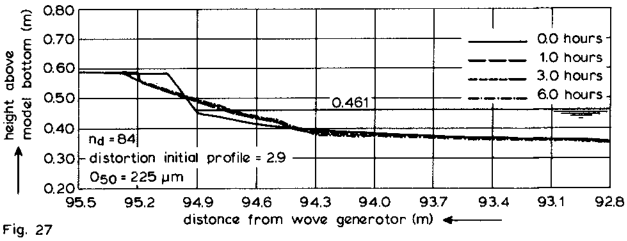

Fig. 27

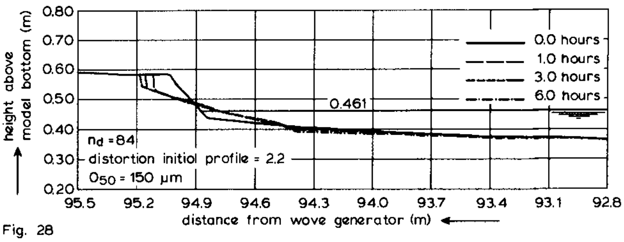

Fig. 28

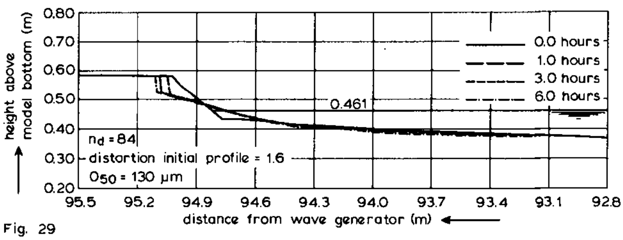

Fig. 29

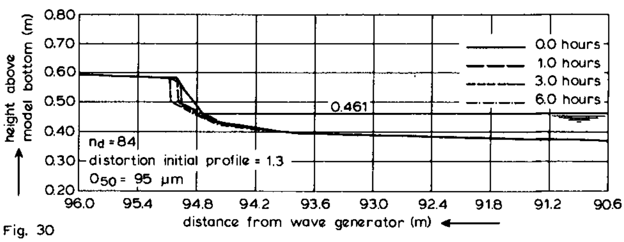

Fig. 30

surge level has been computed from these recordings, and the cumulative result is shown in Table 1. As from the first recording it was found that the initial profile was not in all cases reproduced as desired, a corrected steepness factor has been introduced (see Table 1). Other phenomena have also been recorded, like wave height, grainsize, ripples and water temperature.

From the wave height recordings it appears that close to the wave generator the significant wave height shows some scatter but is generally reasonably in accordance with scale; further down the flume, however, the wave height decreases considerably and is no longer exactly to scale (see Tables 1 and 2).
The bottom sediment, sampled at t = 40 hrs, was found to be the coarsest just seaward of the still water line.
The ripples were measured at t = 6 hrs (see Table 3); but a clear variation pattern could not be determined.
The water temperature was 12 ± 3° C for all tests.

5 Conversion of model results to prototype

The scaling relations established in the earlier scale series, combined with the dimensionless fall velocity parameter, are:

$n_t = 1$ and $n_l/n_d = (n_d/n_w{}^2)^{0.28}$.

A reasonable agreement among the erosion quantities was found when all test results were converted to prototype with these scaling relations. A closer look, however, revealed that the erosion quantities, as well as the profile forms, from the tests with finer sands showed a clear dependency with the depth scale. This indicated that the α-value for the finer sands may not equal 0.28. Therefore a correlation analysis to find the optimal combination of time scale and distortion relationship, as described in [1], was carried out for each individual type of sand.

6 Correlation analysis of test results

The erosion quantities above storm surge level were taken as a basis to determine the "best" value of the empirical exponents in the relations $n_l/n_d = (n_d)^\alpha$ and $n_t = n_d{}^\beta$. For a certain β-value each α-value gives a correlation coefficient for the conformity of the erosion quantities of the tests with the different depth scale factors. The analysis was carried out for discrete model time-steps that, taking the time scale into account, fell within the relevant time period for dune erosion in the field (2 to 10 hours).
Each time step provided a "best" α-value and a corresponding maximum correlation coefficient. To find the "best" combination the average of the maximum correlation coefficients for the relevant time period has been plotted as a function of the value of β. In Figures 31 to 34 this graph is shown for the present tests, while in Figures 35 and 36 the results are shown for the combination of the present tests and the previous ones with coarser sands. The "best" combination of α and β can be seen to vary with the type of sand. An important trend to be noticed is that for the finer sands the best morphological time scale approaches the hydrodynamical time scale. Regarding the coarser sands, it was found that the differences in correlation coefficient are hardly significant when the hydrodynamical time scale is compared with the formerly found time scale $n_t = 1$. Therefore the time scale with more physical background $n_t = (n_d)^{0.5}$ was chosen for further elaboration of all tests results.

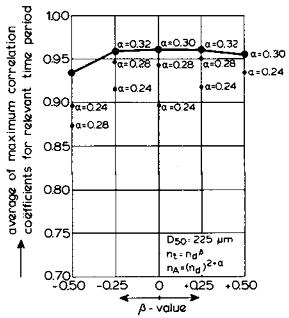

Fig. 31

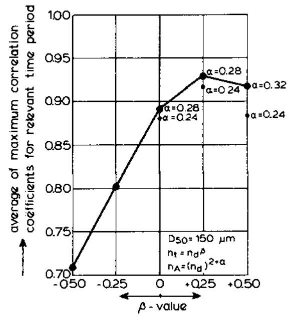

Fig. 32

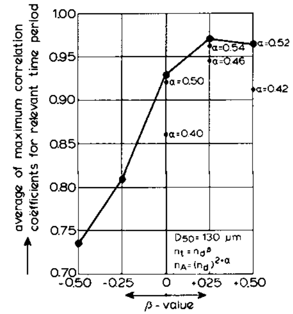

Fig. 33

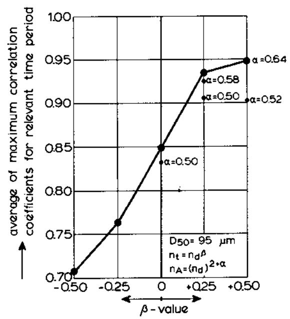

Fig. 34

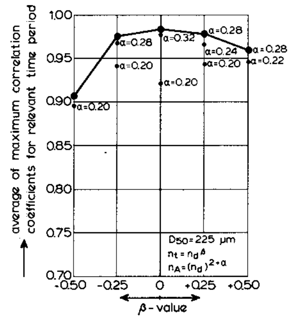

Fig. 35 present and earlier tests

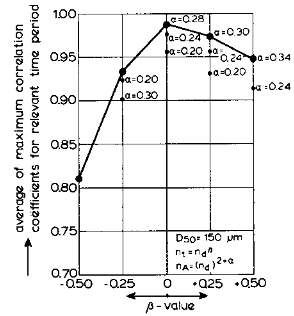

Fig. 36 present and earlier tests

Fig. 31 ... 36 Results of correlation analysis

The "best" α-values found for this time scale are shown in the mentioned graphs. It appears that α increases with decreasing particle diameter and that the "theoretical" value of 0.5 is approached for the finer sands. This seems logical, because the suspended transport with finer sands is more predominant than with coarser sands and thus the theoretical distortion relation based on kinematical similarity for a suspended particle should be more valid.

7 Discussion of the results

From the fact that the α-value was found to be a function of the absolute fall velocity of the sand particles it may be concluded that the dimensionless fall velocity parameter does not apply for the comparison of the test results. The higher α-values, however, may have purely physical reasons and perhaps the substitution of the significant deep water wave height H_{0s} and the spectrum top period $\hat{T}$ and the fall velocity in stagnant water w in the H/Tw parameter is too simple. A better parameter may be something like H_*/Tw or H/Tw_* in which H_* is some function of H in the breaker zone and w_* is an adjusted fall velocity under breaking waves. However, the limited number of tests prohibited the determination of such adjusted parameters for the conversion of the model results to prototype values.

Another cause of the varying α-values may be the fact that the wave height recorded just outside the breaker zone was not exactly to scale due to wave height attenuation along the flume. This attenuation has been greater for tests with greater depth scale factors and finer sands, and so this phenomenon may have led to an overestimation of the α-value. Therefore, renewed analysis based on a H_{br}/Tw parameter in which H_{br} is determined from the actual wave recordings may well be more succesful. Especially because this will lead to lower values of α for the finer sands there is a chance that a unique value for α will be found covering all types of sand. To carry out this analysis a large number of corrections has to be carried out because the scales of wave height, wave period and initial profile do not correspond. Consequently any prototype result found after such a correction would have a limited reliability.

For practical reasons, therefore, a simple approach has been made. Given a prototype situation that is to be reproduced to scale. It is assumed that the best tests to be performed are those with a H/Tw value equal to that in prototype. Unfortunately such tests could not be performed in the available model facility due to wave height and grainsize limitations. Therefore a series of tests were carried out with various types of sand on various depth scales covering a range of smaller H/Tw values. Subsequently the results of these tests were extrapolated, for each type of sand separately, to imaginary tests having the required H/Tw value. The results obtained that way were converted to prototype by means of lineair scaling ($n_l = n_d$) as follows from the H/Tw concept.

The elaboration of the test results as indicated above can be summerized by means of the scaling relation $n_l/n_d = (n_d/n_w{}^2)^{\alpha}$ in which α is dependent on the type of sand and has values as already found from the correlation analysis.

8 Conversion to prototype with renewed scaling relations

The result of the conversion to prototype with the tentative scaling relations is rather good. Only the results from the tests with the second

finest sand (D_{50} = 130 μm) fall a little apart. The reliability of the α-value applied for this type of sand is relatively low due to the small number of tests. Therefore a correction based on the extrapolation of the α-values for the coarser sands with reference to the finest sand seems acceptable.
The ultimate α-values to be applied now are shown below, together with the corresponding grain sizes and fall velocities (from the Shore Protection Manual for 10° C [6]):

D_{50}	μm	225	150	130	95
fall velocity	m/s	0.0250	0.0130	0.0100	0.0060
α-value	-	0.28	0.34	0.40	0.64

The prototype results show greater conformity now; the erosion quantities are shown in Figure 37. On the horizontal axis the value 1 refers to model tests with an initial profile related to the prototype reference profile with the scaling relation $n_l/n_d = (n_d/n_w{}^2)^{\alpha}$. And thus the corresponding erosion refers to the average profile along the Dutch coast. Automatically the tests with initial profiles a factor S steeper than required correspond to prototype profiles a factor S steeper than the reference profile.

Also the erosion profiles have been converted to prototype, as shown in Figure 38. The water line has been chosen as a reference. Above this line the conformity is rather poor, but below it the erosion profiles agree very well. It should be borne in mind that comparison is only valid for the part of the profile that has really changed, thus to a depth of about ½ H_{0s} (see Figures 7 to 30).

9 Evaluation

The conformity among the erosion quantities and the erosion profiles for prototype conditions gives support to the applied scaling relations. Regarding the actual prototype erosion quantities to be expected, it should be stated that a correction for the actual wave height in the model as suggested before will lead to lower α-values and consequently to smaller prototype erosion quantities.

The consequences for the prototype erosion caused by the uncertainty in the derived α exponent is shown in Figure 39. In this graph the prototype erosion quantity for the reference profile, derived from the tests with depth scale factor n_d = 26, is shown as a function of the α-value. The difference in prototype erosion for α-values between of 0.5 and 0.3 is only 20% for the finest sand.

From the model tests with prototype sand the corresponding difference is found to be 400%, and so it must be concluded that the reliability of the model tests has been greatly increased by the additional tests with very fine sands.

10 Reproduction of stormsurge 1953

To verify the H/Tw parameter in a different manner, a final test was carried out. The 1953 storm surge, of which some prototype observations were available, was reproduced in the model. For this test α-values were not of any

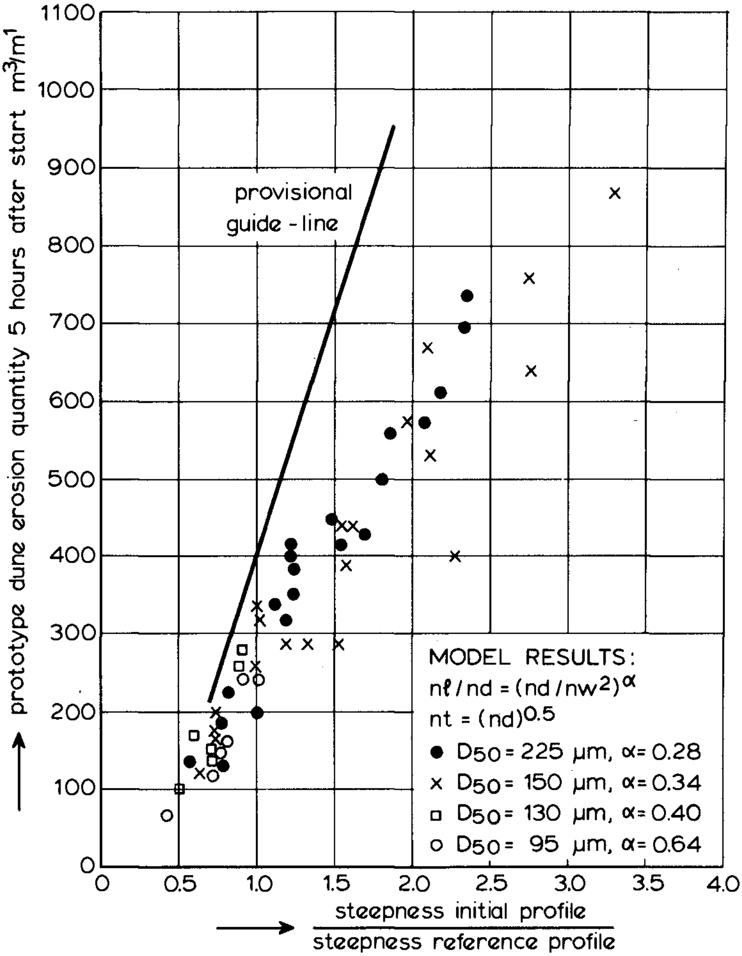

Fig. 37 prototype erosion quantity, model result compared with empirical guide - line

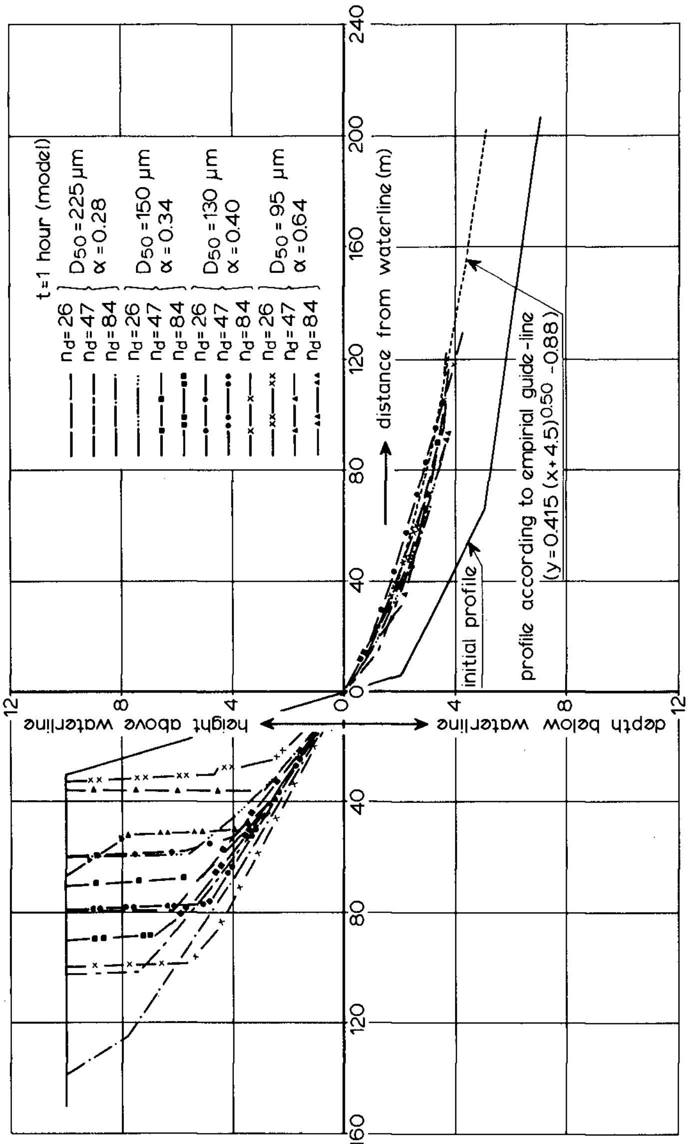

Fig. 38 prototype erosion profile

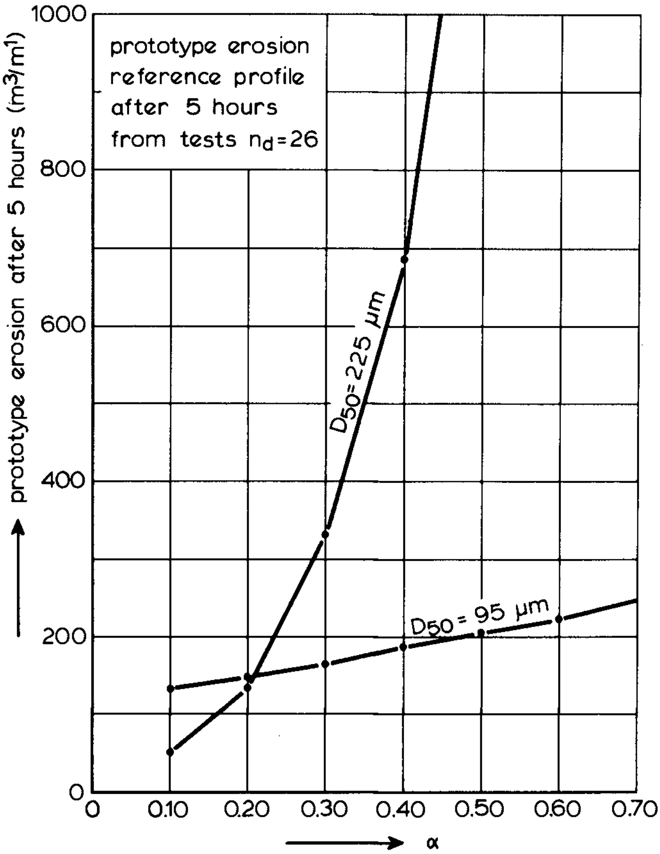

Fig. 39 prototype erosion as a function of α importance because the H/Tw-value of the field conditions could be obtained in the model and consequently a profile distortion was not necessary. The field conditions showing a maximum storm surge level of 3.9 m above M.S.L., a wave height H_{0s} = 5.0 m, and a beach sand with w = 0.025 m/s have been reproduced with depth scale factor $n_d = 17$, thus $n_d = n_l = n_T^2 = n_w^2 = n_u^2 = 17$. Unfortunately the varying wave and water level conditions were reproduced on the formerly established time scale $n_t = 1$, because the time scale $n_t = n_d^{0.5}$ was not yet recognized at this stage of the model investigations. The final erosion quantity found from this test, and also the deliberately corrected quantity for $n_t = (n_d)^{0.5}$, fell within the range of quantities measured in the field, with the corrected value fitting best. Also the erosion profile agreed rather well with the field measurements, and therefore it must be concluded that this test supports the validity of the dimensionless fall velocity parameter H/Tw for small-scale modelling of beach processes.

11 Conclusions

- Results of model tests on dune erosion with very fine sand support the validity of the dimensionless fall velocity parameter H/Tw for small-scale modelling of beach processes.

- If the requirement n(H/Tw) = 1 cannot be satisfied in the model, a profile distortion based on kinematical similarity $n_l/n_d = n_u/n_w = (n_d/n_w^2)^\alpha$ with $\alpha = 0.5$, gives good results for the finer sands. For coarser sands (D_{50} = 130 - 225 μm) values of α ranging from 0.5 to 0.3 are found.

- A morphological time-scale equal to the hydrodynamical time scale $n_t = n_d^{0.5}$ is most plausible in view of the scaling of the fall velocity. This is supported by the model results of tests with very fine sand ($D_{50} \simeq 100$ μm) and irregular waves.

- For the gentle beach profiles along the Dutch coast the model results support the earlier-developed and presently-used "provisional guide-line for dune erosion". For the steeper profiles, the model results fall below this guide-line.

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test number	sand size D_{50} in µm	fall velocity at 10° C in m/s	depth scale factor n_d	distortion initial profile (S)		water depth (m)	wave characteristics		time of sounding after start of test (hours) cumulative dune erosion quantity above storm surge level 10^{-4} m³/m¹									
				desired	actual		H_{0s} (m)	$\bar{T}$ (sec)	hours	0.1	0.3	1.0	3.0	6.0	10.5	16.5	25.5	40.0
111	225	0.0250	84	4.0	3.90	0.461	0.091	1.31	erosion	124	132	148	158	150	174	206	248	334
115	225	0.0250	84	2.9	2.71	0.461	0.091	1.31	erosion	51	52	59	51	37	32	36	49	87
112	150	0.0130	84	2.9	2.93	0.461	0.091	1.31	erosion	77	104	162	176	176	249	313	411	542
116	150	0.0130	84	2.2	1.89	0.461	0.091	1.31	erosion	37	56	66	72	95	117	145	199	282
113	130	0.0100	84	2.2	2.09	0.461	0.091	1.31	erosion	44	56	91	95	116	170	193	229	306
117	130	0.0100	84	1.6	1.44	0.461	0.091	1.31	erosion	46	47	55	76	101	145	191	256	310
114	95	0.0060	84	1.8	2.00	0.461	0.091	1.31	erosion	21	49	85	145	191	320	389	484	584
118	95	0.0060	84	1.3	1.18	0.461	0.091	1.31	erosion	21	25	58	95	165	242	312	443	496
101	225	0.0250	47	3.4	3.50	0.585	0.163	1.76	erosion	383	449	510	600	651	760	872	1034	1303
105	225	0.0250	47	2.5	2.45	0.585	0.163	1.76	erosion	308	331	366	395	419	468	523		838
102	150	0.0130	47	2.5	2.44	0.585	0.163	1.76	erosion	465	571	636	776	865	975	1153	1381	1843
106	150	0.0130	47	1.8	1.79	0.585	0.163	1.76	erosion	253	320	415	478	529	603	753	936	1225
103	130	0.0100	47	2.0	2.02	0.585	0.163	1.76	erosion	377	469	540	634	754	903	1093	1337	1682
107	130	0.0100	47	1.5	1.62	0.585	0.163	1.76	erosion	216	261	336	396	448	547	703	910	1197
104	95	0.0060	47	1.6	1.73	0.585	0.163	1.76	erosion	318	473	646	956	1300	1648	2151	2662	2979
108	95	0.0060	47	1.2	1.40	0.585	0.163	1.76	erosion	244	266	411	552	739	995	1314	1774	2271
121	225	0.0250	26	3.0	3.08	0.806	0.292	2.35	erosion	1425	1838	2250	2914	3230	3623	3916	4141	3832
125	225	0.0250	26	2.0	1.95	0.806	0.292	2.35	erosion	870	1052	1107	1265	1230	1260	1328	1349	1611
122	150	0.0130	26	2.2	2.30	0.806	0.292	2.35	erosion	1327	1751	2207	2670	2734	2688	2747	2743	3027
126	150	0.0130	26	1.5	1.48	0.806	0.292	2.35	erosion	493	1015	1293	1634	1690	1677	1729	1813	1946
123	130	0.0100	26	1.6	1.62	0.806	0.292	2.35	erosion	978	1543	2345	3129	3464	3624	3836	4079	4077
127	130	0.0100	26	1.1	1.10	0.806	0.292	2.35	erosion	520	779	1435	1964	2253	2300	2470	2606	3099
124	95	0.0060	26	1.3	1.32	0.806	0.292	2.35	erosion	911	1610	2781	3891	4644	5183	5369	5323	5439
128	95	0.0060	26	1.0	1.04	0.806	0.292	2.35	erosion	585	1175	1898	2673	3108	3943	4538	4729	4775

Table 1 Test conditions and resulting erosion quantities

t	X	test number			
		111	112	113	114
		H_s	H_s	H_s	H_s
hours	m	m	m	m	m
3.25	24	0.087	0.083	0.084	0.080
3.50	40	0.085	0.080	0.079	0.079
4.00	76	0.073	0.072	0.067	0.056
4.25	71	0.074	0.075	0.068	0.060
4.50	66	0.077	0.076	0.069	0.064
4.75	61	0.076	0.074	0.070	0.067
5.00	56	0.074	0.073	0.071	0.067
5.25	51	0.076	0.073	0.073	0.068

t	X	test number			
		115	116	117	118
		H_s	H_s	H_s	H_s
hours	m	m	m	m	m
0.50	24	0.096	0.093	0.094	0.089
0.75	40	0.087	0.084	0.083	0.082.
1.25	89.50	0.073	0.068	0.064	0.052
1.50	86.50	0.077	0.072	0.068	0.054
1.75	83.50	0.076	0.072	0.066	0.055
2.00	80.50	0.076	0.071	0.066	0.058
2.25	77.50	0.080	0.077	0.071	0.062
2.50	74.50	0.084	0.076	0.073	0.067
2.75	71.50	0.079	0.075	0.071	0.064

t	X	test number			
		101	102	103	104
		H_s	H_s	H_s	H_s
hours	m	m	m	m	m
0.40	24	0.154	0.148	0.147	0.139
0.70	45	0.148	0.142	0.139	0.134
1.25	80	0.134	0.128	0.130	0.118
1.50	83	0.141	0.139	0.129	0.119
1.75	86	0.133	0.125	0.122	0.107
2.00	89	0.133	0.129	0.115	0.109
2.25	92	0.116	0.106	0.101	0.094
3.25	80	0.127	0.125	0.123	0.113
3.50	75	0.139	0.131	0.131	0.123
3.75	70	0.131	0.126	0.127	0.120
4.00	65	0.138	0.135	0.136	0.128
4.25	60	0.139	0.133	0.130	0.127

t	X	test number			
		105	106	107	108
		H_s	H_s	H_s	H_s
hours	m	m	m	m	m
0.75	45.00	0.164	0.159	0.159	0.146
1.25	94.50	0.120	0.110	0.105	0.079
1.50	91.50	0.130	0.118	0.112	0.097
1.75	88.50	0.134	0.125	0.116	0.109
2.00	85.50	0.140	0.132	0.125	0.119
2.25	82.50	0.144	0.138	0.130	0.114
2.50	45.00	0.164	0.156	0.160	0.147
2.75	24.00	0.161	0.154	0.152	0.145
4.00	73.50	0.147	0.141	0.137	0.124
4.25	68.50	0.154	0.146	0.143	0.127
4.50	63.50	0.158	0.151	0.147	0.134
4.75	58.50	0.146	0.140	0.136	0.128
5.00	53.50	0.155	0.147	0.145	0.135

t	X	test number			
		121	122	123	124
		H_s	H_s	H_s	H_s
hours	m	m	m	m	m
0.24	20.00	0.298	0.298	0.295	0.288
0.42	65.00	0.276	0.290	0.262	0.235
1.30	70.00	0.282	0.276	0.260	0.231
1.45	75.00	0.250	0.245	0.228	0.218
2.00	80.00	0.262	0.250	0.223	0.199
2.15	85.00	0.250	0.227	0.216	0.184
2.30	90.00	0.220	0.199	0.187	0.175
3.15	65.00	0.277	0.280	0.263	0.236
3.30	60.00	0.283	0.282	0.277	0.243
3.45	55.00	0.262	0.267	0.264	0.253
4.00	50.00	0.279	0.284	0.281	0.272
4.15	45.00	0.278	0.290	0.286	0.283
4.30	40.00	0.287	0.292	0.291	0.283
4.45	35.00	0.278	0.276	0.280	0.271
5.00	20.00	0.302	0.305	0.307	0.295

t	X	test number			
		125	126	127	128
		H_s	H_s	H_s	H_s
hours	m	m	m	m	m
2.00	20.00	0.295	0.291	0.298	0.298
2.15	45.00	0.285	0.282	0.262	0.260
2.30	70.00	0.243	0.235	0.215	0.212
4.15	50.00	0.280	0.278	0.256	0.253
4.30	55.00	0.284	0.266	0.254	0.242
4.45	60.00	0.265	0.257	0.232	0.225
5.00	65.00	0.267	0.252	0.228	0.217
5.15	70.00	0.250	0.243	0.217	0.211
5.30	75.00	0.250	0.234	0.192	0.191
6.15	93.50	0.185	0.159	0.126	0.129
6.30	90.50	0.204	0.175	0.165	0.135
6.45	87.50	0.200	0.189	0.181	0.164
7.00	84.50	0.214	0.203	0.182	0.185
7.15	81.50	0.232	0.208	0.188	0.184
7.30	78.50	0.247	0.219	0.197	0.194
7.45	75.50	0.244	0.229	0.203	0.189

Table 2 Wave height recordings

t is time after start, X is distance from wave generator, H_s is significant wave height

	test number	depth scale factor	distortion initial profile	average ripple height (cm) H_r	standard deviation σ_H(cm)	average ripple length (cm) L_r	standard deviation σ_{L_r} (cm)	L_r/H_r
D_{50} = 225 µm	111	84	3.90	1.25	0.097	6.78	0.931	0.184
	115	84	2.71	1.25	0.161	6.69	0.836	0.187
	101	47	3.50	1.58	0.137	9.65	0.827	0.164
	105	47	2.45	1.54	0.113	9.37	0.636	0.164
	121	26	3.08	1.31	0.299	10.30	0.852	0.127
	125	26	1.95	1.50	0.197	10.67	0.948	0.141
D_{50} = 150 µm	112	84	2.93	0.99	0.159	5.94	0.331	0.167
	116	84	1.89	1.02	0.054	5.65	0.319	0.181
	102	47	2.44	1.11	0.025	7.15	0.405	0.155
	106	47	1.79	1.09	0.081	7.12	0.241	0.153
	122	26	2.30	0.94	0.098	7.32	0.920	0.128
	126	26	1.48	1.07	0.101	7.41	0.526	0.144
D_{50} = 130 µm	113	84	2.09	0.96	0.067	5.47	0.318	0.176
	117	84	1.44	0.90	0.107	5.41	0.354	0.166
	103	47	2.02	0.99	0.032	6.59	0.500	0.151
	107	47	1.62	1.01	0.082	6.49	0.503	0.156
	123	26	1.62	0.84	0.078	6.67	0.418	0.126
	127	26	1.10	0.91	0.088	6.59	0.440	0.138
D_{50} = 95 µm	114	84	2.00	0.75	0.084	4.50	0.391	0.167
	118	84	1.18	0.77	0.103	4.51	0.488	0.171
	104	47	1.73	0.77	0.105	5.30	0.421	0.145
	108	47	1.40	0.78	0.036	5.30	0.247	0.147
	124	26	1.32	0.68	0.181	6.21	0.713	0.110
	128	26	1.04	0.84	0.120	6.22	0.378	0.135

Table 3 Recordings of ripples