waterloopkundig laboratorium
delft hydraulics laboratory

beach and dune erosion during storm surges

P. Vellinga

publication no. 276

August 1982

beach and dune erosion during storm surges

P. Vellinga

publication no. 276

August 1982

BEACH AND DUNE EROSION DURING STORM SURGES

by P. Vellinga *)

ABSTRACT

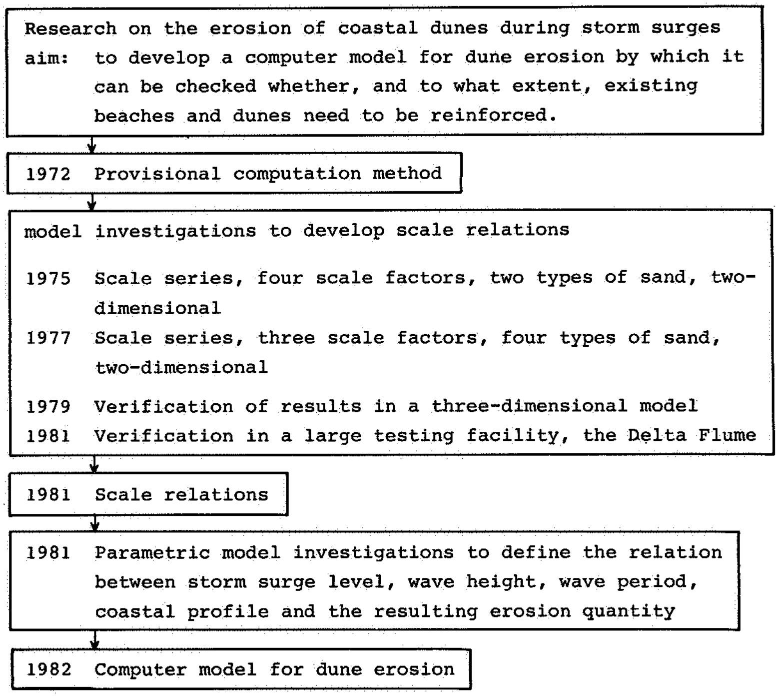
This paper presents the set-up and results of an extensive research programme concerning the erosion of coastal dunes during storm surges. A large number of two-dimensional and three-dimensional mobile bed model tests has been carried out to investigate the process of dune erosion. The state of art after a series of small scale tests is summarized. Attention is focussed on large scale tests carried out in the Delta Flume with random waves up to 2 m significant height. Sediment concentration and orbital velocity measurements are discussed. The large scale tests have confirmed the validity of a modelling technique based on the dimensionless fall velocity parameter H/Tw. The model results are being applied to check the safety of existing coastal dunes as a water-retaining structure that has to protect the major part of the Netherlands from inundation during storm surges.

*) Deputy Head Harbours and Coasts Branch
Delft Hydraulics Laboratory

INTRODUCTION

Most of the inhabitants of the Netherlands live well-below storm surge level. The population and also industrial facilities are only protected from the sea by a narrow stretch of sandy beaches and dunes. At some places along the coast the row of dunes is thinning down due to long term erosion. Reinforcement works will be required to maintain their vital function. The question is how wide must the row of dunes be to withstand the design storm surge.

Research activities on this subject have been carried out at the Delft Hydraulics Laboratory for many years. The research programme since 1972 is shown in Table 1.



Research on the erosion of coastal dunes during storm surges
aim: to develop a computer model for dune erosion by which it can be checked whether, and to what extent, existing beaches and dunes need to be reinforced.

1972 Provisional computation method

model investigations to develop scale relations

1975 Scale series, four scale factors, two types of sand, two-dimensional
1977 Scale series, three scale factors, four types of sand, two-dimensional
1979 Verification of results in a three-dimensional model
1981 Verification in a large testing facility, the Delta Flume

1981 Scale relations

1981 Parametric model investigations to define the relation between storm surge level, wave height, wave period, coastal profile and the resulting erosion quantity

1982 Computer model for dune erosion

Table 1 Research on the erosion of coastal dunes during storm surges

The framework and the results of this programme will be presented in this paper. Most attention will be paid to the large scale tests that have been carried out in the recently constructed Delta Flume at De Voorst Laboratory. Besides, the following items will be discussed:

1. Dune erosion mechanism;
2. Sediment concentrations and return-flow velocities;
3. Effect of fall velocity on beach profile slope;
4. General applicability of the derived scale relations.

PROVISIONAL COMPUTATION METHOD

The question "how wide must the dunes be" can also be put as "how much dune erosion will occur under design storm surge conditions". A provisional answer to this question has come from the analysis of field observations of dune erosion. Storm surge levels and recorded erosion quantities for major storm surges since 1894 are shown in Figure 1. The highest storm surge, 1953, caused a dune erosion quantity of about 100 m^3/m^1, this corresponds with a recession of the dune front of 10 m to 20 m. It was observed after the storm surge that a more or less uniform beach profile had developed along the coast. Beach profiles with a similar form had been found after less severe storm surges. This information has been the basis of a provisional dune erosion model. The following assumptions had to be made to obtain a well defined computational method:

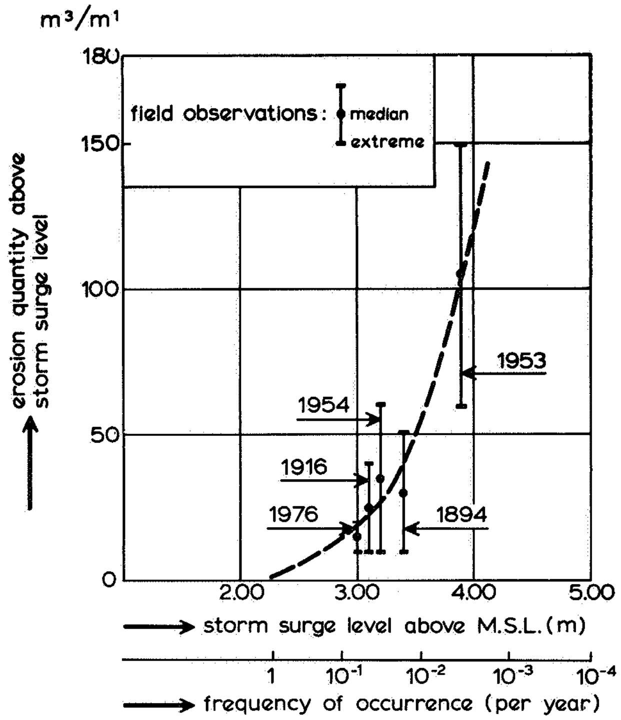
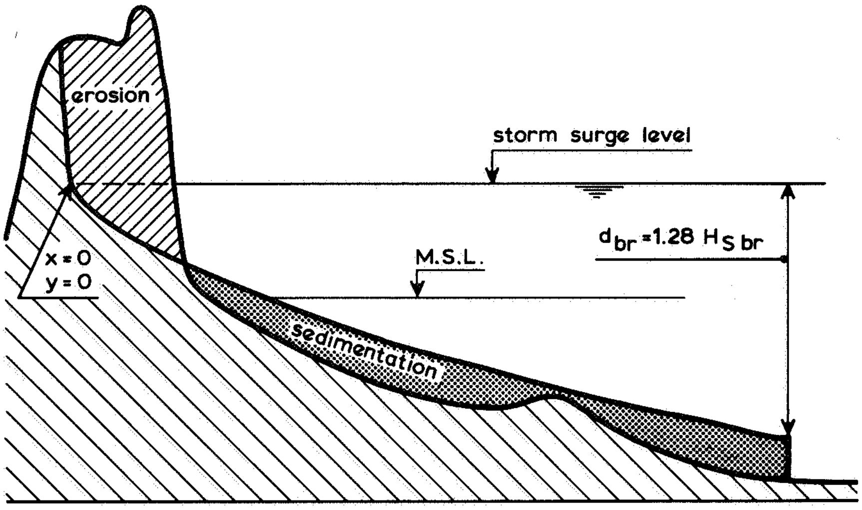


Fig. 1 Storm surge levels and erosion quantities at Delfland since 1894

- The beach profile recorded after the 1953 storm surge will also be present after higher storm surges.
- The level of the erosion profile is directly determined by the storm surge level (in this paper defined as the maximum water level during the storm surge).
- The profile will be developed from the post storm dune front up to a water depth of 1.28 H_{0s} below storm surge level.
- There is a mass balance of sand in the profile perpendicular to the coast.

The principle of the dune erosion model is shown in Figure 2. The erosion profile should be shifted in a landward direction until the erosional area equals the depositional area. The model was developed in 1972 by Van de Graaff (1977) and until now has been used to check the safety of the dunes. However, the model is still regarded as a provisional one as it is based on assumptions

that are rather speculative, especially in view of the vital importance of a reliable storm surge protection.
It was decided therefore to investigate the process of dune erosion more thoroughly by means of model experiments as a theoretical approach was considered impracticable.



uniform erosion profile $y = 0.415\ (x + 4.5)^{0.5} - 0.88$ (x and y in m)
seaward limit of sand distribution $d_{br} = 1.28\ H_{S\,br}$
erosion area = sedimentation area

Fig. 2 Principle of the provisional computation method

TWO-DIMENSIONAL MODEL TESTS

As no adequate scale relations were available a series of two-dimensional model tests was carried out with four different scale factors and two types of sand. The set up and the results of the tests were published by Van de Graaff (1977). A summary is presented below.

The schematized coastal profile and the storm surge conditions for the situation in prototype are shown in Figure 3. The profile shows a gently sloping beach with sandy dunes up to M.S.L. +15 m. The design storm surge conditions are characterized by a storm surge level of M.S.L. +5.0 m and deep water wave conditions with H_{0s} = 7.6 m and wave period, top of spectrum, $\hat{T}$ = 12 s. For reproduction in the model the following scale factors for depth were applied: n_d = 150, n_d = 84, n_d = 47 and n_d = 26. Two types of sand were used as bed material: D_{50} = 225 μm and D_{50} = 150 μm. Wave conditions were scaled according to Froude. It was anticipated that the model should be distorted for an adequate reproduction, therefore various length scale factors were applied for the reproduction of the initial profile. The philosophy of the scale series is illustrated in Figure 4. Scale relations were developed on the basis of a curve fitting of erosion quantities and erosion profiles. A prototype value was found by application of the best fit scale relations.

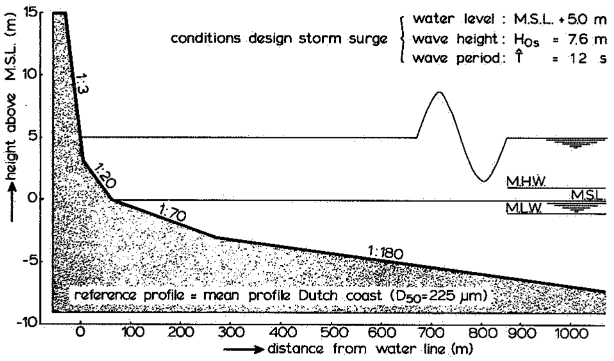


Fig. 3 Schematized coastal profile

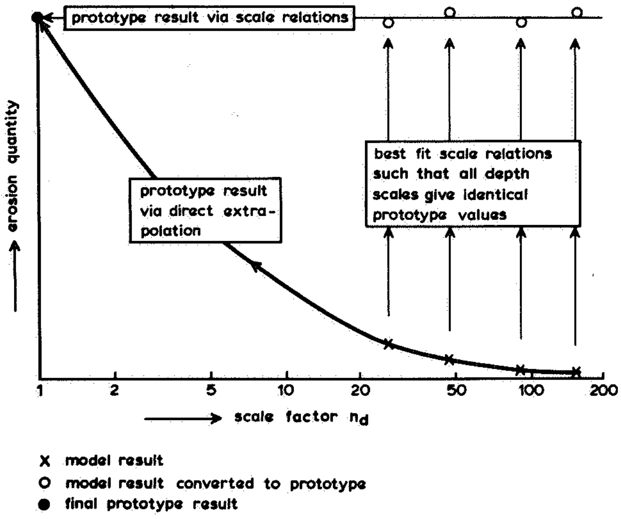


Fig. 4 Philosophy of a scale series

The approach to study the process of dune erosion by means of a scale series was considered successful. However, considerable scale effects were still observed and the gap between $n_d = 26$ and $n_d = 1$ is relatively large. Model tests in the range from $n_d = 26$ to $n_d = 1$ would be required to improve the reliability of the extrapolation. However, model facilities with random waves larger than the one already used were not available at that time. So, more ingenious ways had to be found.

The model tests described above had demonstrated that tests with equal deep water wave steepness H_o/L_o and equal H/Tw value show geometrically similar erosion profiles (H is significant wave height, T is wave period $\hat{T}$ and w is the fall velocity of the bottom material). In other words finer sand has the same effect on profile development as higher waves (with equal steepness). Others have also suggested this effect: Saville (1950), Kemp and Plinston (1968), Saville and Watts (1969), Noda (1972), Dean (1973), Dalrymple and Thompson (1976), Noda (1978), and Gourlay (1980).

Using this effect the behaviour of the model for depth scales between $n_d = 26$ and $n_d = 1$ could be investigated in an imaginary way using very fine sands in the model. The set-up and the results of such tests have been published by Vellinga (1978). A summary of the results is presented as follows:

Twenty-four tests were carried out covering four types of sand and three scale factors. The prototype situation as indicated in Figure 3 was reproduced with the depth scale factors $n_d = 84$, $n_d = 47$ and $n_d = 26$. Sands with $D_{50} = 225$ µm, $D_{50} = 150$ µm, $D_{50} = 130$ µm and $D_{50} = 95$ µm were applied in the model. The results of the tests with the various types of sand confirmed the dimensionless fall velocity parameter, in combination with the Froude scale for wave conditions, as a similarity parameter for the reproduction of beach profile changes during a storm surge. Consequently the tests with fine sand could be converted into imaginary tests of a larger scale.
By doing so a new set of tests was generated ranging from $n_d = 84$ up to $n_d = 2.3$. Various methods of curve fitting were applied to derive the best fit scale relations. Finally the following relations were found:

$$n_t = (n_d)^{0.5} \quad (1)$$

$$n_l/n_d = (n_d)^{0.28} \quad (2)$$

$$n_l/n_d = (n_d/n_w^2)^{0.28} \quad (3)$$

in which:
n_t = time scale factor for the morphological process
n_d = depth scale factor for beach profile and hydraulic conditions
n_l = length scale factor for beach profile
n_w = scale factor for the fall velocity of the sand (D_{50})
n = prototype value over model value.

Relation (1) has been found to be independent of sand size. Relation (2) describes the required distortion as a function of the depth scale for situations with sand from prototype in the model ($n_w = 1$). Relation (3) describes the required model distortion as a function of the depth scale and the fall velocity scale. An undistorted model can be applied when the fall velocity of the bottom material has the same scale as the orbital velocity u:

$$n_w = n_u = (n_d)^{0.5} \tag{4}$$

Relation (3) differs from the results presented by Vellinga (1978) where it was suggested that the exponent in the distortion relation would be a function of the sand size. A re-analysis of all test results revealed that a systematic relation had been present between the wave height attenuation outside the breaker zone and the depth scale of the model, due to the layout of the model. After leaving out the tests that had suffered a wave height attenuation of more than 15%, the value of the exponent appeared to be constant after all, see Delft Hydraulics Laboratory (1981).

The initial profiles tested in the model relate to the reference profile shown in Figure 3 with various combinations of scale factors for length and depth. Relation (3) shows that for a given bottom material just one combination is correct. Still, the results of tests with initial profiles that do not satisfy (3) can be used. Namely, the initial profiles with a distortion that is a factor S larger than required, automatically refer to initial profiles in prototype that are a factor S steeper than the reference profile. From the model tests it was found that a more or less linear relation exists between the steepness of the initial profile and the resulting erosion quantity. This relation is shown in Figure 5 for all tests after a conversion to prototype. S = 1 corresponds with the reference profile shown in Figure 3, S = 2 refers to an inital profile that is twice as steep. The result of the computations with the provisional computation method are also indicated. The results of the model tests are presented for the stage at five hours after start, prototype, which is considered relevant for the erosion process during a storm surge in situ.

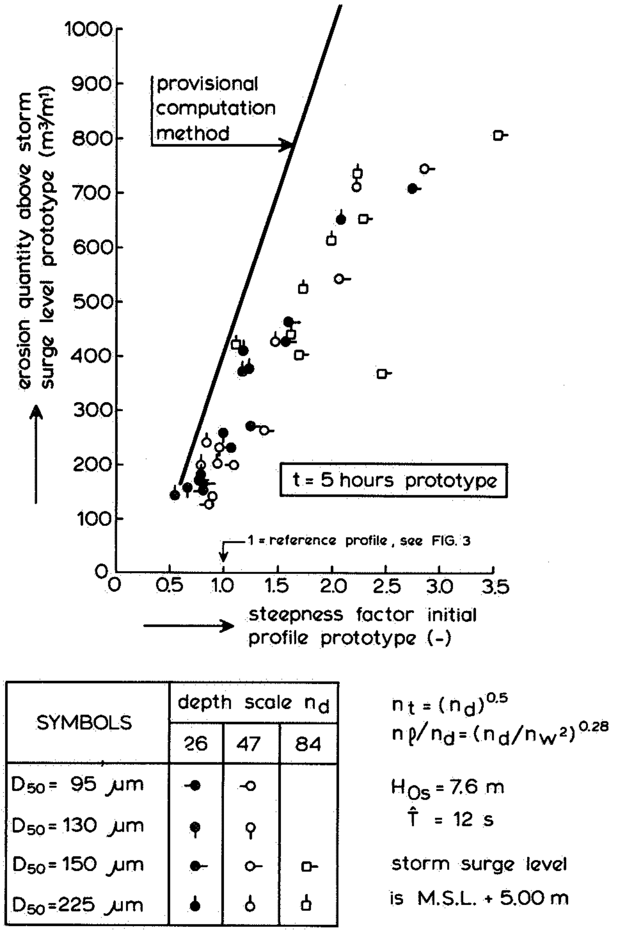


Fig. 5 Initial profile and erosion quantity

THREE-DIMENSIONAL MODEL TESTS

It had been assumed so far that the erosion process during a storm surge can be considered as a two-dimensional process. This assumption was supported by observations in the field. Always, after high storm surges, a straight dune front and rather uniform beach profiles were found along the coast. The assumption is also plausible for situations without a longshore sand transport gradient considering the mass balance of sand. However, there existed no explicit proof of the hypothesis that longshore currents and rip currents will not intensify the erosion rate and not create an irregular erosion pattern. Therefore, three-dimensional model tests were carried out to verify the two-dimensional approach.

In a basin 30 m by 30 m with a 0.38 m water depth, the design storm surge conditions and the erosion process were reproduced with $n_d = 60$ and $n_w = 3$. The length scale of the model was found from (3):

$$n_l/n_d = (n_d/n_w^2)^{0 \cdot 28} \quad \text{consequently:} \quad n_l = 102$$

Wave angles of $\Theta_o = 0^0$, $\Theta_o = 10^0$ and $\Theta_o = 20^0$ were applied in the model, where Θ_o stands for the angle between the shoreline and the wave crests at a water depth of 22.8 m prototype.

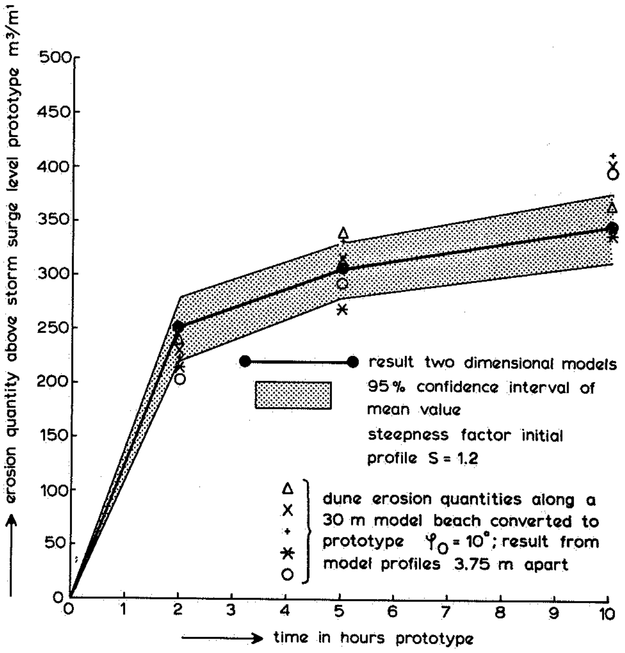


Fig. 6 Dune erosion in two- and three-dimensional models

During the tests no significant variations were observed in the erosion process along the 30 m model beach. As an example the erosion quantities as a function of time are shown in Figure 6 for $\Theta_o = 10^0$ together with the results of the two dimensional models. It can be seen that the results agree favourably. As a similar agreement was found for $\Theta_o = 0^0$ and $\Theta_o = 20^0$ it was concluded that a two-dimensional reproduction is fully acceptable, see Delft Hydraulics Laboratory (1981).

LARGE SCALE MODEL TESTS

So far rather promising results had been found, showing that the development of a new computational dune erosion model was within reach which would lead to a more reliable and possibly a more economic design of dunes and dune reinforcements. However, ever present doubts concerning the validity of small scale models in view of the vital importance of a reliable sea defence system, made it hard to decide on a new computational model. The best verification of the small scale model results would be a very high storm surge in situ. The frequency of a storm surge yielding useful results, however, is about once in a lifetime.
Fortunately at that time a large-scale model facility became available that enabled a nearly full-scale verification of the results (see Figures 7 and 8).

In total five tests were carried out in the large wave flume, see also Table 2:

- Three tests to verify the scale relations with $n_d = 5$.
- One test with $n_d = 3.3$ as a reproduction of the field conditions of the 1953 storm surge, to make a final check on the validity of the model.
- One test to be considered as a full scale reproduction of a moderate storm surge.

test number	hydraulic conditions	water depth in front of wave generator d(m)	wave height at depth d H_s(m)	wave period at depth d $\hat{T}$(s)	initial profile	depth scale n_d	length scale n_l
1	constant	4.20	1.50	5.4	S prototype = 1.91 *)	5	7.85
2	constant	4.20	1.50	5.4	S prototype = 1.27 *)	5	7.85
3	variable	4.20(max)	1.50(max)	5.4(max)	S prototype = 1.27 *)	5	7.85
4	variable	4.20(max)	1.85(max)	5.0(max)	Delfland-profile	3.27	4.56
5	constant	5.00	2.00	7.6	arbitrary profile	1	1

*) S prototype = 1.91 means that the initial prototype profile is a factor 1.91 steeper than the profile shown in Figure 3

Table 2 Programme of large scale tests

Fig. 7 Delta Flume breaking wave, test 5 (photograph)

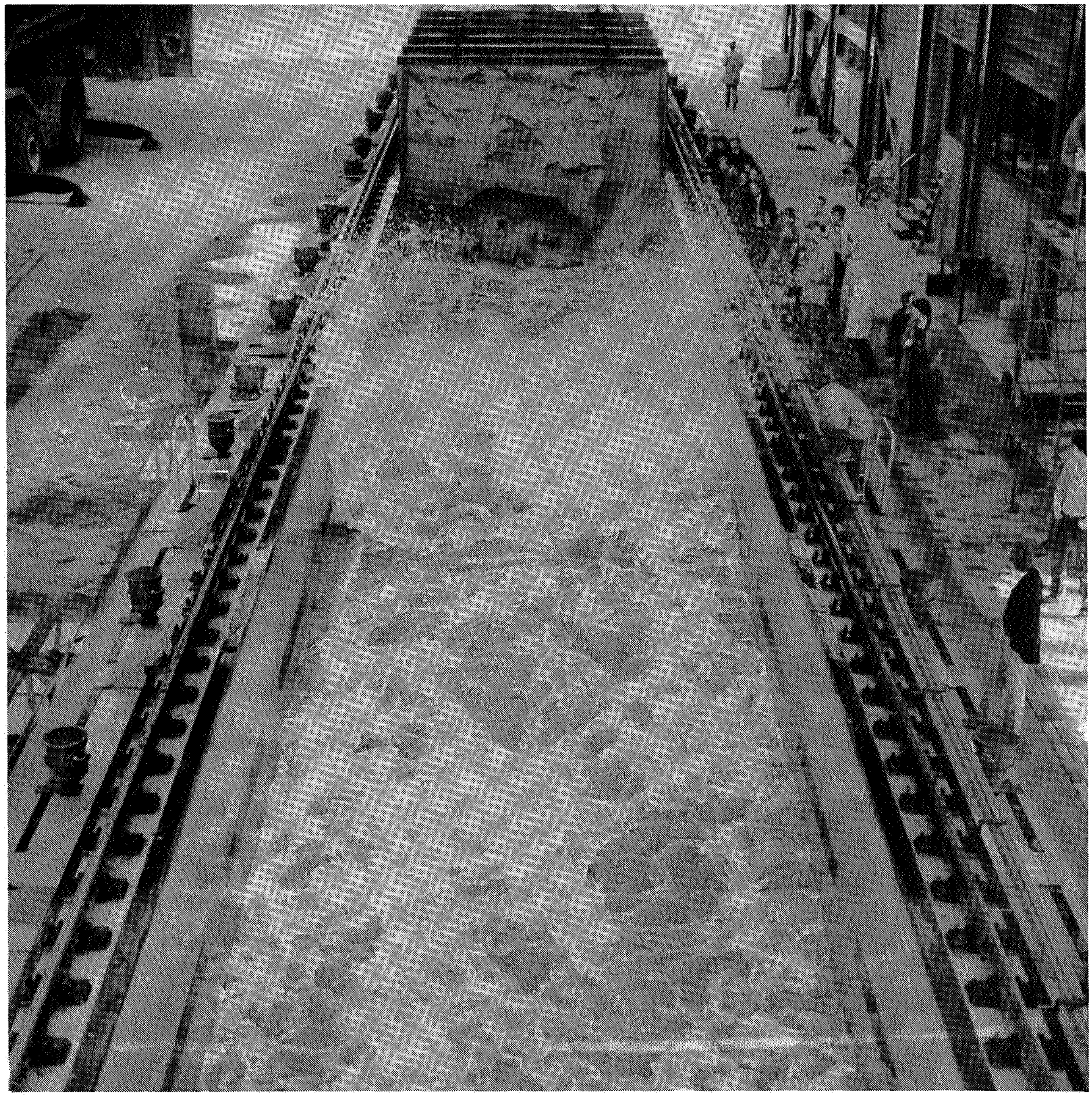


Fig. 8 Delta Flume eroding dune front test 5 (photograph)

DELTA FLUME

The dimensions of the so-called Delta Flume are as follows:

length	233 m
depth	7 m (locally 9 m)
width	5 m

The facility is equipped with a flap-type programmable wave generator,

maximum wave height random waves : $H_s = 2$ m

maximum wave height periodic waves: $H = 3$ m

wave period range : $T = 2$ s to $T = 10$ s.

VERIFICATION OF SCALE RELATIONS

The prototype conditions shown in Figure 3 were taken as a reference. Initial prototype profiles were tested relating to the reference profile with $S = 1.91$ respectively $S = 1.27$. Sand from prototype with $D_{50} = 225$ µm was used as a bed material. The scale factor for depth, $n_d = 5$. The scale factor for length was derived from (3) with $n_w = 1$:

$$n_l = (n_d)^{1 \cdot 28} = 7.85 \qquad (6)$$

The wave conditions were scaled according to Froude:

$$n_H = n_T^{\,2} = n_d = 5 \qquad (7)$$

Two tests were carried out with a constant water-level. For the third test, the initial profile with $S = 1.27$ was retested this time with varying water level conditions. The initial profile, the hydraulic conditions and the development of an erosion profile are shown for the three tests in Figures 9 to 11.

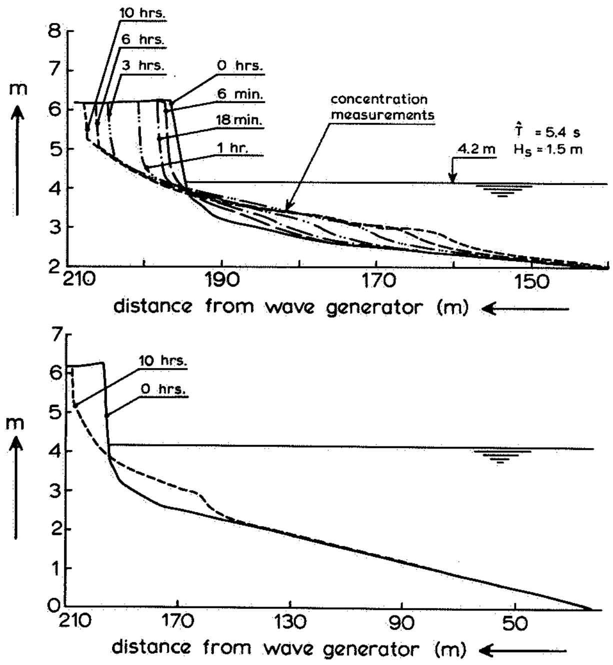


Fig. 9 Erosion profile development, test 1

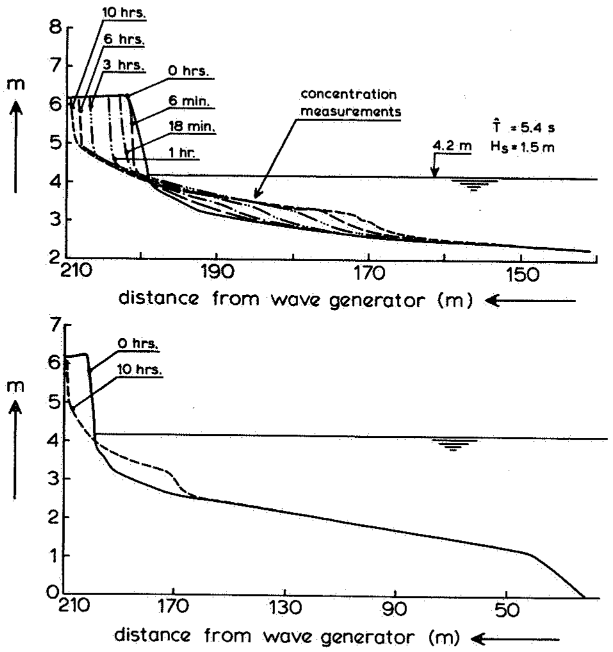


Fig. 10 Erosion profile development, test 2

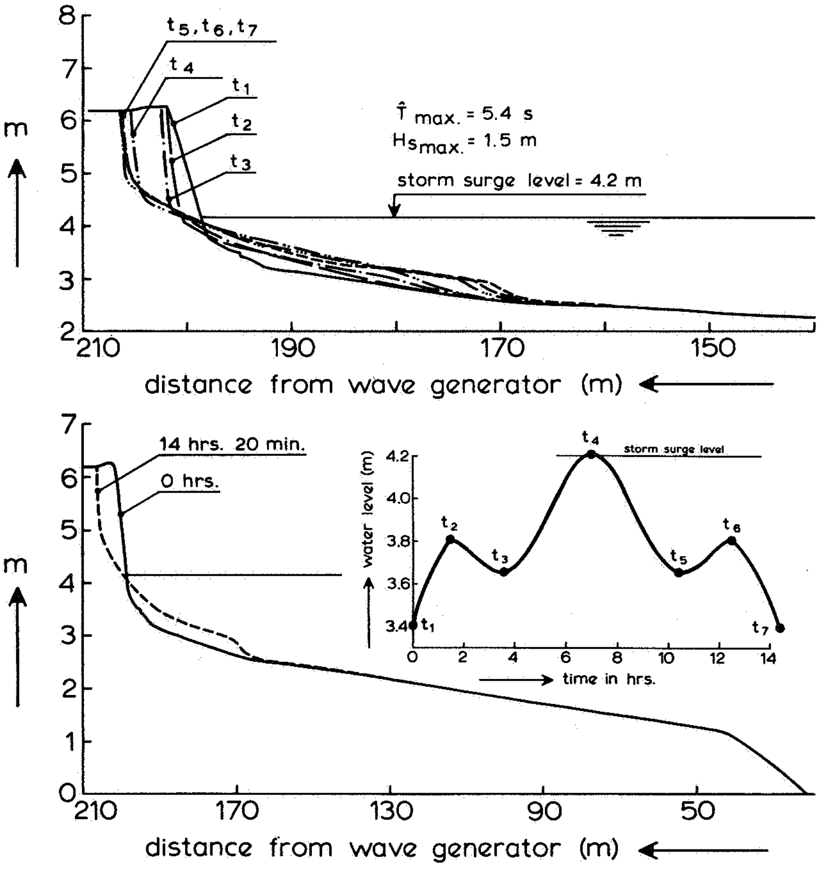


Fig. 11 Erosion profile development, test 3

The model results have been converted to prototype with $n_d = 5$, $n_l = 7.85$, $n_t = (n_d)^{0.5} = 2.24$ and $n_A = n_d * n_l = 39.3$ (A is area). The erosion quantities as a function of time, converted to prototype are compared with the results of the small-scale models in Figure 12. The erosion quantity of tests 1 and 2 after five hours, and the final quantity of test 3 are compared to the small-scale model results in Figure 13. The erosion quantities recorded in the large scale model favourably agree with the results of the small-scale models. Thus so far it may be concluded that the scale relations are confirmed.

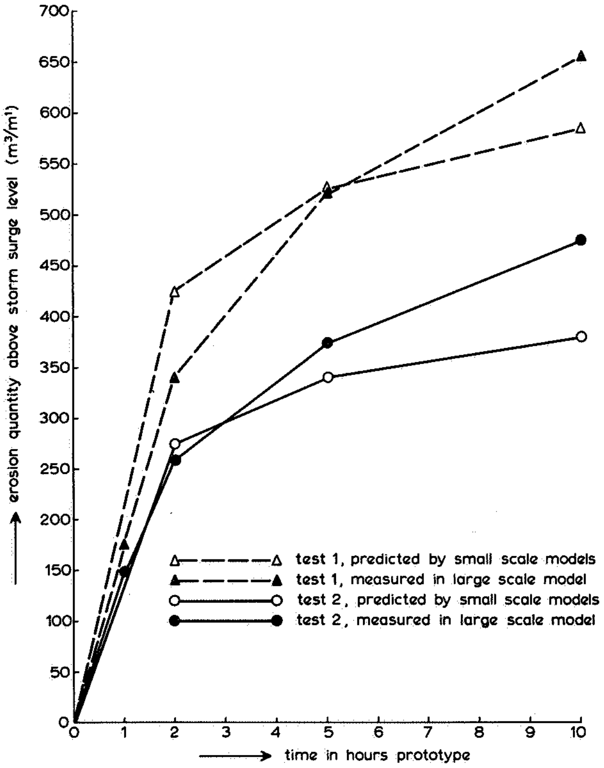


Fig. 12 Erosion quantity as a function of time, predictions and measurements

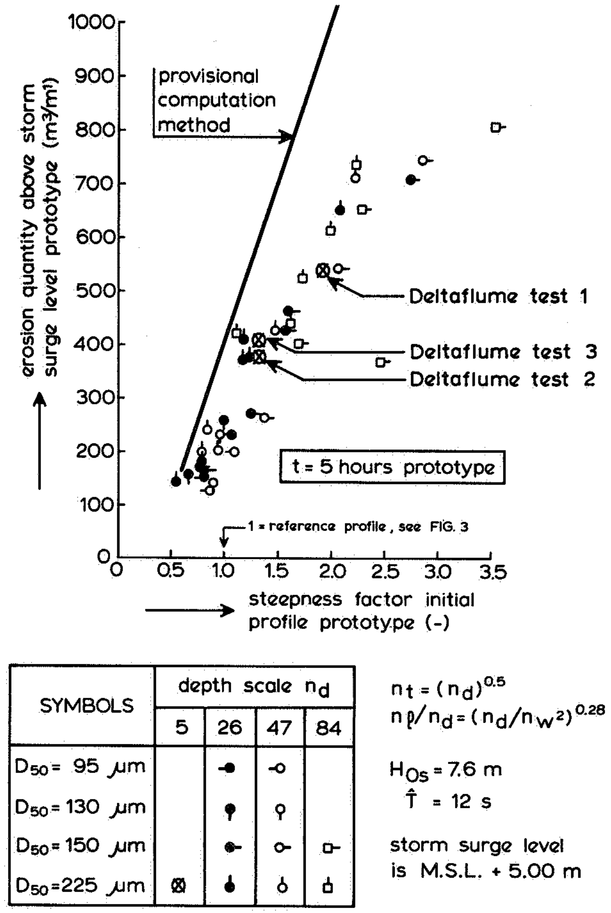


Fig. 13 Initial profile and erosion quantity

Another way to verify the scale relations is to compare the erosion profiles. In Figure 14 results are shown of tests with D_{50} = 225 m and depth scales n_d = 84, n_d = 47, n_d = 26 and n_d = 5. The agreement is not fully satisfactory. A distinct scale effect is present in the profile above storm surge level. The distribution of sand below storm surge level reproduces reasonably well. A better agreement is found when small-scale tests with very fine sand are compared to large-scale tests with coarser sand. As an illustration a Delta Flume test with H_s = 1.50 m and D_{50} = 225 μm is compared to a small-scale test with H_s = 0.25 m and D_{50} = 95 μm in Figure 15. Identical initial profile and hydraulic conditions were reproduced in the two models. The results have been converted to prototype with $n_t = (n_d)^{0.5}$ and $n_l/n_d = (n_d/n_w^2)^{0.28}$. Summarizing it may be concluded that if prototype sand is used in the model the scale relations are not fully adequate for the reproduction of erosion profiles. However, if finer sands are applied an overall agreement of erosion profiles is found.

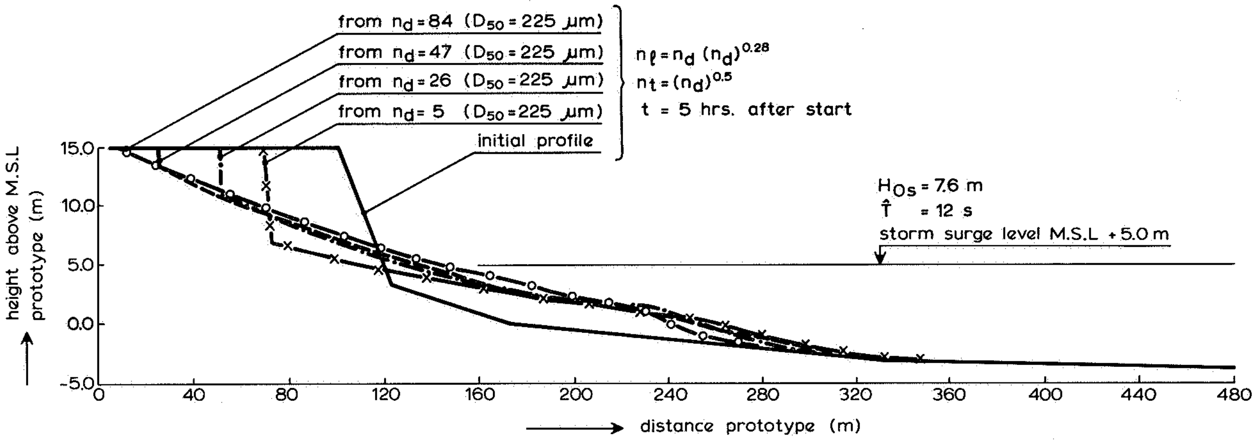


Fig. 14 Erosion profiles, prototype

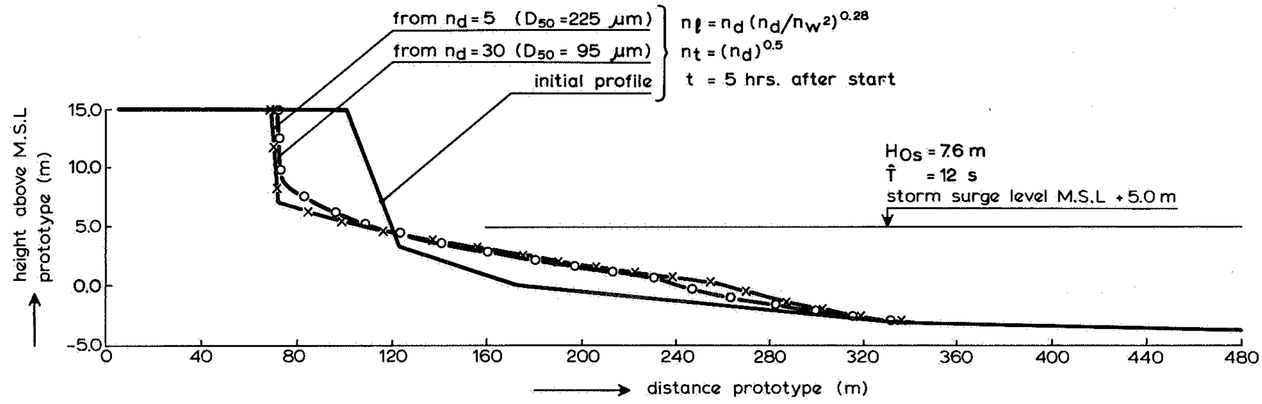


Fig. 15 Erosion profiles, prototype

COMPARISON WITH FIELD DATA

The major aim of the Delta Flume tests is to verify scale relations. Besides an internal verification (between tests with different scales) an external verification (comparison with field data) is also essential for investigating the reliability of the model. External verification, however, is difficult as very few field data on dune erosion are available. The largest dune erosion quantity in recent history was recorded after the 1953 storm surge (see Figure 1). It was decided therefore to reproduce the 1953 storm surge, accepting the uncertainties in the field data. The erosion quantities were derived from the recording of dune front recessions along a 17 km-long beach close to The Hague a few days after the storm surge. The time period between the pre-storm profile recording and the storm surge was 3 to 6 months. The scatter in the erosion quantities of Figure 1 will for a large part be caused by this insufficiency.

The water-level during the 1953 storm surge is well known from tidal gauges in nearby harbours. Wave data available from ship observations indicate a "deep water" wave height $H_s = 5$ m. The wave-observations, however, are not considered fully reliable. A wave hindcast study on the basis of meteorological data has lead to a maximum height $H_s = 6.5$ m. The latter result was applied to the model test. Storm surge conditions and the reconstructed initial profile were reproduced in the model with the following scale factors:

$n_d = 3.27$; $n_l = (n_d)^{1.28} = 4.56$; $n_t = (n_d)^{0.5} = 1.81$.

The initial profile and the development of the erosion profile during the storm surge are shown in Figure 16. The erosion quantity has been converted to prototype with $n_A = n_d * n_l = 14.9$. The final erosion quantity is shown in Figure 17 together with the field data. The agreement is satisfactory.

A small number of beach profiles was recorded a few weeks after the 1953 storm surge in the north of the Netherlands close to Den Helder. The field data together with the model profiles are presented in Figure 18. The model profiles have been converted to prototype with the scale relations mentioned above. The agreement between model and field is satisfactory.

An additional test was carried out in the Delta Flume aimed at approaching the conditions of a storm surge in situ as closely as possible. The wave height in the "model" $H_s = 2$ m, the wave period $\hat{T} = 7.6$ s the dune height above storm surge level = 4 m, the water level is kept constant at 5.0 m above the bottom of the flume. The development of the erosion profile is shown in Figure 19. The erosion quantity above storm surge level measured in the model is 50 m^3/m^1 after six hours of testing.

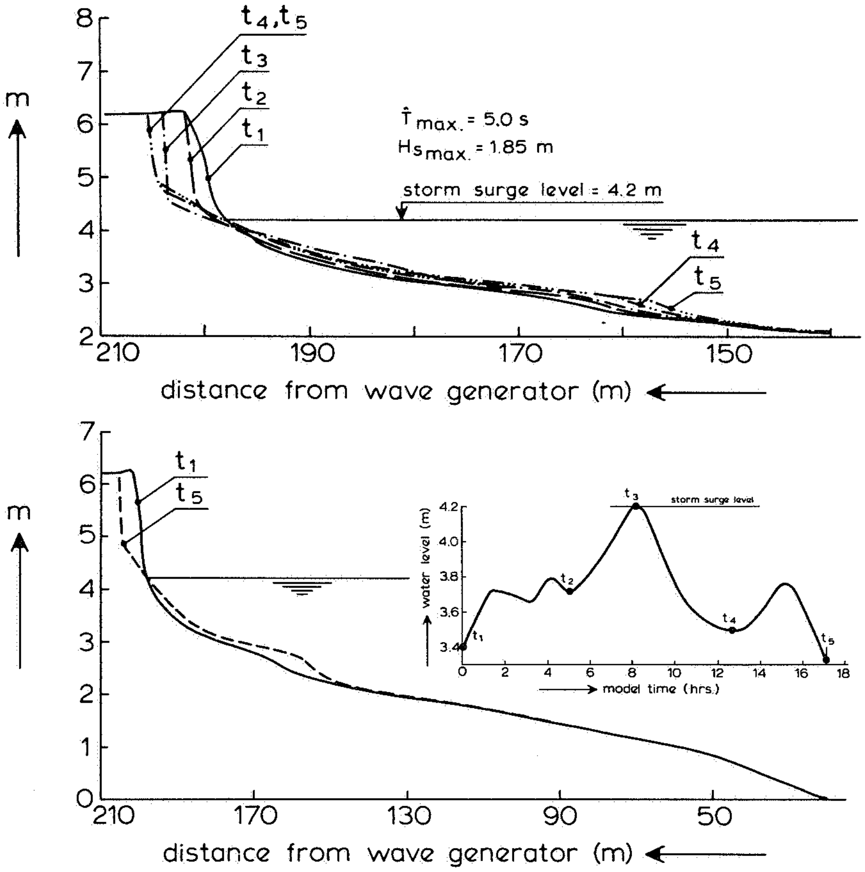


Fig. 16 Erosion profile development, test 4

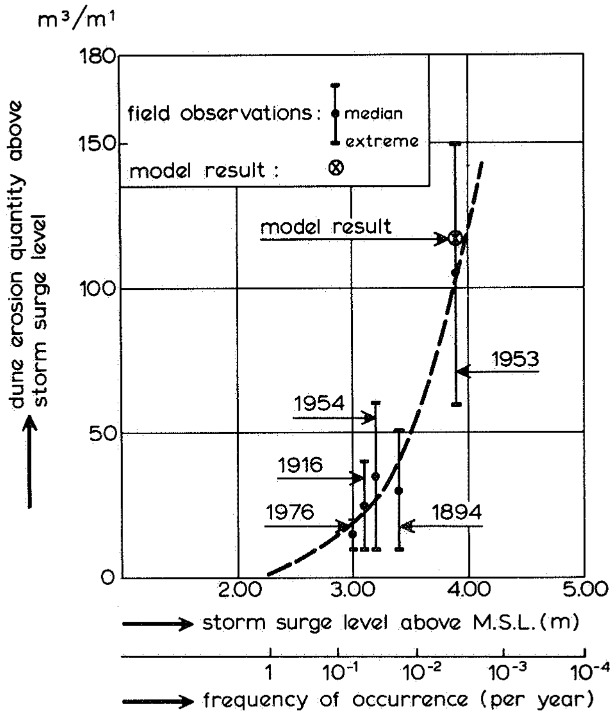


Fig. 17 Erosion quantity model result and field data

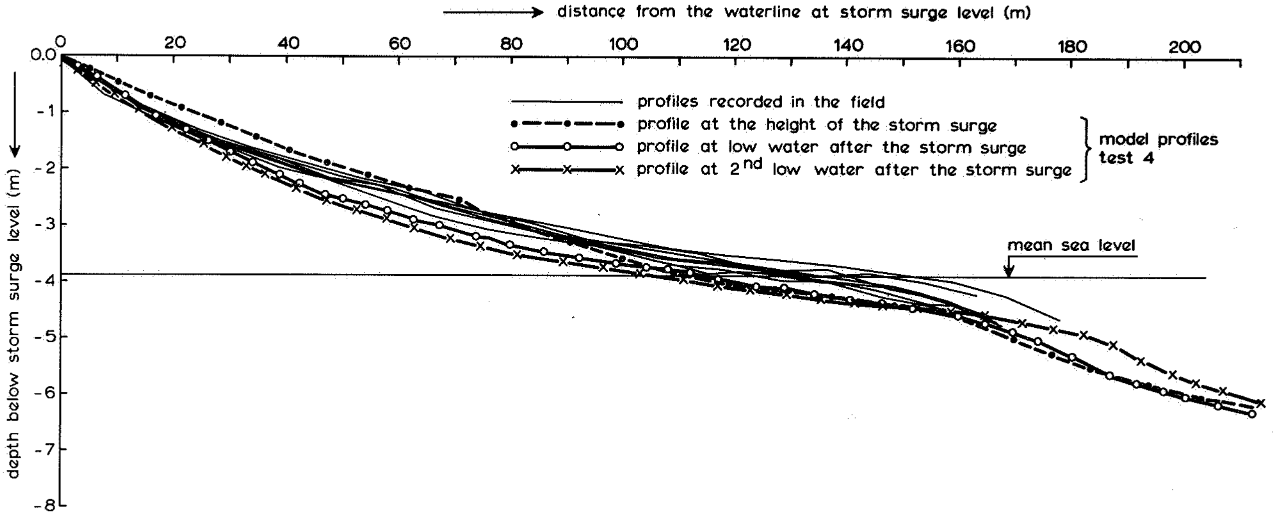


Fig. 18 Erosion profiles model and field, 1953 storm surge

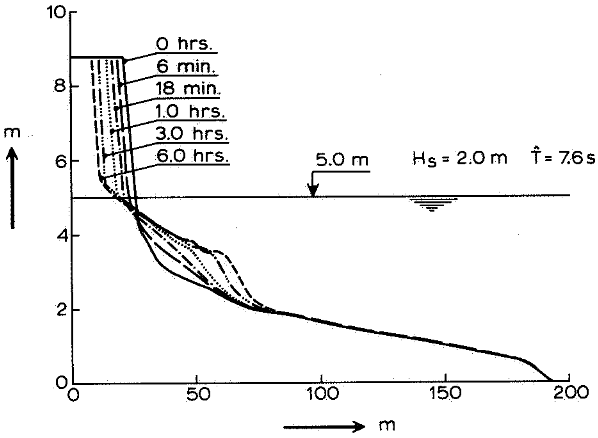


Fig. 19 Erosion profile development, test 5

OFFSHORE TRANSPORT MECHANISM

During a storm surge the sea level is several metres higher than under normal high water conditions. As a result relatively high waves reach the dune front. The wave-breaking process under such conditions is very intensive with considerable wave reflection and predominantly plunging breakers. In the shallow water the overtopping waves with the air that is being enclosed touch down to the bottom. As a consequence large quantities of sand are stirred up showing the highest concentration of sediment near the bottom. A net seaward sand transport is caused by the vertical circulation that has a seaward direction below the wave troughs. To investigate the process more into detail the sediment concentration and the velocity field has been recorded during the tests. Sediment concentrations have been measured by means of sampling the sand-water mixture; the sampling period is three minutes. The horizontal component of the velocity field has been recorded by means of an accoustical, doppler type, current meter. A selection of the analysed results is presented as follows:

The sediment concentrations measured at the beginning and end of the erosion process of test 1 (see Figure 9) are shown in Figure 20. The results demonstrate that in the beginning, when the erosion rate is very high the sediment concentrations range from 5,000 up to 15,000 milligram per liter. The concentration decreases to a value of 2,000 to 4,000 mg/1 at the end of the erosion process at the same location, 182.5 m from the wave generator. The horizontal orbital velocity, u_{15}, roughly equal to the velocity amplitude of the significant wave, appeared to be nearly the same for the two situations that are compared. This also holds for the time-averaged seaward current velocity between the bottom and the wave troughs, V_{res}. The water depth has changed only slightly. The major difference for the two situations is the bottom profile. At t = 0.3 hrs the bottom slope is about 1 : 15, at t = 6 hrs the bottom slope is about 1 : 35. Consequently the decrease of the offshore transport can only be explained by the decrease in the sediment concentrations. Thus the rate of offshore sand transport must be fully controlled by the sediment concentration, that in its turn must be related to the wave-breaking process, that in its turn must be related to the bottom slope. A simple but important conclusion is that the waves are the stirring agent and the vertical water circulation is the transporting agent.

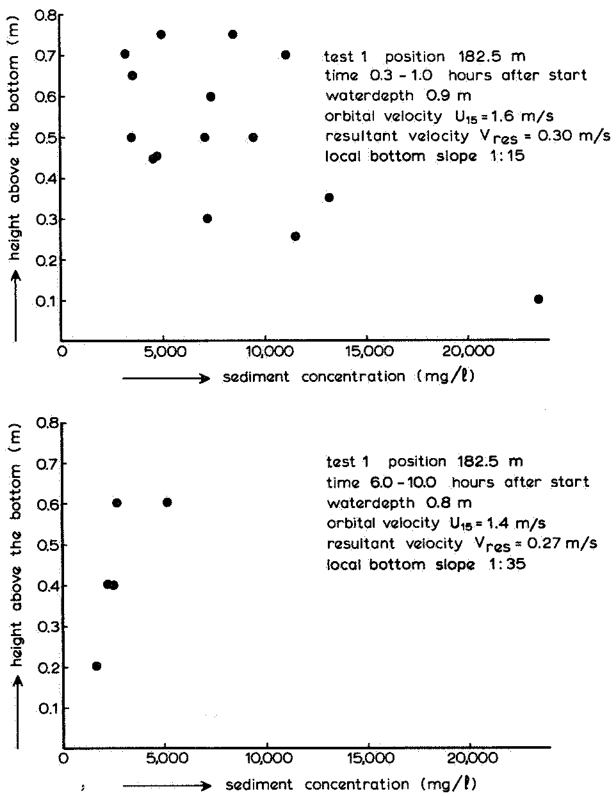


Fig. 20 Sediment concentrations, test 1

By means of a more or less speculative computation it can be shown that the rate of off-shore sand transport found from the profile changes is roughly equal to the product of the time-averaged sediment concentration and the time-averaged current velocity.
The time-averaged current in seaward direction between the bottom and the level of the wave troughs (h_1) will be balanced by a shoreward current above this level. The sand transport in the bottom part can be computed, using the results shown in Figure 20:

$$S_1 = \int_o^{1hr} \int_o^{h_1} v(z,t) * C(z,t)\ dz\ dt \simeq \bar{v}\ \bar{C}\ h_1\ t$$

$$= 0.3 * 12,000 * 0.63 * 10^{-6} * 0.8 * 3600 = 6.5\ m^3/m'\ hr$$

in which C is dimensionless sediment concentration in volume of sediment, bulk including voids, per volume of water ($mg/l * 10^{-6}\ kg/mg * 0.63\ l/kg = 0.63 * 10^{-6}$).

The sand transport above the level of the wave troughs can be found from the ratio of the sediment concentrations above and below the level h_1:

$$S_2 \simeq (\bar{C}_2/\bar{C}_1) * 6.5 \simeq \frac{4,000}{12,000} * 6.5 = 2.2\ m^3/m'\ hr$$

So, $S_{resulting} = S_1 - S_2 = 6.5 - 2.2 = 4.3\ m^3/m'$ hr in seaward direction.

The offshore sand transport rate for test 1 at 182.5 m, between t = 0.3 hrs and t = 1.0 hrs computed from the profile changes of Figure 9 is 4.7 m^3/m' hr which is roughly equal to the product of time-averaged current and sediment concentration.

The erosion mechanism described above illustrates that the sand is transported from an area with very intensive wave breaking to regions with moderate wave breaking. So the sand from the dunes is not simply distributed over the entire breaker zone as was assumed in the provisional computation method. Instead, the model tests show that a storm profile has been developed (during the storm surge) to a depth of 0.5 H_{0s} to 0.8 H_{0s} below storm surge level.

The results presented above give rise to the following statements:
1) The data of sediment concentrations show that the way the waves are breaking is of vital interest for the concentration of sediment. Thus any model

describing the sediment concentration in the surf zone as a function of wave parameters should take into account the effect of the breaking of the waves. It is most plausible that via turbulence caused by breaking waves, a relation can be found between the rate of energy dissipation per unit mass of water and the concentration of sediment.

2) The dependency of sediment concentration on profile steepness implies that for given deep water wave conditions the longshore sand transport is very much influenced by the shape of the coastal profile. This phenomenon has been described before by Kamphuis and Readshaw (1978).

ILLUSTRATION OF THE VALIDITY OF THE SCALE RELATIONS

An illustration of the validity of the scale relations is presented in Figure 21. The profile development of a Delta Flume test with $H_s = 1.9$ m is compared to a small-scale test with $H_s = 0.253$ m. The relation between the two tests is as follows: $n_d = n_H = n_T^2 = n_t^2 = 7.5$; $n_w = 0.027/0.009 = 3.0$; $n_l = n_d \, (n_d/n_w^2)^{0.28} = 7.13$.

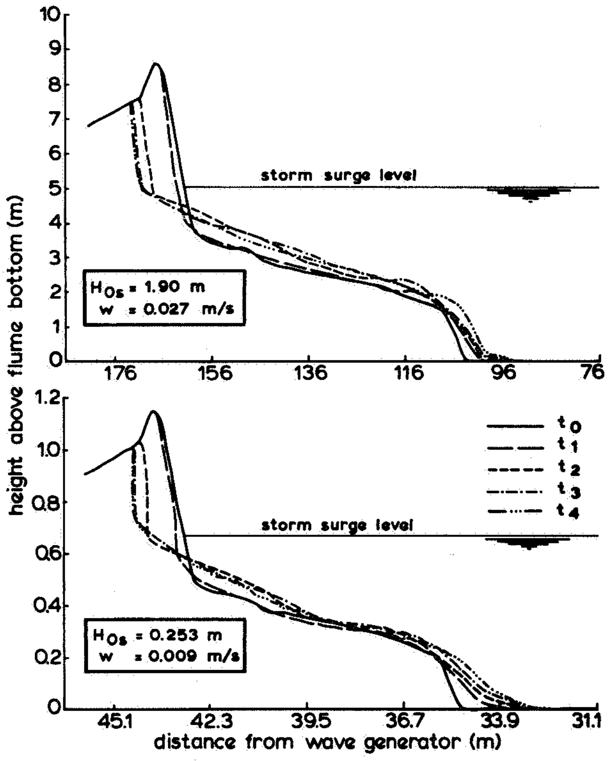


Fig. 21 Erosion profile development, small scale and large scale model

The model is practically undistorted ($n_l/n_d = 7.13/7.5 = 0.95$). Identical storm surges with a varying water-level have been reproduced for the two tests. The development of the erosion profiles is very similar, for the peak of the storm surge as well as for the lower water-level conditions just before and after the surge. Consequently the scale relations are very promising for the small-scale reproduction of beach processes in general. An additional advantage of the scale relations is that beach profile changes can now be reproduced in a small-scale model without the need of distortion. This enables the model testing of morphological developments around structures in the surf zone where diffraction and/or reflection of waves plays an important role.

SEDIMENT CONCENTRATIONS IN MODEL AND PROTOTYPE

For models with wave conditions scaled according to Froude and with a bottom material so that n(H/Tw) = 1 it can be shown that the sediment concentration should have the same value in model and prototype.

The scale relations are as follows: $n_d = n_l = n_H = n_L = n_T^2 = n_u^2 = n_w^2 = n_t^2$. Ignoring minor roughness and viscosity effects the scale factor for water transport must also be according to Froude:

$$n_Q = n_V/n_t = (n_d)^3/(n_d)^{0.5} = (n_d)^{5/2}$$

in which Q = water transport [m³/s], V = water volume [m³], t = time [s].

The scale factor for the transport of sand $n_E = n_A/n_t$, in which A = volume of sand [m³], the scale factor for the volume of sand, $n_A = (n_d)^3$.

It has been found from the model tests that the time scale of the erosion process is equal to the hydrodynamical time scale, $n_t = (n_d)^{0.5}$.
Thus $n_E = n_A/n_t = (n_d)^3/(n_d)^{0.5} = (n_d)^{5/2}$.

The scale factor for the sediment concentration can be found from the ratio of the scale factor of sand transport and water transport: $n_C = n_E/n_Q = (n_d)^{5/2}/(n_d)^{5/2} = 1$.

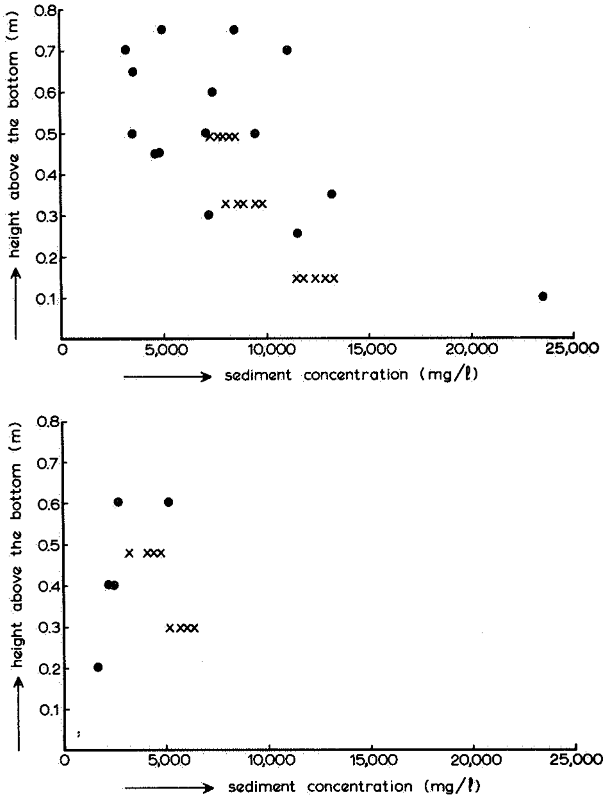


Fig. 22 Sediment concentrations, small scale and large scale model results

A verification of this result is presented in Figure 22. Sediment concentrations measured in a large-scale model (H_s = 1.5 m, D_{50} = 225 μm) are compared with results from a small-scale model for corresponding phases of the erosion process. The agreement is quite satisfactory for the stage of rapid profile changes (see the upper part of the Figure). During quasi-equilibrium conditions (see the lower part of Figure 22), the vertical distributions are different for the two models but the vertical average agrees.

On the basis of this limited verification, it may be concluded that the model data give encouraging support to the concept $n_C = 1$ for models that have scale factors according to Froude and n(H/Tw) = 1.

This result opens a new way for the computation of longshore sand transport. Earlier it was concluded that for given deep water wave conditions the sediment concentration, and thus the longshore sand transport, is very much dependent on the shape of the coastal profile. Consequently the commonly used longshore sand transport formulae should be considered not fully reliable, especially not for storm surge conditions. A more accurate way to determine longshore sand transport is as follows: the wave-driven longshore current and the distribution of it across the surf zone is computed by means of a numerical model based on the theory of Battjes (1974) or a similar theory. Next, the sediment concentration is measured in a two-dimensional scale model for various coastal profiles and various wave and water-level conditions. Finally, the recorded concentrations are integrated with the computed longshore currents resulting into the longshore sand transport. Naturally, on a longer term sediment concentrations should also be modelled numerically aiming at a fully computerized prediction of longshore sand transport. The approach sketched above is only valid under the assumption that the entrainment and stirring capacity of the breaking waves is much larger than that of the longshore current. This assumption is plausible in view of the ratio of the energy dissipated by the two phenomena.

FALL VELOCITY AND PROFILE SLOPE

The series of model tests with sand from prototype has illustrated that smaller models have steeper erosion profiles. This effect is plausible considering the fact that the fall velocity is not to scale. The eroded sand in the model settles relatively fast to the bottom and so relatively steep profiles are generated. The dependency between the post-storm profile and the depth scale has been described by the distortion relation:

$$n_l/n_d = (n_d)^{0.28} \qquad (2)$$

Tests with four different types of sand have shown that the relation between profile steepness (distortion), depth scale and fall velocity can be described by (3):

$$n_l/n_d = (n_d/n_w{}^2)^{0.28} \qquad (3)$$

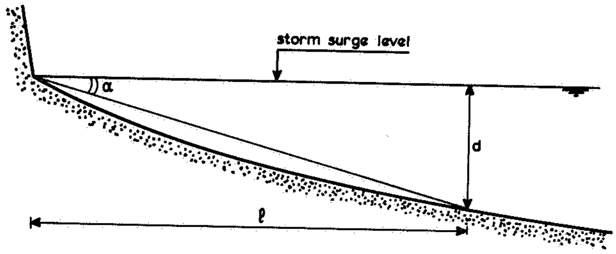


Fig. 23 Definition sketch tg α

The distortion of the model, n_l/n_d, can also be written as $n(tg\alpha)^{-1}$, defining tgα as follows: $tg\alpha = d/l$, in which d is water depth below storm surge level at a certain distance l from the waterline, (see Figure 23).

So, $n_l/n_d = n(tg\alpha)^{-1} = (n_d/n_w^2)^{0.28}$

For situations with identical wave conditions the depth scale $n_d = 1$. For such conditions a relation can be derived between fall velocity and profile steepness:

$n(tg\alpha)^{-1} = (1/n_w^2)^{0.28}$

or

$n(tg\alpha) = (n_w)^{0.56}$

which can be written as

$tg\alpha/tg\alpha_{ref} = (w/w_{ref})^{0.56}$

in which:

$tg\alpha_{ref}$ = the slope of a beach with sand having a fall velocity $w = w_{ref}$

$tg\alpha$ = the slope of a beach with sand having a fall velocity w = w, under identical wave conditions.

The relation has been derived from an analysis of a series of model tests. A verification of the relation with field data is presented as follows:

The relation between fall velocity and beach profile slope is shown in Figure 24, for a number of beach profiles covering the entire coast of the Netherlands. The field data have been recorded about one week after a heavy storm surge on January 3rd 1976, see Delft Hydraulics Laboratory (1978). The symbols in this figure represent the beach slope from storm surge level to storm surge level -1.5 m and from storm surge level to storm surge level -4.5 m. The relation

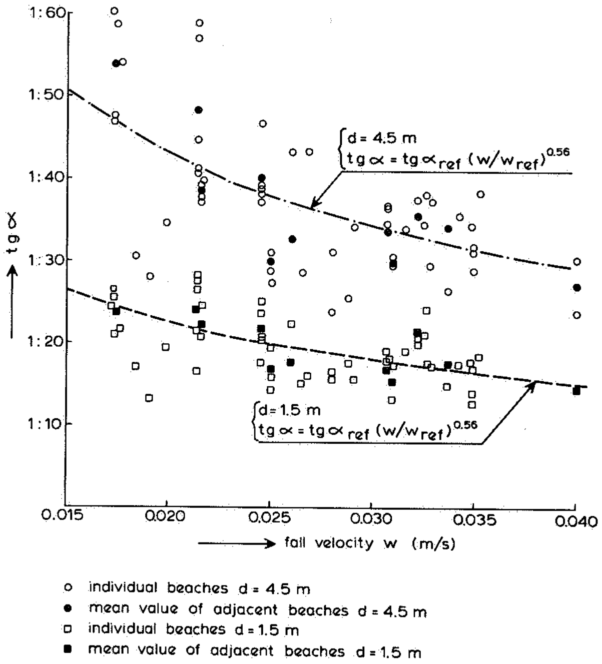


Fig. 24 Fall velocity and beach profile slope after a storm surge

presented above is shown by the dotted line. The reference beach slope, $tg\alpha_{ref}$, refers to the erosion profile of the provisional dune erosion model, see Figure 2; w_{ref} refers to the mean grain size along the Dutch coast, D_{50} = 225 μm. The agreement is rather poor, only the trend of the field data agrees with the relation found from the model tests. The large scatter for the individual beach profiles may be due to irregularities characteristic to beaches accreting after a storm. A better agreement is found when the field data are averaged over a number of adjacent beach profiles. It can be concluded from the latter result that the relation derived from the model experiments is supported by the field data. Consequently it can be used for the prediction of erosion profiles and as such for the design of (artifical) beaches.

BASIC ELEMENTS FOR THE PREDICTION OF DUNE EROSION DURING A STORM SURGE

The large-scale tests have confirmed the validity of the earlier developed scale relations. Consequently it is now possible to test any coastal profile in a small-scale model and to define the required dimensions. The final aim however is to develop a general model for the computation of the erosion quantity as a function of the hydraulic conditions and the coastal profile. The tests so far have been carried out for rather schematized conditions. More variables should be tested for the development of a general model.

With this aim in mind a series of small-scale tests has been initiated. Various combinations of storm surge level, wave height, wave period and coastal profile have been tested. At present a computer model is being developed having the following basic elements:

1) During a storm surge a uniform erosion profile will develop. The shape of the erosion profile is determined by the wave height and the fall velocity of the bed material. The level of the profile is determined by the storm surge level.
2) There will be a mass balance of sand in the coastal profile for straight or nearly straight coastlines.
3) The erosion quantity is determined by the difference between the initial profile and the uniform erosion profile.
4) The eroded sand will be distributed over a relatively short distance, being 150 m to 250 m for waves with $H_{0s} = 7.6$ m. The erosion profile will be developed to a depth of 0.5 H_{0s} to 0.8 H_{0s} below storm surge level.

CONCLUSIONS

1) The erosion of beaches and dunes under storm surge conditions can be reproduced in small-scale models with a high degree of accuracy. Large-scale tests and field data reproduction have demonstrated the validity of a modelling technique based on the dimensionless fall velocity parameter H/Tw and the use of fine sand in the model (see Figures 13 and 15).

2) Large-scale model tests with waves of 1.5 m significant height have confirmed the earlier developed scale relations: $n_t = (n_d)^{0.5}$; $n_l/n_d = (n_d/n_w{}^2)^{0.28}$; $n_H = n_T{}^2 = n_d$. In which n_t is the time scale of the morphological process, n_l, n_d and n_w are the scale factors for length, depth and fall velocity respectively; n_H and n_T are scale factors for wave height H_s and wave period $\hat{T}$; n stands for prototype value over model value.

3) For given storm surge conditions, a linear relation exists between the steepness of the initial profile and the resulting erosion quantity above storm surge level. The sand eroded from the dunes settles on the beach within a relatively short distance (150 m to 250 m for waves with $H_{0s} = 7.6$ m).

4) The relation between the slope of the erosion profile and the fall velocity of the bed material can be described by $tg\alpha/tg\alpha_{ref} = (w/w_{ref})^{0.56}$ in which $tg\alpha$ and $tg\alpha_{ref}$ are the slopes of beaches under identical wave conditions, with sand having fall velocities w respectively w_{ref}.

5) Sediment concentrations under breaking waves can be reproduced in a small-scale model on a scale 1 : 1 by the use of very fine sand applying the same scale factor for orbital velocity and fall velocity of the bottom material.

6) The (local) sediment concentration in the zone of breaking waves is very much dependent on the (local) beach slope. It is suggested that via turbulence, a relationship is present between the dissipation of wave energy per unit of mass of water and the sediment concentration.

7) A computer model for the prediction of dune erosion is being developed on the basis of the investigations described in this paper. The model will be applied to check the safety of existing dunes as primary sea defence structure and to design the necessary reinforcements.

ACKNOWLEDGEMENT

The research activities presented in this paper were carried out by order of the Ministry of Transport and Public Works - Rijkswaterstaat of the Netherlands (RWS/COW) on behalf of the Technical Advisory Committee on Water Retaining Structures. The author thanks Prof. E.W. Bijker for his stimulating support during the studies. Thanks are also due to Mr. R. Reinalda, Mr. J. van de Graaff and Mr. W.M.K. Tilmans for their suggestions and contributions.

REFERENCES

Battjes, J.A., 1974. Computation of set-up, longshore currents, run-up and overtopping due to wind-generated waves. Comm. on Hydraulics, Dept. of Civil Eng., Delft Univ. of Technology, 74-2, 244 p.

Dalrymple, R.A. and Thompson, W.W.,1976. Study of equilibrium beach profiles. Proc. 15th Coastal Eng. Conf. Honolulu, pp. 1277-1299.

Dean, R.G., 1973. Heuristic models of sand transport in the surf zone. Proc. Conf. Engineering Dynamics in the Coastal Zone, Sydney, pp. 208-214.

Delft Hydraulics Laboratory, 1978. Duinafslag ten gevolge van de stormvloed op 3 januari 1976; toetsing van de voorlopige richtlijn. Report on Investigation R 587, May 1978, 26 p. (In Dutch).

Delft Hydraulics Laboratory, 1981. Schaalserie duinafslag. Report on Model Investigation M 1263, Part II A: 73 p. and Part II B: figs., April 1981 (In Dutch).

Delft Hydraulics Laboratory, 1981. Onderzoek naar de duinafslag tijdens superstormvloed; toetsing van de resultaten van het twee-dimensionale modelonderzoek door middel van onderzoek in een drie-dimensionaal model. Report on Model Investigation M 1653, Part A: 59 p. and Part B: figs., Dec. 1981 (In Dutch).

Graaff, J. van de, 1977. Dune erosion during a storm surge. Coastal Eng., 1: 99-134.

Gourlay, M.R., 1980. Beaches: profiles, processes and permeability. Proc. 17th Coastal Eng. Conf. Sydney, pp. 1320-1339.

Kamphuis, J.W. and Readshaw, J.S., 1978. A model study of alongshore sediment transport rate. Proc. 16th Coastal Eng. Conf. Hamburg, pp. 1656-1674.

Kemp, P.H. and Plinston, D.T., 1968. Beaches produced by waves of low phase difference. Proc. ASCE, J. Hydr. Div., 94: 1183-1195.

Noda, E.K., 1972. Equilibrium beach profile scale-model relationship. Proc. ASCE, J. Waterw., Port, Coast. and Ocean Div., 98: 511-528.

Noda, H., 1978. Scale relations for equilibrium beach profiles. Proc. 16th Coastal Eng. Conf. Hamburg, pp. 1531-1541.

Saville, T. Jr., 1950. Model study of sand transport along an infinitely long, straight beach. Trans. Am. Geophys. Union, 31: 555-565.

Saville, T. Jr. and Watts, G.M., 1969. Coastal Regime, recent U.S. experience. XXIInd Int. Navigation Congress, Paris, Sect.II, subj. 4, pp. 249-271.

Vellinga, P., 1978. Movable bed model tests on dune erosion. Proc. 16th Coastal Eng. Conf. Hamburg, pp. 2020-2039.