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CHANGES IN BEDFORM DIMENSIONS UNDER UNSTEADY FLOW CONDITIONS IN A STRAIGHT FLUME

by

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Summary

Flume tests are being carried out at the Delft Hydraulics Laboratory to study the changes in bedform dimensions and resistance to flow for unsteady flow conditions. The tests are carried out in a straight flume with uniform bed material (D_m = 0.77 mm). Results are presented for a sudden increase or decrease of the discharge. A comparison is made with the experiments by Gee (1973) and the theoretical work by Allen (1976[a] and subsequent articles) and Fredsøe (1979). It is concluded that Fredsøe's method does not correctly simulate the phenomena observed during the tests in the flume, while also Allen's computational model should be adapted before it can be applied for predicting the resistance to flow of the minor bed of the Rhine branches in the Netherlands during extreme flood conditions.

1. Introduction

Until some decades ago, the height of the main levees along the large rivers in the Netherlands was based on the highest recorded stage. Nowadays, the design height of these levees is determined by means of a frequency analysis of a series of historical flood discharges. A discharge with a probability of exceedance of only 8% in 100 years has recently been accepted as the design basis.

To determine the waterlevels along the main rivers during the passage of this decisive flood, (two-dimensional) computations are carried out by the Dutch Water Control and Public Works Department (Jansen, 1979, and Ogink, 1981). The computed stages are governed by the resistance to flow of both the flood plain and the minor bed. The roughness of the flood plain is made up by the roughness of grasslands, (fruit)trees, hedges and fences. The resistance to flow of the alluvial minor bed consists of the grain roughness, bedform roughness and additional roughness due to structures such as bridge piers and groynes. It has been demonstrated (Vreugdenhil and Wijbenga, 1982) that also the lateral diffusion of momentum plays an important role. For a correct reproduction of the flow field all roughness components have to be estimated correctly.

The determination of the roughness of the minor bed poses the largest problem. Several methods have been proposed (Einstein and Barbarossa, 1952, Engelund and Hansen, 1967, and White et al., 1980). From White et al. (1980) it may be concluded that even under steady flow conditions, the prediction of the waterdepth by these methods has only a limited accuracy.

Under unsteady flow conditions the predicted value may differ even more from the actual level, due to the time-lag with which the dimensions of the bedforms change (Allen, 1976; Nasner, 1978). A fairly accurate prediction of the resistance to flow for varying flow (as occurs during the passage of a flood wave) can therefore only be obtained if this time-lag is taken into account explicitly.

Unfortunately the knowledge about the changes in bedform dimensions during varying flow conditions is very limited. To deepen the insight in these phenomena flume tests are being carried out at the Delft Hydraulics Laboratory. In these tests the changes in both bedform dimensions and resistance to flow are studied. During the experiments the conditions are such that only dunes with some superimposed ripples are present in the sandflume.

The present paper reports on these investigations which are carried out within the framework of a basic research programme on the sediment transport and resistance to flow of rivers in close cooperation between the Delft Hydraulics Laboratory and the Dutch Water Control and Public Works Department. Chapter 2 gives a review of related experimental and theoretical work. A description of the tests and some preliminary results are presented in Chapter 3. The results enable a verification of some existing theories, which is the subject of Chapter 4. In Chapter 5 the continuation of the flume tests and the related field measurements are briefly indicated.

2. Review of earlier studies

Theoretical studies

Changes in bedform dimensions can be determined by means of mathematical models, if the water movement over a dune-covered riverbed and the local sediment transport along dunes for varying flow conditions can be determined accurately enough. The description of the water movement should explicitly take into account the occurrence of recirculation downstream of the dune crest and the extra turbulence generated in the shear larger between the main flow and this separation zone. Promising results on this subject have recently been reported by Klaassen (1978) and Sündermann et al. (1980), but at present (1981) no operational models for detailed simulation of changes in dune dimensions are available that can be used for varying flow.

A less detailed approach has been presented by Fredsøe (1979). For the form roughness especially the dune height is of importance (Engelund, 1978). Fredsøe concentrated on the prediction of the dune height changes. He derived a relation for the initial change in bed elevation at the top of the dune based on the local change in flow conditions, a change in sediment transport, the continuity equation for sediment and the total derivative for the bed elevation. The derived expression reads as follows:

$$\frac{dH}{dt} = \frac{\sqrt{\Delta g D_{50}^3}}{(1-\varepsilon)L} \{1 - \frac{(\Theta'F)_2}{(\Theta'F)_1}\} \phi_2 \qquad (1)$$

in which

$$F = \frac{1}{\phi}\frac{d\,\phi}{d\Theta'} \qquad (2)$$

where g = acceleration of gravity (m/s^2), H = dune height (m), D_{50} = characteristic grain diameter (m), ε = porosity (-), L = dune length (m), Θ' = local value of the dimensionless shearstress (-) acting as a skin friction on the surface of the dune defined as $\Theta' = h'i/\Delta D_{50}$, h = waterdepth (m), i = energy slope (-), $d\Theta'$ = change in dimensionless shear stress due to the change in flow (-), ϕ = dimensionless sediment transport (-) defined as $\phi = s/\sqrt{\Delta g D_{50}^3}$, s = sediment transport per unit width (m^2/s), Δ = relative density of sediment under water (-) defined as $\Delta = (\rho_s - \rho)/\rho$, ρ = specific density of the water (kg/m^3), ρ_s = specific density of the sediment (kg/m^3), t = time (s).

The following remarks should be made regarding Fredsøe's method:
(1) No expression is presented for the change in dune length.
(2) The transport relation is the one proposed by Engelund & Fredsøe (1976). Fredsøe claims that also other transport formulae may be used. However, from Equations (1) and (2) it can be concluded that no changes in dune height would occur if the dimensionless sediment transport is defined as a power function of the dimensionless shear stress (e.g. Engelund and Hansen, 1967).

A totally different approach to the description of changes in bedform dimensions with varying flow conditions has been followed by Allen (1976^a, and subsequent publications). This computational model assumes the creation and destruction of dunes to be a stochastic process and is furthermore based on the inability of dunes to respond perfectly to changes in flow conditions. For the flow conditions in the computational model it is assumed that they can be considered as quasi-steady, with a Darcy-Weisbach coefficient which is constant in place and time.

After a dune has traveled a certain assigned excursion it is destroyed, and a new one, adjusted to the instantaneous flow conditions, is created. At the moment of creation the bedform dimensions correspond to the instantaneous flow conditions as if steady flow exists. The dimensions of the bedform at the moment of creation are random, with mean dimensions which are a function of the flow conditions and standard deviations to be specified. During the life of the dunes only the dune height is (partially) adapted to changes in flow conditions, in accordance with a first order relation:

$$\frac{dH(t)}{Ht} = \frac{Ac_b}{H(t)} (H_\infty - H(t)) \qquad (3)$$

where A = coefficient of change (-), $H(t)$, H_∞ = dune height at time t and for $T \rightarrow \infty$, respectively, for the flow conditions considered (m), c_b =bedform celerity (m/s).

With respect to Allen's computational model the following remarks have to be made:

(1) Several constants such as the dune excursion C and the coefficient of change A have been introduced. The influence of some of them on the time-lag of the dunes has been investigated in Allen's subsequent publications, but their actual values have not been given.

(2) A number of relations have to be introduced in the computational model, viz. a method to predict the bedform dimensions under steady flow conditions (Yalin, 1964, or Stein, 1965) and the bedform celerity as a function of flow velocity. The results of the computational model are highly dependent on the applicability of the formulae used.

(3) If Allen's method is to be applied to predict the resistance to flow of the minor bed of rivers during the passage of flood waves, the assumption of a constant Darcy-Weisbach coefficient should be dropped. Instead this coefficient should be related to the bedform dimensions. According to a recent verification carried out at the Delft Hydraulics Laboratory, reasonably reliable results are obtained with the relationships suggested by Vanoni and Hwang (1967) and Engelund (1978).

Experimental studies

Simons et al. (1962) carried out flume tests with a flood-wave type of discharge variation. Only qualitative conclusions are presented with respect to the occurrence of loop-type depth-averaged relations. Jensen (1969) measured bedform dimensions during triangular discharge variations in a scale model of the River Oubangue (Africa). He observed a time-lag in the bedform dimensions. The shorter the period of the discharge variation, the longer the time-lag that was recorded. Jensen's results are too limited to allow any generalization.

Gee (1973) carried out flume tests to study the response of bed roughness to changes in discharge. Given a rough bed composed of dunes the discharge was suddenly increased so as to obtain a flat bed in the following equilibrium situation (high Froude numbers) and vice versa. During the transition between both equilibrium conditions the bedform dimensions were not recorded.

Prototype data of the Rivers Weser and Niger and the Rio Parana was analysed by Nasner (1978). Measurements of the dune height changes during the hydrograph yielded contradictory results. For tidal conditions in the River Weser a decreasing dune height was measured with increasing discharge, while for the uni-directional conditions in the River Niger the dunes were smaller during the rising stage than during the falling stage, which implies an increase in dune height with increasing discharge.

Starting from an initially flat bed, Bishop (1977) carried out flume tests to study the growth of dunes. The developing time of dunes was determined by measuring the dune length as a function of time. Only very limited information on the initial growth in dune height was presented. For each bed material used (sand, D = 1.1 mm; sand, D=0.54 mm and bakelite, D=1.0 mm) a different growth curve was found.

It may be concluded from the earlier theoretical and experimental studies reviewed above that it is not yet possible to predict the changes in dune dimensions (length and height) by means of a mathematical model of the detailed flow over a dune-covered riverbed. Promising methods have been proposed by Fredsøe (1979) and Allen (1976), but no sufficiently detailed and accurate measurements of bedform changes are available that have been carried out under controlled conditions so as to enable testing of these methods.

3. Flume experiments

To deepen the insight into the phenomenon of increase and decrease of dune dimensions under varying flow conditions, the Delft Hydraulics Laboratory is carrying out a series of experiments in a flume with a movable bed. The experimental facility, the testing procedure, the tests carried out and some results will be described below.

Experimental facility

The tests are carried out in a sandflume built especially for fundamental research into sediment transport and resistance to flow (Klaassen, 1978). The sandflume has been constructed in reinforced concrete, with a measuring section consisting of a steel frame with glass windows. The main dimensions of the flume are (see also Figure 1 and Photograph 1):

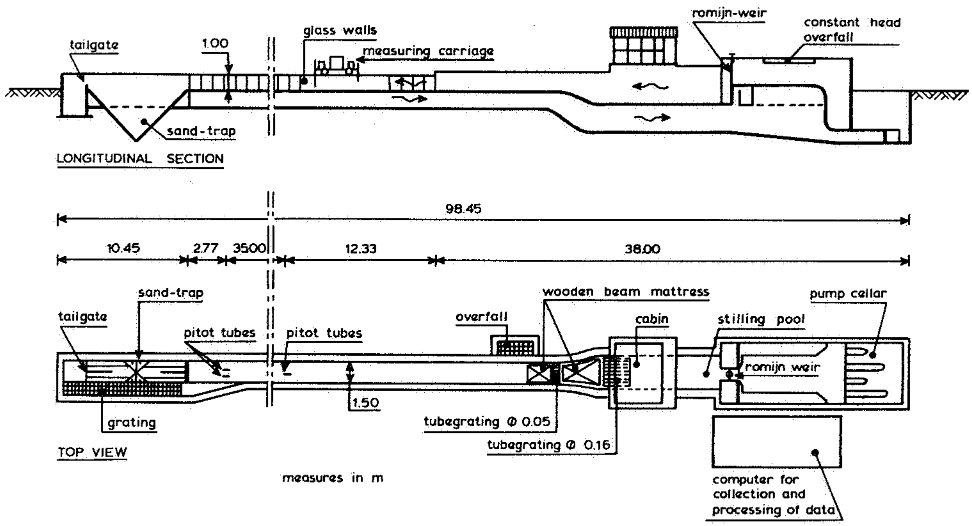
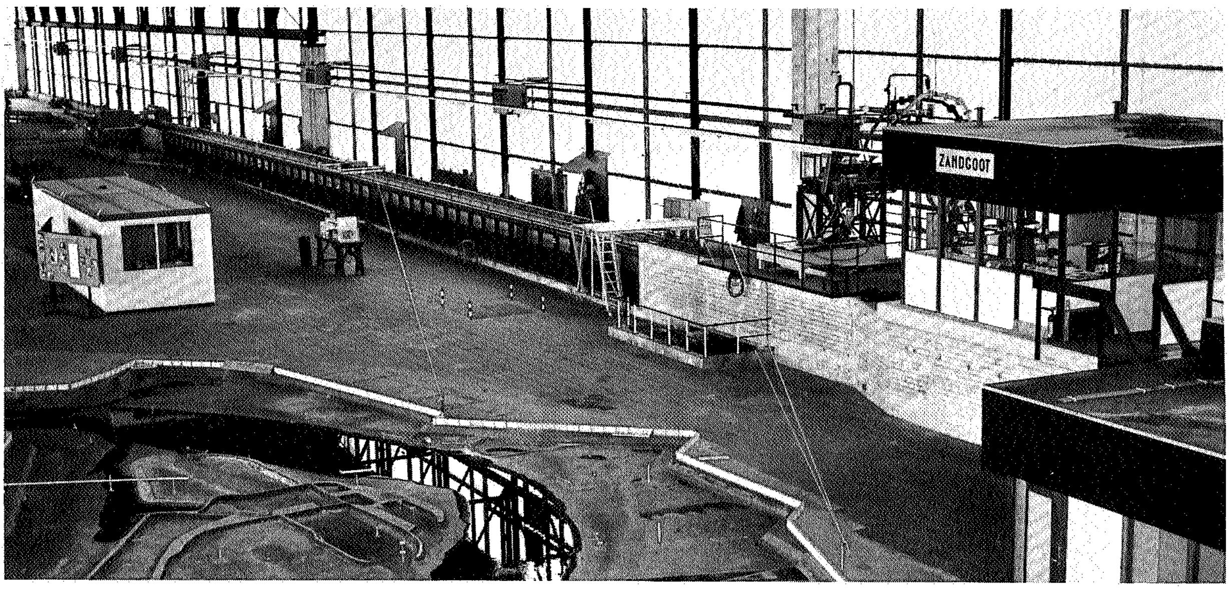


Figure 1 Longitudinal section and top view of sandflume at the Delft Hydraulics Laboratory



Photograph 1 Sandflume in Delft Hydraulics Laboratory

- overall length 98 m
- length of section with glass windows 50 m
- measuring length for bedlevel records 30 m
- width of the measuring section, variable between 0.30 and 1.50 m
- maximum water depth without sediment 1.00 m

Various control and measuring devices have been installed in and around the flume. The discharge is regulated by means of a Romijn weir. The water discharge may be varied from 0.02 m^3/s to 0.80 m^3/s. In the return flume, located beneath the sand flume, a Rehbock measuring device has been installed to enable a constant control on the discharge. In the return flume a heating and cooling system has been installed to maintain a constant water temperature. Sediment can be supplied by means of a hydrocyclone to a maximum of 800 kg/h submerged weight ($\simeq$ 0.8 m^3/h). The amount of sediment which is supplied upstream and caught downstream of the flume is weighed under water by means of a hydrocyclone.

For measuring the energy slope two sets of pitot tubes have been installed. One of these sets was installed recently for a slope control system with which the energy slope can be kept constant through continuous adjustment of the tail gate by a feed-back system. When the flume is operated with the slope control system, the water depth and the sediment transport become dependent variables. In the other case, the tail gate is set to a certain position and the sediment transport is imposed, the waterdepth and the energy slope thus becoming the dependent variables (van Rijn and Klaassen, 1981).

A minicomputer has been installed for the acquisition and part of the processing of data. Recently a microprocessor has been added. The minicomputer together with the microprocessor enable automatic acquisition of data and automatic imposition of changing boundary conditions (such as the discharge) as a function of time. Over the glass window section rails have been mounted for an instrument carriage. On the carriage three profile indicators and a waterlevel indicator are installed. Thus three longitudinal bed level profiles are measured, usually one in the middle of the flume and two at $1/6$ of the flume width from the walls. Initially the recorded data collected by the minicomputer are stored in a disc memory. Then a number of simple calculations are made to check the operation of the instruments and the progress of the test. Finally the data stored on disc are transferred to magnetic tape to be used for more complicated calculations at a later stage.

Testing procedure

For the first series of tests a sudden increase or decrease of the discharge in the flume was selected. Furthermore, the energy slope was kept constant, in order to simulate the conditions in the field as accurately as possible. For the discharge variation a sudden increase or decrease was preferred for the following reasons:
(1) to enable the verification of the method of Fredsøe (1979);
(2) to check whether the adaptation of the dunes developes according to a first-order system (Equation (3));
(3) Gee (1973) and Bishop (1977) also carried out their measurements for a discontinuous change in discharge.

The tests were carried out as follows. First the discharge and sediment supply were kept constant until equilibrium conditions (defined via sediment supplied upstream = measured sediment transport downstream) were reached. Once this equilibrium had been reached, the waterdepth, energy slope, bed slope, bed level and bedform celerity were measured. Then the discharge and sediment supply were suddenly changed in such a way that the energy slope during the following equilibrium corresponded with the initial energy slope. The tail gate was set to a new position to avoid excessive backwater effects. This procedure had to be accepted because the slope control method had not yet been installed at the time the tests described in this paper were carried out.

The phase between the two equilibrium stages is called the transition. During the transition and during the following equilibrium the flow and bedform characteristics as mentioned above were measured. In Figure 2 the expected changes in the resistance to flow (expressed in terms of the Chezy coefficient), waterdepth and dune height during the transition after a sudden increase in discharge are indicated. For a sudden decrease in discharge the opposite behaviour may be expected.

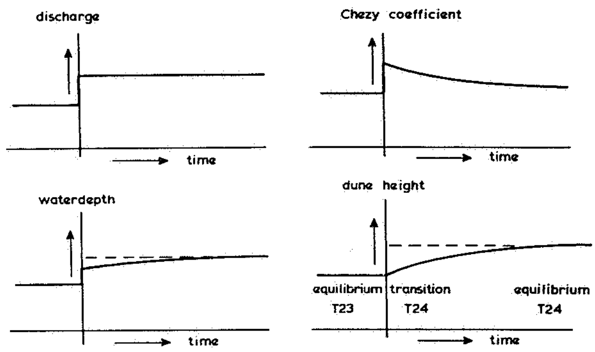


Figure 2 Expected changes in Chezy coefficient, waterdepth and dune height after sudden increase in discharge (energy slope constant)

Performed tests

The tests described in the present paper were all carried out for a flume width of 1.50 m. The water temperature was maintained at 18° C. The energy slope was kept constant at a value of about $1.6 * 10^{-3}$. The characteristic grain sizes of the applied uniform bed material are indicated hereafter:

D_{10} = 0.70 mm
D_{35} = 0.75 mm
D_{50} = 0.78 mm
D_{65} = 0.80 mm
D_{90} = 0.84 mm
D_{m} = 0.77 mm

A number of transitions were studied. A schematic overview is given in Figure 3.

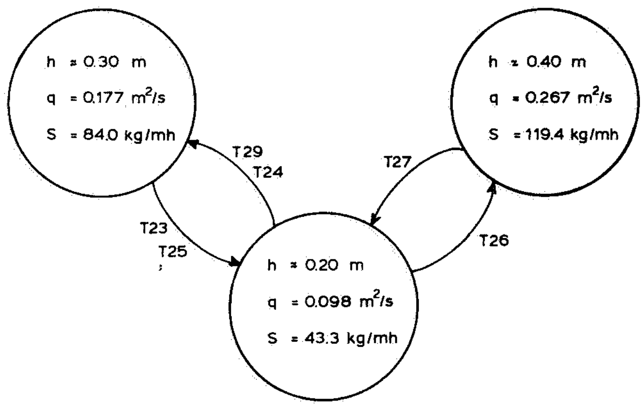


Figure 3 Diagram of tests with sudden change of discharge with constant slope of 1.6×10^{-3} (sediment transport in kg/mh submerged weight)

A transition is preceded by the equilibrium stage of the previous test and followed by the equilibrium stage of the test under consideration. An example is given in Figure 2 (sequence equilibrium T23 - transition T24 - equilibrium T24). For administrative reasons the designation T28 was not used. A summary of the performed tests is presented in Table 1.

Transition	Equilibrium phase preceding transition	Equilibrium phase following transition
T23	T22	T23
T24	T23	T24
T25	T24	T25
T26	T25	T26
T27	T26	T27
T29	T27	T29

Table 1 Transitions and equilibrium phases preceding and following the transitions

Measurements and data processing

The hydraulic and bedform characteristics were measured during the initial equilibrium phase, during the transition and during the equilibrium phase following the transition. Each measurement consisted of the following observations:

- the energy slope, by means of one pair of pitot tubes located 35 m apart,
- the discharge,
- the bed level in three longitudinal profiles at every cm of the 30 m long measuring section,
- the water level in the middle profile at every cm of the measuring section.

During the equilibrium phases about 20 of such measurements were carried out, at intervals sufficiently large to guarantee statistical independency. During the transitions the time-interval between two measurements was about 6 minutes, which is the minimum time-interval that can be realized with the present data collection system.

After the operation of the flume had been checked, the data were stored on magnetic tape. These data were processed on a larger computer system. This processing included the determination of the water surface slope and the slopes of the recorded bed levels by means of a least square method. Next the bedform dimensions were determined on the basis of the zero-level crossings. Also the bed roughness was determined, applying a wall correction as proposed by Einstein (see Wijbenga, 1978). Details on the data processing are given in Bogirski (1977).

The obtained data were not only used to make a comparison with Allen (1976) and Fredsøe (1979) but also to check whether the initial change in dune height can be considered as a first-order system, which can be written as:

$$\frac{dH(t)}{dt} = A_H \, (H_\infty - H(t)) \tag{4}$$

where A_H = coefficient of adaptation for the dune height (s^{-1}).

Note that there is a relation between this coefficient of adaptation for the dune height and the coefficient of change according to Allen ($A_H = A\, c_b/H$). To be able to determine the coefficient of adaptation A_H for the dune height immediately after the change of discharge, it is necessary to know the dune height during equilibrium conditions and the initial change in dune height. The equilibrium dune height as a function of the waterdepth is determined from a regression analysis of a limited number (15) of flume tests (Figure 4). This figure is only applicable for the specific conditions in the sandflume during the described tests.

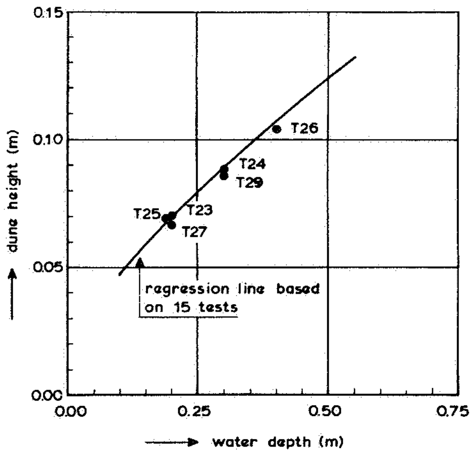


Figure 4 Relation between dune height and waterdepth for steady flow conditions in sandflume ($i = 1.6 \times 10^{-3}$, $D_m = 0.77$ mm, uniform material)

Results

The most important results are presented in Table 2. The differences in observed dune celerities for tests with the same boundary conditions are probably caused by three-dimensional phenomena in the sand-flume (van Rijn and Klaassen, 1981). The complete results will be published in a forthcoming report.

Test number	Number of measure-ments (-)	Discharge per unit width $q\,(m^2/s)$	Sediment transport per unit width (kg/hm)	Energy slope i(-)		Water-depth h(m)		Chezy coef-ficient $C(m^{1/2}/s)$		Dune height H(m)		Dune length L(m)		Average bedforms celerity c_b (m/h)
				$\bar{i}$	σ_i	$\bar{h}$	σ_h	$\bar{C}$	σ_C	$\bar{H}$	σ_H	$\bar{L}$	σ_L	
T22	17	0.177	86.9	1.64	0.13	0.302	0.003	27.5	1.0	0.077	0.013	1.20	0.24	2.43
T23	18	0.097	43.3	1.60	0.09	0.200	0.002	28.1	0.9	0.071	0.010	1.38	0.35	1.38
T24	20	0.177	83.5	1.56	0.12	0.301	0.003	28.5	1.3	0.087	0.013	1.45	0.29	2.38
T25	20	0.098	43.5	1.65	0.10	0.200	0.002	27.7	0.9	0.071	0.008	1.39	0.33	1.44
T26	20	0.267	119.4	1.53	0.12	0.405	0.005	28.1	1.0	0.104	0.013	1.59	0.26	2.88
T27	23	0.098	43.6	1.61	0.11	0.201	0.002	27.9	1.2	0.069	0.009	1.25	0.26	1.93
T29	13	0.177	82.1	1.68	0.06	0.301	0.002	27.4	0.7	0.086	0.009	1.41	0.18	2.46

Note 1: $\bar{x}$ = mean value of x; σ_x = standard deviation of x
Note 2: sediment transport has been measured under water

Table 2 Main results of measurements during equilibrium phases

During every transition a series of longitudinal bed level records were obtained. These records were plotted against the time. An example, relating to transition T27 (waterdepth decreases from 0.40 to 0.20 m), is presented in Figure 5.

After the data had been processed, for each transition the waterdepth, Chezy coefficient, dune height and dune length were plotted versus time. The results obtained for a transition in waterdepth from 0.20 m to 0.40 m and vice versa are presented in Figure 6. The initial change in dune height was measured from the plots of dune height versus time. The results are presented in Table 3, in which also the computed value of A_H (Equation (4)) is tabulated.

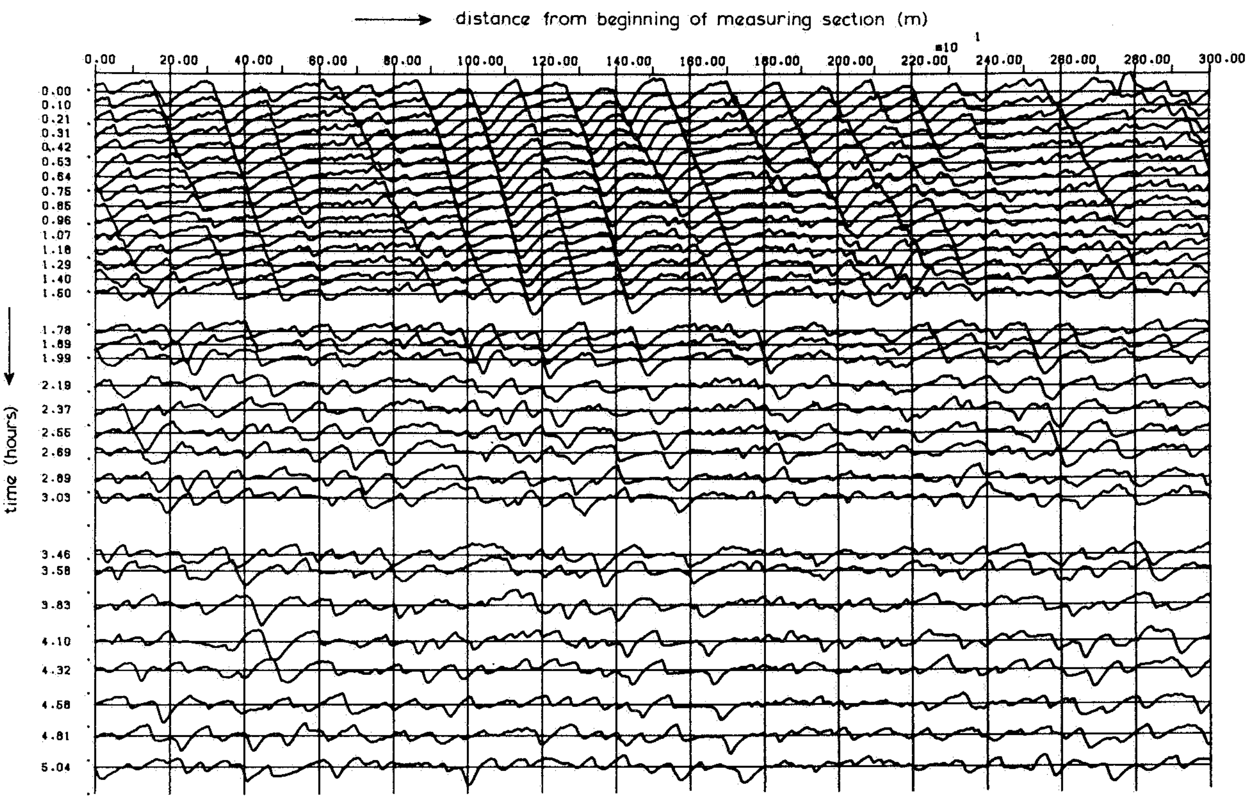
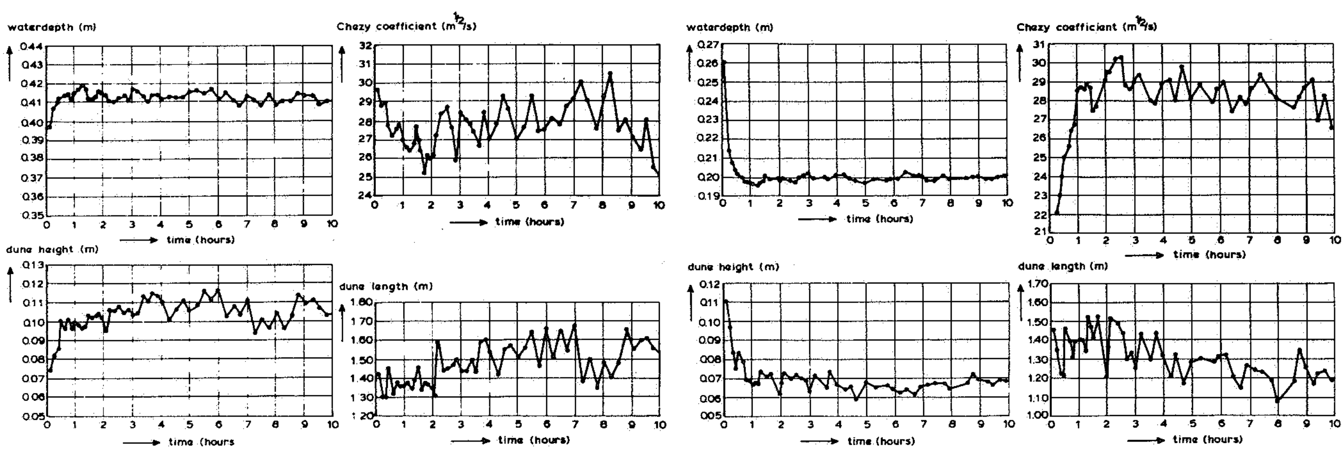


Figure 5 Bed-level records of middle profile versus time for transition T 27 (waterdepth decreases from 0.40 to 0.20 m, flume width 1.50 m, energy slope 1.6 x 10^{-3}, D_m = 0.77 mm, uniform material)



(a) T 26, waterdepth 0.20 → 0.40 m (b) T 27, waterdepth 0.40 → 0.20 m

Figure 6 Changes in waterdepth, Chezy coefficient, length and height of dunes for transitions T 26 (a) and T 27 (b) (flume width 1.50 m, energy slope 1.60 x 10^{-3}, D_m = 0.77 mm, uniform material)

Test number	Water-depth h(m)	Equilibrium dune height at t=0 H_o (m)	Equilibrium dune height at $t \to \infty$ H_∞ (m)	Initial change in dune height $\frac{dH}{dt}$ (10^{-6} m/s)	Coefficient of adaptation for dune height A_H (10^{-3} s^{-1})
T23	0.30→0.20	0.085	0.067	-3.2	0.18
T24	0.20→0.30	0.067	0.085	3.2	0.18
T25	0.30→0.20	0.085	0.067	-1.5	0.09
T26	0.20→0.40	0.067	0.100	15.3	0.46
T27	0.40→0.20	0.100	0.067	-26.7	0.81
T29	0.20→0.30	0.067	0.085	3.0	0.17

Table 3 Main results at start of transition

4. Comparison with earlier studies

Comparison with Gee (1973)

For tests with a sudden change in discharge Gee (1973) concluded that the transformation of flat bed into a dune-covered bed required a lower total sediment transport than the reversed transition. This higher efficiency implies that the coefficient of adaptation is higher for decreasing discharge than for increasing discharge. Similar results were obtained in the present flume tests, as can be seen from Table 3 and Figure 7, where the measured coefficient of adaptation for the dune height is plotted versus the ultimate change in dune height. During the tests the change in dune height takes place at a higher rate for decreasing discharges (and waterdepths) than for increasing discharges (and waterdepths). Furthermore it can be concluded from Figure 7 that the change in dune height cannot be approximated by a first-order curve as assumed in Equation (4).

Legend:
- ● measurement; initial water depth 0.20 m
- o measurement; final water depth 0.20 m
- ——— computed with Engelund and Fredsøe(1976); initial water depth 0.20 m
- – – – computed with Engelund and Fredsøe(1976); final water depth 0.20 m
- —·—·— computed with Meyer-Peter and Müller (1948); initial water depth 0.20 m
- —··—··— computed with Meyer-Peter and Müller (1948); final water depth 0.20 m

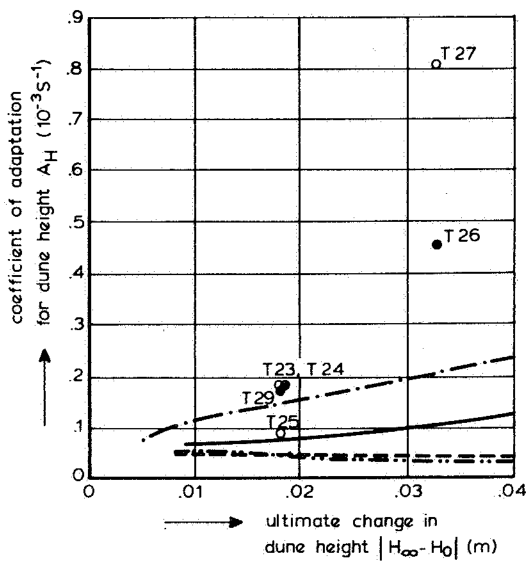


Figure 7 Measured coefficient of adaptation compared with prediction by method of Fredsøe (1979) with two different transport formulae (energy slope 1.60×10^{-3}, flume width 1.50 m, D_m = 0.77 mm, uniform material)

Comparison with Allen (1976[a])

In his computational model Allen (1976[a]) applied two parameters, viz.:
- the dune excursion (length over which a dunes travels before it looses its identity),
- coefficient of change A (Equation (3)).

The value of these two parameters can be derived from the results of the present tests.

To characterize the life-span of dunes during equilibrium conditions a cross-correlation technique was applied for a set of two measurements with an increasing time lapse. The maximum correlation coefficient was plotted versus the time lapse. The intersection of the tangent for t=0 with the horizontal axis is considered as a measure for the life-span of dunes (see Figure 8). The dune excursion C was calculated from:

$$C = \frac{c_b \cdot T}{L} \qquad (5)$$

where T = life-span (s)

The computed values for the dune excursion are presented in Table 4. For the present flume tests (see Figure 9) the dune excursion is in the order of 1 to 2. A similar value for the dune excursion is found when the plots of bed-level records versus time (Figure 5) are inspected visually.

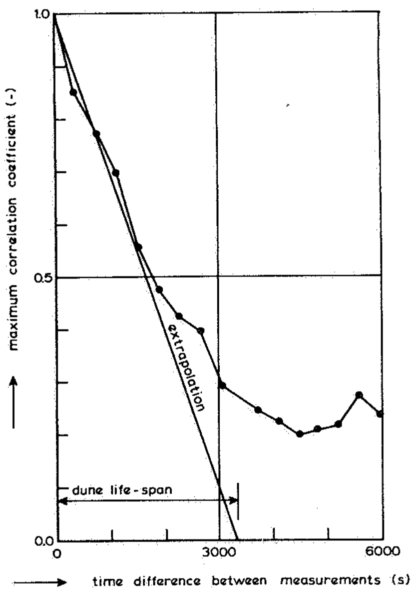


Figure 8 Determination of the life-span of dunes

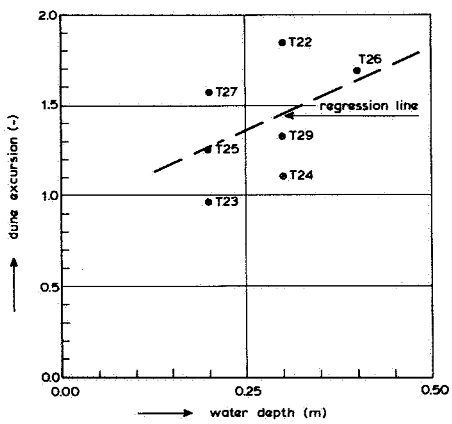


Figure 9 Measured dune excursion as defined by Allen (1976[a]) for the sandflume data

The coefficient of change A appears to vary with the ultimate change in dune height. This can be concluded from Table 4, in which also the computed values of A are listed. Apparently the assumption of a constant value for A in Equation (3) does not hold. It should be remarked that the computed value of A includes both the change in dune height according to Equation (3) and the change in dune height due to the selective process of creation and destruction of bedforms during the transition. It may be assumed, however, that during the initial phase of the transition the latter plays only a minor role.

Test number	Water-depth h(m)	Measured dune length L L(m)	Bedform celerity c_b(m/h)	Lifespan of dunes T(h)	Dune excursion according to Allen (1976) (-)	Change in dune height $(H_\infty - H_o)$ (m)	Coefficient of change A(m)
T22	0.302	1.20	2.43	0.91	1.84		
T23	0.200	1.38	1.38	0.97	0.97	0.018	0.040
T24	0.301	1.45	2.38	0.67	1.10	0.018	0.018
T25	0.200	1.30	1.44	1.22	1.26	0.018	0.019
T26	0.405	1.59	2.88	0.93	1.68	0.033	0.039
T27	0.201	1.25	1.93	1.02	1.57	0.033	0.151
T29	0.301	1.41	2.46	0.70	1.33	0.018	0.017

Table 4 Dune excursion and coefficient of change for sandflume data

Comparison with Fredsøe (1979)

The results of the flume tests were also used to make a comparison between the measured value of the coefficient of adaptation A_H and the value calculated on the basis of the initial change in dune height (Equation (1)) as proposed by Fredsøe (1979). The results for two transport formulas (Meyer-Peter & Müller, 1948 and Engelund & Fredsøe, 1976) are plotted in Figure 7.

Apparently there are differences between the coefficient of adaptation for a decrease in discharge (with the same final water depth) and an increase in discharge (starting from the same initial water depth). During the latter a higher coefficient of adaptation is found. During the flume tests, however, lower values were measured for an increase in discharge and higher values during a decrease in discharge (see Figure 7).

Furthermore it may be concluded that for the present flume tests the coefficient of adaptation determined with Fredsøe's relation using the Meyer-Peter & Müller formula yields good results as long as the change in discharge (and thus the ultimate change in dune height) is not too large.

5. Additional remarks

The following remarks should be made regarding the described flume tests and the whole study into the resistance to flow of the minor bed during the passage of flood waves:

(1) A similar set of tests with a increase or decrease in discharge was carried out for a flume width of 0.5 m. This was done because it was expected that three-dimensional phenomena in the flume (van Rijn and Klaassen, 1981) might have influenced the results of the described tests. The results have not been processed completely, but it would appear that the results are approximately similar.

(2) Recently a number of tests has been started with an imposed discharge variation similar to a real flood wave in a river. Also during these test (with a constant slope and a waterdepth variation between 0.15 and about 0.50 m) the resistance to flow and the bedform dimensions are measured as a function of time.

(3) Apart from these laboratory tests, also extensive field measurements of the resistance to flow and the changes in bedform dimensions are being carried out since 1979 (Havinga and van Urk, 1980). These measurements are made in two of the Rhine branches in the Netherlands. The results of these field measurement will be used for checking the applicability of the results of the present tests for prototype-conditions.

(4) To be able to apply the methods of Allen (1976) or Fredsøe (1979) it is necessary to have a prediction method for H_∞. Methods have been proposed by Yalin (1977) and Allen (1968), but verification of these methods, especially for field conditions, is required. Also for this reason field measurements are carried out in the various Rhine branches.

6. Conclusions

The following conclusions can be drawn from the results of the flume tests described in this paper and the comparison with earlier investigations:

(1) The change in bedform dimensions does not follow a first-order curve as assumed in Equation (4).

(2) The coefficient of adaptation for the dune height is higher for decreasing discharges than for increasing discharge, if the ultimate change in water depth is the same (see Figure 7).

(3) For the flume tests considered the dune excursion C from Allen's (1976[a]) computational model is in the order of 1 to 2, and increases slightly for increasing water depth. The coefficient of change A (see Section 2) determined with the flume tests is not constant.

(4) The coefficient of change determined with the relation proposed by Fredsøe (1979) depends on the transport formula used. Besides, the difference in coefficient of adaptation for the dune height is slightly higher for increasing discharges then for decreasing discharges, which is just opposite to the measured results (see Figure 7).

(5) Fredsøe's (1979) method does not adequately describe the observed increase and decrease of bedform dimensions during the described tests, while a number of adaptations should be made to the computational model of Allen (1976) before it can be applied for the simulation of the time-dependent behaviour of dune dimensions.

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