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DHL-RESEARCH ON BEDFORMS, RESISTANCE TO FLOW AND SEDIMENT TRANSPORT

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SUMMARY

A review is presented of activities of the Delft Hydraulics Laboratory in the field of bedforms, resistance to flow and sediment transport in uni-directional flow. Both theoretical and experimental work is dealt with. The experimental work comprises both measurements in straight laboratory flumes and field measurements, the latter being carried out by the Dutch Ministry of Public Works and Water Management. Excluded from the review are 2-dimensional conditions where helical flow plays an important role (river bends and bifurcations) and the mathematical modelling of river morphology. For these two subjects reference is made to Struiksma et al. (1985) and Klaassen et al. (1982).

1. Introduction

The increased use of the River Rhine and its branches in The Netherlands for navigation and water supply and the need to protect low-lying areas of the country against floods has necessitated the development of more refined methods to predict the effects of any human interference in the river system. This has resulted in the development of sophisticated mathematical models in which existing knowledge on morphological processes is integrated (Klaassen et al., 1982). It has, however, also created the need for improved understanding of the morphological processes in rivers. In view of this, the Dutch Ministry of Public Works and Water Development has commissioned the Delft Hydraulics Laboratory (DHL) to carry out an extensive research into bedforms, resistance to flow and sediment transport in alluvial rivers. This paper provides a review of the results obtained until now, while it includes also some results of internally financed research work by DHL. No results are presented of DHL research related to 2-dimensional conditions where helical flow plays a dominant role (like river bends and bifurcations) while also the development of mathematical models for river morphology is excluded here. For the latter two items reference is made to Struiksma et al. (1985) and Klaassen et al. (1982).

The research into morphological processes reviewed here is carried out jointly by the Delft University of Technology (mainly working on sediment transport of mixtures), the Dutch Ministry of Public Works and Water Management (mainly field measurements) and the Delft Hydraulics Laboratory. As the research reviewed here is still in progress, not all the results have already been published in official (DHL-) reports or other publications.

2. Research approach and research topics

2.1 Research approach

The research activities reviewed here are guided by the following strategy:

- The topics to be studied should be related to and be derived from problems experienced in actual river engineering and river management.
- Theoretical and experimental investigations in the laboratory should be guided and be complemented by field investigations and by field applications.
- The research should be a combination of short-term research for improvement of existing predictors and long-term research primarily aiming at improving the understanding of alluvial channel mechanics.

- As the important role of bedforms in alluvial channel mechanics is fully appreciated, the research programme should concentrate on bedforms, their occurrence and dimensions, and their effect on resistance to flow and sediment transport.
- As the research programme funded by the Dutch Ministry of Public Works and Water Management is mainly focussed on rivers with predominant bed load, the internally financed research of DHL deals mainly with suspended load phenomena.

2.2 Research topics

The topics covered in the research described here are summarized in Table 1. In this table it is also indicated whether the purpose of the research is short-term improvement of predictors or whether the research is aiming at an increased understanding of alluvial channel mechanics. Furthermore the table allows to appreciate to what extent field or flume data are being gathered within the framework of the research described.

SUBJECTS	Theoretical research		Experimental research				
	short-term improvement	long-term understanding	field measurements	DHL sand flume	other DHL flumes	Delft University of Technology flume	Extended World Flume Data
BEDFORMS							
. occurrence	*		*	*			*
. characterization	*	*	*	*		*	
. equilibrium dimensions	*	*	*	*			*
. dimensions for unsteady conditions	*	*	*	*			
RESISTANCE TO FLOW							
. roughness of bedforms	*	*	*	*			*
SEDIMENT TRANSPORT							
. bed load	*	*	*	*	*		*
. suspended load	*				*		*
. mixtures	*	*		*		*	
. armouring	*	*		*			

Table 1 Research topics covered in the present review

3. Experimental facilities

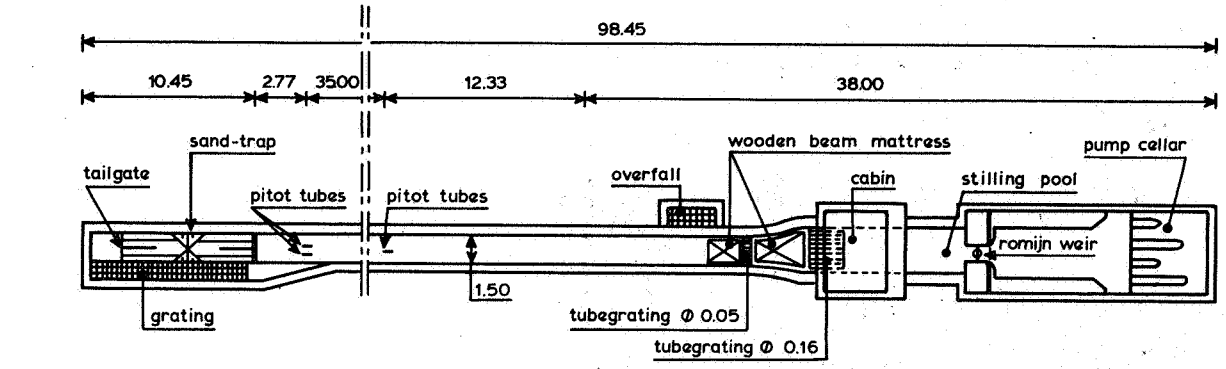
3.1 Field measurements

Extensive mesurements are being carried out in the three branches of the River Rhine (viz. the Waal River, Pannderdens Kanaal/Nederrijn/Lek and the IJssel River) in The Netherlands. Some characteristic data of these branches are:
- width varying between 400 and 100 m,
- discharge between 50 and 10,000 m^3/s,
- slope $2.0*10^{-4}$ to $0.5*10^{-4}$,
- maximum depth up to 15 m,
- D_m varying between 6 and 0.4 mm.

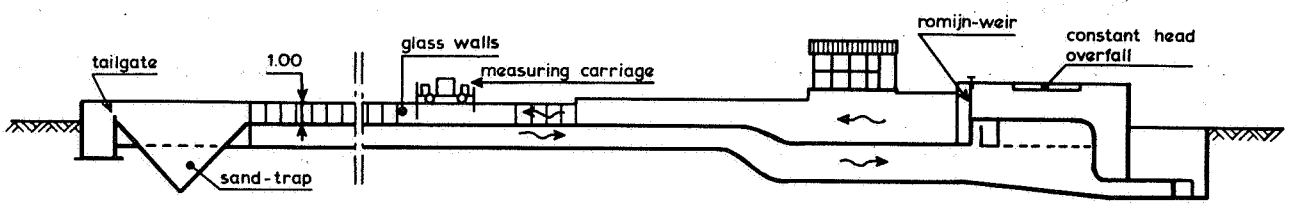
Sophisticated measuring boats have been built and are used specifically for field experiments required within the present research programme (Havinga and van Urk, 1981). With these boats a.o. longitudinal soundings can be carried out on a regular basis, allowing improved insight in the occurrence of bedforms and changes in their dimensions over time.

3.2 Flume experiments

Most of the laboratory measurements are being carried out in the large sand flume of DHL. Its most important characteristics (see also Plate 1 and Figure 1) are:
- overall length 100 m,
- length measuring section 30 m,
- width variable between 0.3 and 1.5 m,
- depth 1.0 m,
- maximum effective depth (with sediment) 0.6 m,
- maximum discharge 0.8 m^3/s,
- maximum sediment transport 1.5 m^3/hour.

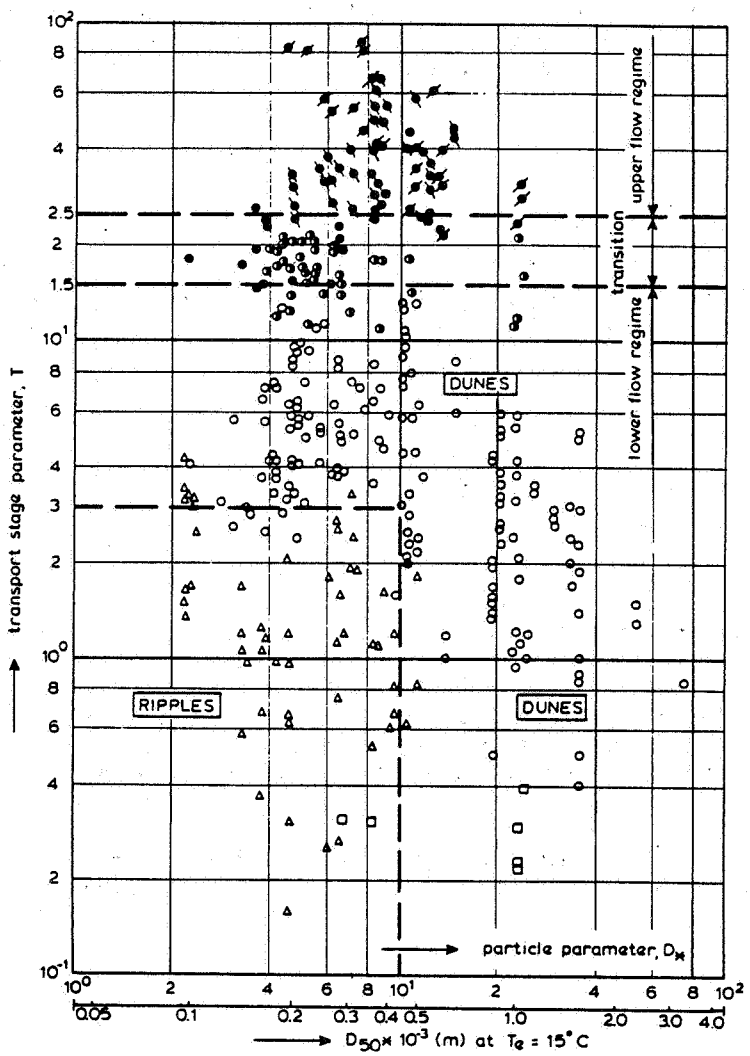


(a) plan view



(b) longitudinal section

Figure 1 DHL sandflume



Bed-forms	Source: Flume Data	Source: Field Data
□ Plane bed (no motion)	Guy et al	
△ Ripples	Guy et al Ackers Laursen	
○ Dunes	Guy et al Delft Hydr Lab.	Dutch Rivers Pakistan Canals
	Stein Williams Znamenskaya	Rio Parana Hii River (Japan)
● Transition	Guy et al	Missouri River (U.S.A.)
● Plane bed	Guy et al	
Anti-dunes (standing waves)	Guy et al	Rio Grande (U.S.A.)
Anti-dunes (breaking waves)	Guy et al	

Figure 2
Classification of bedforms
(van Rijn, 1984c)

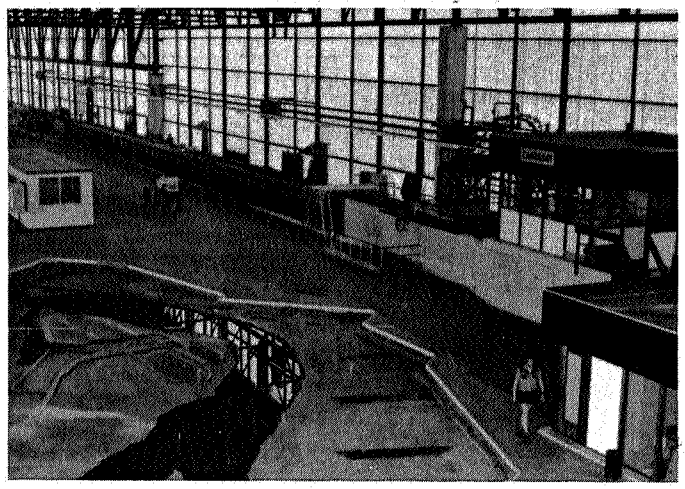


Plate 1 Large sand flume in the Delft Hydraulics Laboratory

For more details on the DHL sand flume reference is made to Bakker (1984) or Wijbenga and Klaassen (1981).

Also smaller flumes are being used, in particular one in the laboratory of the Delft University of Technology.

3.3 Other data

In the various theoretical investigations extensive use is being made of the Howell and Peterson (1973) compendium of alluvial channel data (hereafter referred to as WFD = World Flume Data). Recently also the Brownlie (1981a) collection is used, being an extension and improvement of the WFD. DHL has extended these compendia by adding more data to the already compiled measurements (e.g. bedform dimensions, whenever available) and by including more sets of measurements, a.o. the ACOP data. This is referred to as the Extended WFD set.

4. Bedforms

4.1 Occurrence of bedforms

Van Rijn (1984c) studied the occurrence of bedforms for various conditions using the Extended WFD. He prepared a graph on which the bedforms are classified according to the transport stage parameter T, defined via:

$$T = \frac{(u_*')^2 - (u_{*cr})^2}{(u_{*cr})^2} \qquad (1)$$

and the characteristic particle parameter D_*, defined via:

$$D_* = D_{50} \left\{\frac{(\rho_s-\rho)}{\rho}\frac{g}{\nu^2}\right\}^{1/3} \qquad (2)$$

in which: $u_*' = (g^{0.5}/C').\bar{u}$ = bed shear velocity related to grains, $\bar{u}$ = mean flow velocity, $C' = 18 \log(12 R_b/3 D_{90})$ = Chézy coefficient related to grains, R_b = hydraulic radius of the bed, D_{90} = particle diameter of bed material not exceeded by 90% by weight of the particles, u_{*cr} = critical bed shear velocity for initiation of motion according to Shields, D_{50} = particle diameter of bed material not exceeded by 50%, ρ_s = sediment density, ρ = fluid density, g = acceleration of gravity and ν = kinematic viscosity coefficient.

The graph obtained by van Rijn (1984c) is shown in Figure 2. The origin of the points which are plotted in the figure is indicated in the table next to it. From the figure it is

possible to read the type of bedforms that will occur in a river or a flume for equilibrium conditions. In flumes and even more so in rivers it may take quite some time before equilibrium conditions have been reached. This is illustrated in Figure 3, which shows the changes over time of various parameters during one particular test in the DHL sand flume. In this test also the overall energy slope had to adapt to the new conditions, the imposed variables being the discharge Q and the sediment transport s.

4.2 Bedform characterization

The dimensions of individual bedforms are continuously changing over time, also during equilibrium conditions. This can be observed in Figure 4, providing longitudinal soundings in the middle profile of the DHL sand flume. From Figure 5 it can be concluded that dimensions of individual dunes are varying over the width also. In this particular test the aspect ratio (ratio between flume width and water depth) was about 6. For smaller aspect ratios the bedforms become more 2-dimensional, but the influence of the wall roughness increases. Larger aspect ratios result in a more irregular pattern over the width, the crests of the dunes not any longer being perpendicular to the main flow direction. Also alternate bars on which dunes are imposed will develop (see below).

Bogirski (1977) has attempted to apply spectral analysis to londigtudinal soundings in the DHL sand flume. He observed that even during equilibrium conditions the spectrum of the subsequent soundings varied considerably (see Figure 6). This is probably due to the limited number of bedforms present in the sand flume (about 20 for the test from which results are presented in Figure 6). This cast doubts on spectra based on only one sounding in flumes with limited length. In natural rivers it is possible to obtain longer records, but usually the variations in width, overall bed configuration and bed material characteristics in longitidunal direction limit the maximum length of a sounding.

Schilperoort (1984) prepared a critical review of existing methods for characterization of bedforms. He suggested that the application of time series analysis may yield better results than obtained until now. Exploring studies (de Leeuw, 1985; Moll, 1985) dealing with time series analysis of river soundings and flume records are promising. These techniques, however, are not so far advanced that they can already be used on a regular basis. The analysis of the bed level records discussed hereafter is based on averaging the individual height and length of dunes. Klaassen and van Urk (1986) showed that for flume data the arithmetic average provides a sufficient measure for dunes in flumes, while for river records it is preferable to determine a weighted average.

Until recently individual bedforms in the DHL sand flume were identified by means of up-crossings of the bed level record with the corresponding regression line. In general this resulted in an under-estimation of the bedform dimensions due to the presence of ripples and small dunes. Another disadvantage was the presence of alternate bars in the DHL sand flume for aspect ratios larger than about 5 (van Rijn and Klaassen, 1981). Wang (1986) studied the possibility of applying filtering before further analyzing the bed level records. In the Figures 7 and 8 the results of filtering are illustrated. Figure 8 also provides a good insight in the occurrence of alternate bars in the DHL sand flume. On the alternate bars dunes are superimposed. Recently Bakker (1985) developed a new method in which crest and trough of each individual bedform are identified separately and the dune dimensions are obtained from their location and level. When establishing the average bedform dimensions, the results are quite satisfactory.

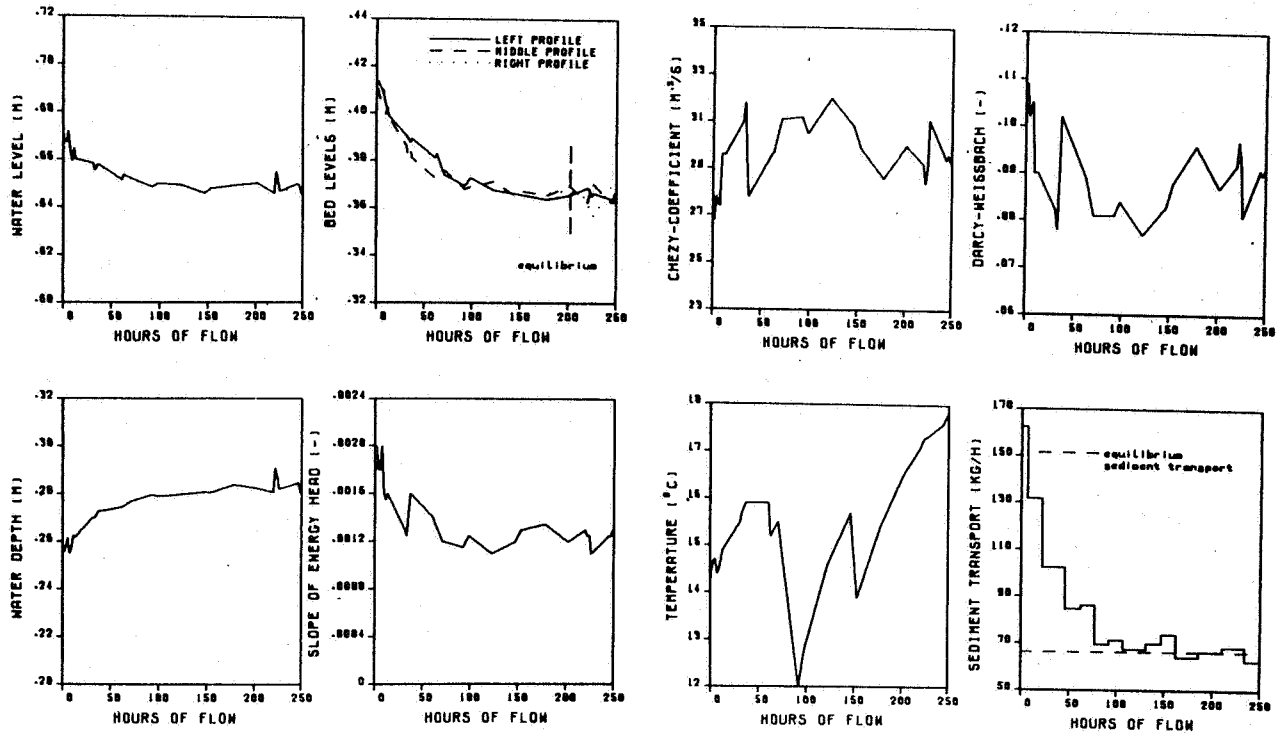


Figure 3 Variation of various parameters during establishment of equilibrium conditions for characteristic test (Bakker, 1985)

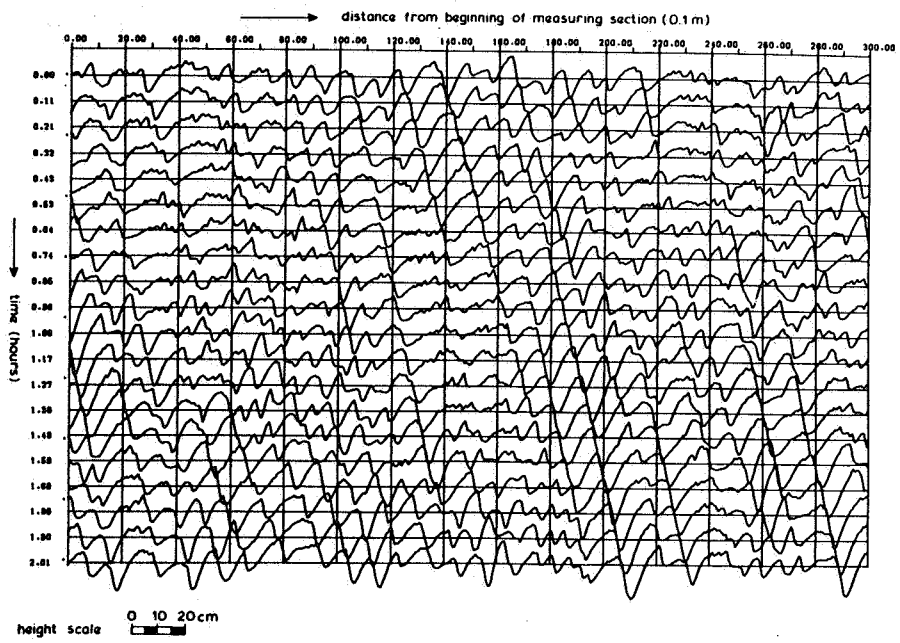


Figure 4 Longitudinal soundings during equilibrium conditions (Bakker, 1985)

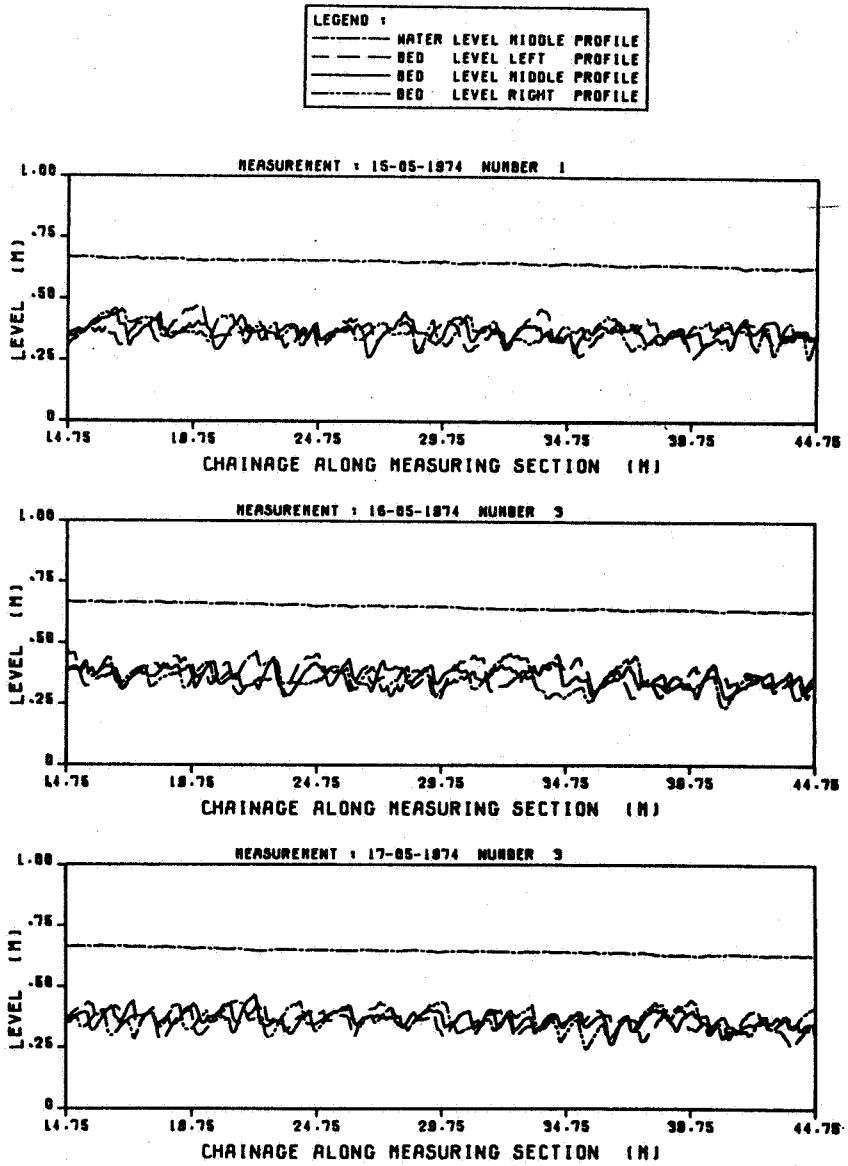


Figure 5
Longitudinal soundings in three parallel profiles in DHL sandflume during equilibrium conditions (Bakker, 1985)

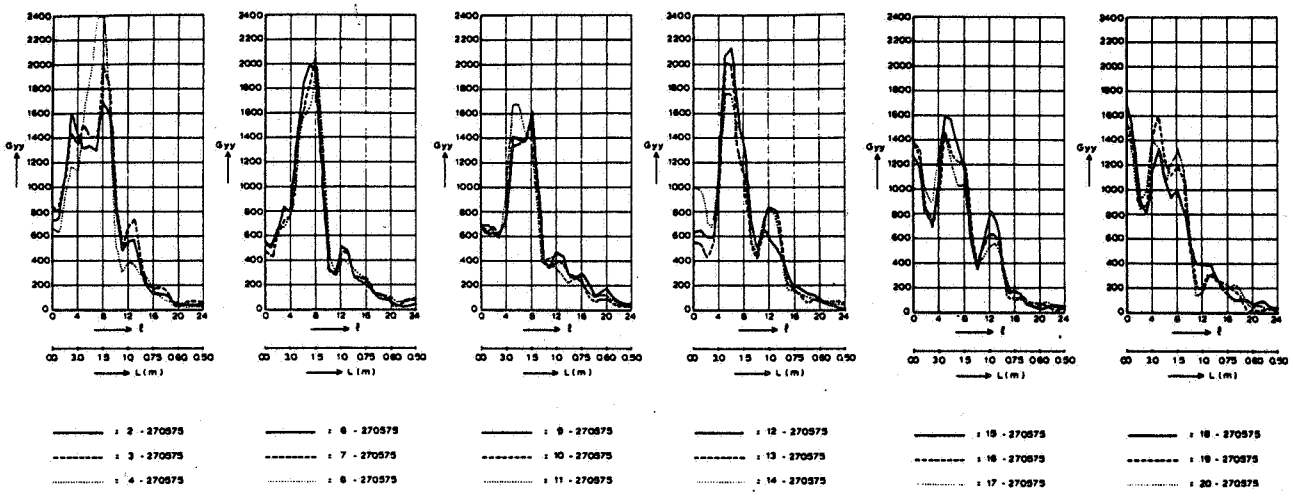


Figure 6 Changes in computed spectrum during equilibrium conditions for longitudinal soundings in DHL sandflume with an interval of about 10 minutes (Bogirski, 1977)

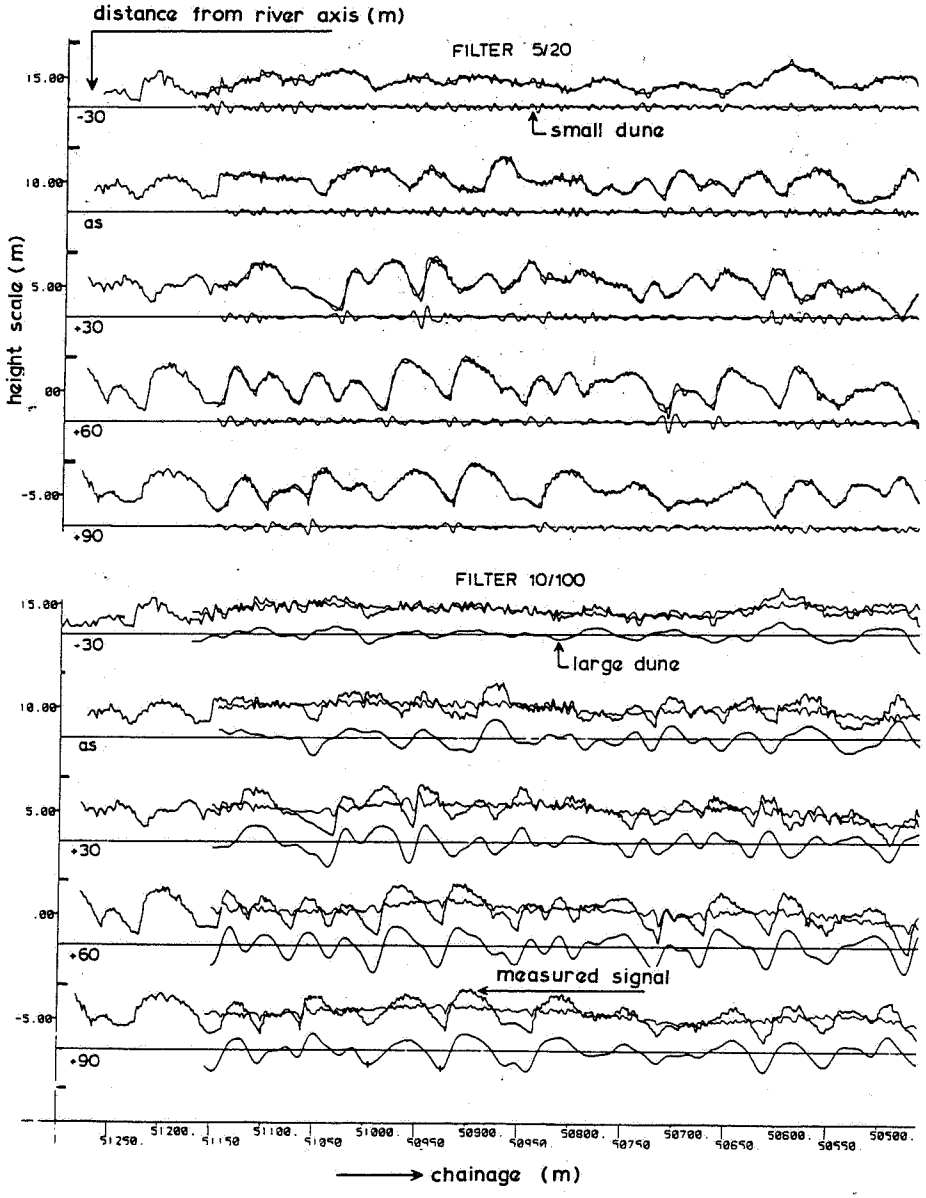


Figure 7 The effect of filtering on bed level records obtained in rivers (Ogink, 1984)

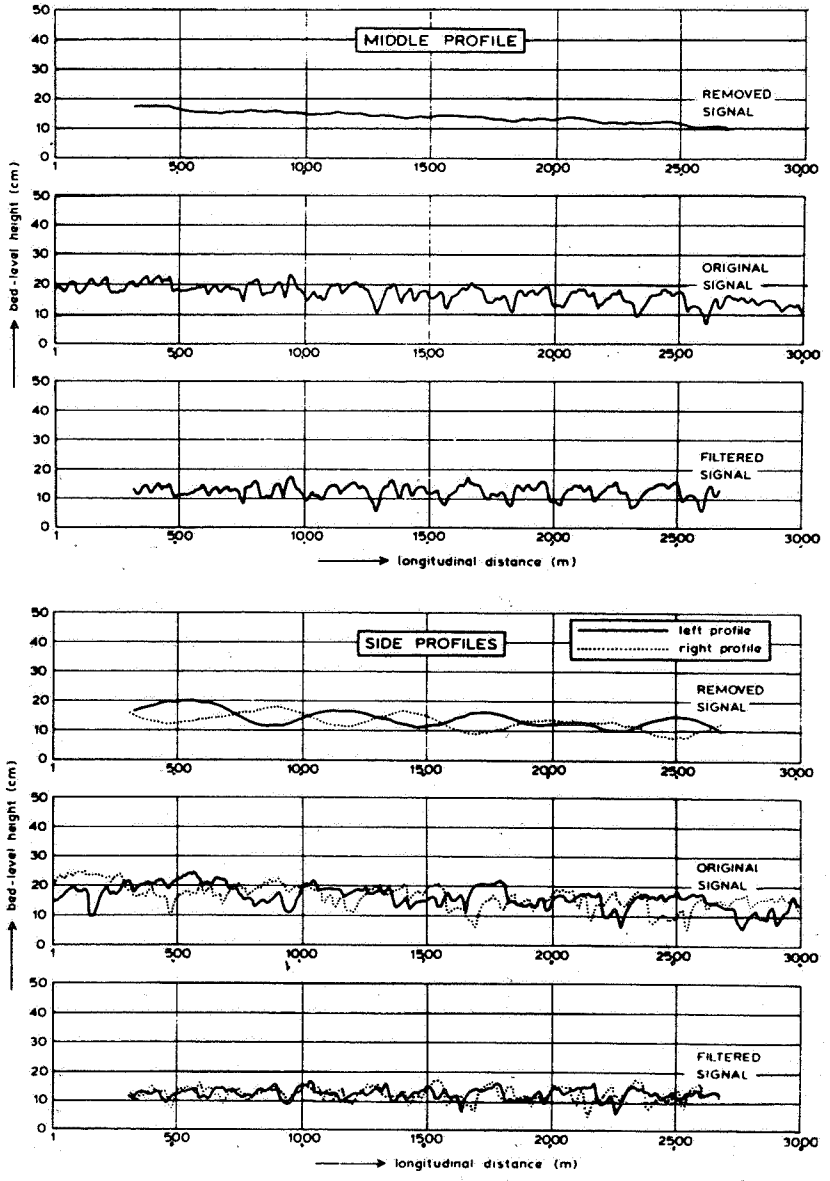


Figure 8 Filtering of DHL sandflume soundings to remove alternate bar pattern (van Rijn and Klaassen, 1981)

4.3 Bedform dimensions for equilibrium conditions

Van Rijn (1984c) argued that the relative dune height H/h and steepness H/L can be expressed as:

$$\frac{H}{h} = F_1\left(\frac{D_{50}}{h}, D_*, T\right) \quad (3)$$

$$\frac{H}{L} = F_2\left(\frac{D_{50}}{h}, D_*, T\right) \quad (4)$$

in which L = bedform length.

To determine these functional relationships, a large quantity of experimental bedform data were analyzed. In all, 84 flume data with particle diameters ranging from 190-2300 μm and 22 field data with particle diameters ranging from 490-3600 μm were used (van Rijn, 1982). The influence of the D_*-parameter was found to be negligibly small. The best agreement between measured and computed results was obtained for:

$$\frac{H}{h} = 0.11 \left[\frac{D_{50}}{h}\right]^{0.3} \left[1 - e^{-0.5T}\right] \left[25 - T\right] \quad (5)$$

$$\frac{H}{L} = 0.015 \left[\frac{D_{50}}{h}\right]^{0.3} \left[1 - e^{-0.5T}\right] \left[25 - T\right] \quad (6)$$

It is assumed that for $T \leq 0$ and $T = 25$ the bed is almost plane. Equations (5) and (6) as well as the error range of a factor 2, are shown in Figures 9 and 10. Nearly all data are within the plotted error range.

The above equations were derived essentially already some years earlier (van Rijn, 1982b). Since then research has been continued and this has resulted in the following observations to be made:

(i) From the Equations (5) and (6) it follows that:

$$L = 7.3\ h \quad (7)$$

A further analysis of the available data suggest that this relationship does not hold universally. Probably longer dunes are present for smaller values of D_* and shorter dunes for larger values of D_* (Ogink, 1984b). At present this subject is being studied in more detail.

(ii) Recently an experimental study was carried out (Termes, 1986) to investigate in more detail the reduction of dune height for larger transport rates. This reduction is predicted a.o. by the theory of Fredsøe (1981) and by van Rijn (1984c). Tests were done for sand as bed material with characteristic particle sizes of D_{50} - 0.4 mm and D_{84} - 0.8 mm. The bed slope was maintained at about 3.10^{-3}. For increasing discharge it was observed that the relative dune height remained approximately constant, while the average dune length increased considerably. Some longitudinal bed records are presented in Figure 11, while in Figure 12 a comparison is made between the observation made and the theory of Fredsøe (1981). It may be concluded that for these tests changes in dune length are more important than changes in relative dune height, while also a revision of the theory of Fredsøe appears to be necessary.

The above Equations (5) and (6) are based on data fitting but no consistent theory is underlying them. Within the research programme reviewed here there is also a component aiming at an improved understanding of bedform mechanics. This is done on the basis of a mathematical mode DUGRO in which all understanding of bedform mechanics is integrated. The model consists of a sub-model that computes the water movement over dunes and a sub-model that computes changes in bed levels of the dunes and the deposition in the lee-side of the dunes. The sub-model for the simulation of the water movement described by Klaassen (1978) was improved by applying the boundary layer concept over the whole dune length and by including the Coles velocity profile (van der Knaap, 1986). At present it provides a

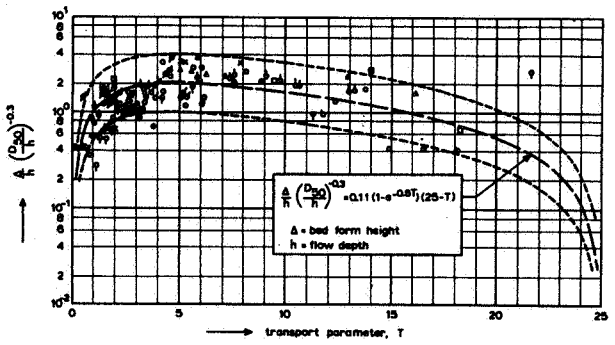


Figure 9 Bedform height H as a function of particle size (D_{50}), flow depth (h) and transport stage (T) (van Rijn, 1982)

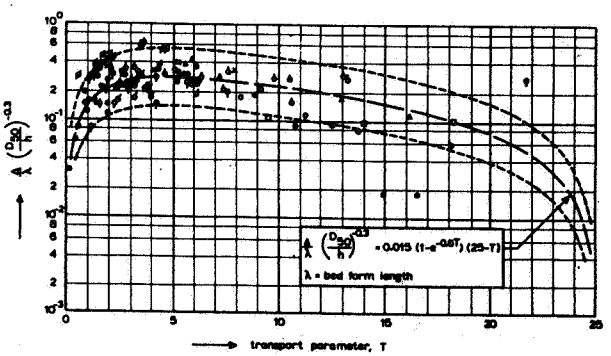


Figure 10 Bedform steepness H/L as a function of particle size (D_{50}), flow depth (h) and transport stage (T) (van Rijn, 1982)

(a) Q = 0.101 m³/s

(b) Q = 0.295 m³/s

(c) Q = 0.392 m³/s

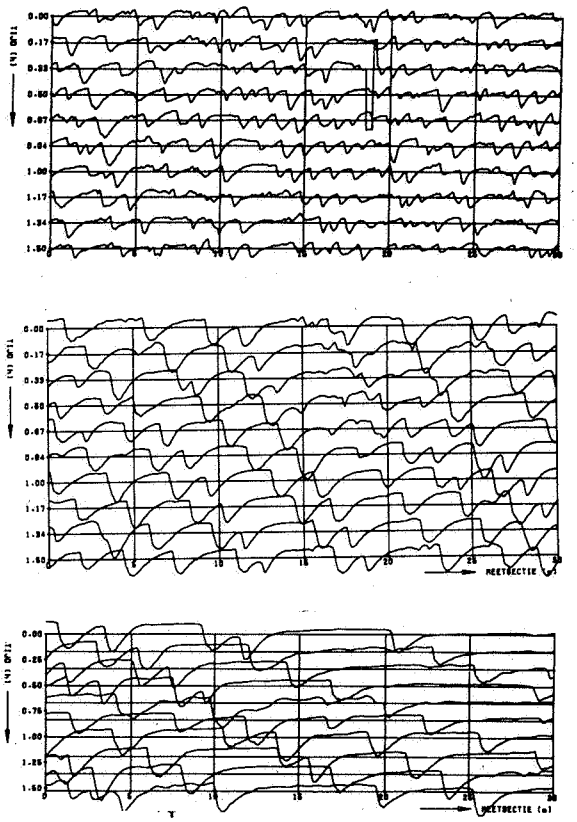
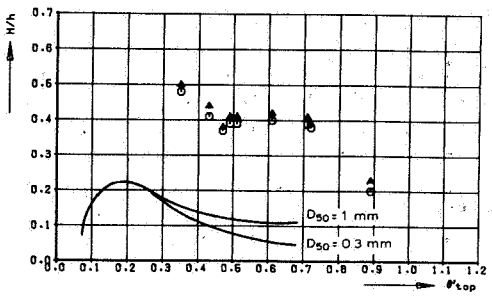


Figure 11 Bed level records for increasing discharge ($D_{50} \cong 0.4$ mm, $D_{84} \cong 0.8$ mm, slope 3.10^{-3})



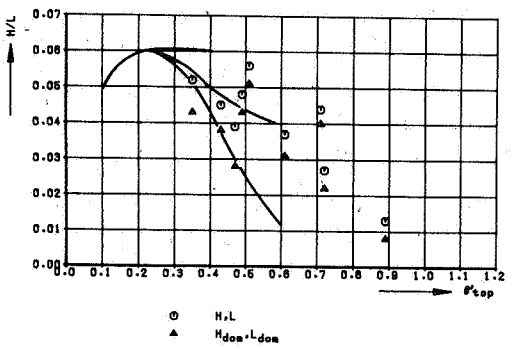


Figure 12 Measured relative dune height and dune steepness ($D_{50} \cong 0.4$ mm) compared with prediction by the method of Fredsøe (1981).

reasonable prediction of the shear stress distribution over dunes; the total resistance to flow, however, is slightly underestimated. The sub-model is less accurate than could be obtained when using a more complicated turbulence model (Puls, 1981), but a relatively simple model was preferred as the sub-model has to be used quite a number of times during one simulation run of the development (conform Klaassen, 1978). Some results of a comparison with the Raudkivi (1976) data are presented in Figure 13. For more details reference is made to van der Knaap (1986). For the sub-model for the changes in bed levels over the dunes, an extensive theoretical study has been carried out into the local erosion, deposition and transport rates on dunes, based on a prediction method for local sediment transport as function of the mean and r.m.s. values of the local bed shear stress. It seems essential to take into account the turbulent fluctuations of the shear stress in theoretical models for dune development. A summary of this research has been published (de Ruiter, 1982). More extensive reporting will be done by de Ruiter (1986b).

The mathematical model DUGRO in which the sub-models are integrated can in principle simulate dune behaviour for steady and unsteady conditions. Some preliminary results of application of the model to an average dune in the sand flume are given in Figure 14. For the time being the model is restricted to bed load and to a series of regular dunes. For irregular dunes the model should be extended to include also the overtaking of one dune by another, while also new dunes should be generated.

As the Raudkivi (1976) and other data are not sufficiently accurate extensive measurements of the turbulent flow field above fixed regular dunes were carried out recently. Velocities in two directions (longitudinal and vertical) were measured with a laser-Doppler-technique and the bed-pressure distribution by means of pressure transducers. The results yield insight in mean velocities, shear stress and pressure distribution along the dunes and their turbulent fluctuations. For this particular configuration (H = 0.08 m, L = 1.80 m), the experiments can be considered as an improvement of the pioneering work by Raudkivi and later work by Vittal et al. (1977), the difference being a.o. better defined boundary conditions, better instruments and higher accuracy. Results are available (de Ruiter, 1986a).

4.4 Bedform dimensions for unsteady conditions

The effect of the passage of flood waves on the bedform dimensions have been and are being studied experimentally both on the field and in the DHL sand flume.

Extensive measurements in the field have been done by Rijkswaterstaat. The measurements comprise longitudinal soundings in many stretches of the Rhine River and its branches in The Netherlands. Repeated soundings during the passage of flood waves have provided a good impression of bedform development in the field. Some preliminary results were published by van Urk (1982). An overall picture of the variation of bedform dimensions in the Rhine and Waal Rivers during the passage of flood waves was published recently by Ogink (1984b). The most remarkable phenomenon observed is the presence of small dunes superimposed on larger dunes and their different response to the flood wave passage (see Figure 15). These small dunes have a considerable effect on the form roughness (see Section 5.3).

Changes in bedforms dimensions for unsteady conditions have been studied in the DHL sand flume since 1977. The following experiments have been done:
- dune-dune transitions, uniform material, D_m = 0.78 mm, stepwise increase and decrease in discharge;
- do, but with flood waves with a base period of 3.75 and 7.5 hours superimposed on a base flow;
- dune-flat bed (high transport rate) transition, uniform material, D_m = 0.4 mm; stepwise increase or decrease in discharge.

Results of the first series of experiments have been published (Wijbenga and Klaassen, 1981). Some results for the flood wave experiments and for the dune-flat bed (high transport rate) transitions are presented in the Figures 16 and 17, respectively.

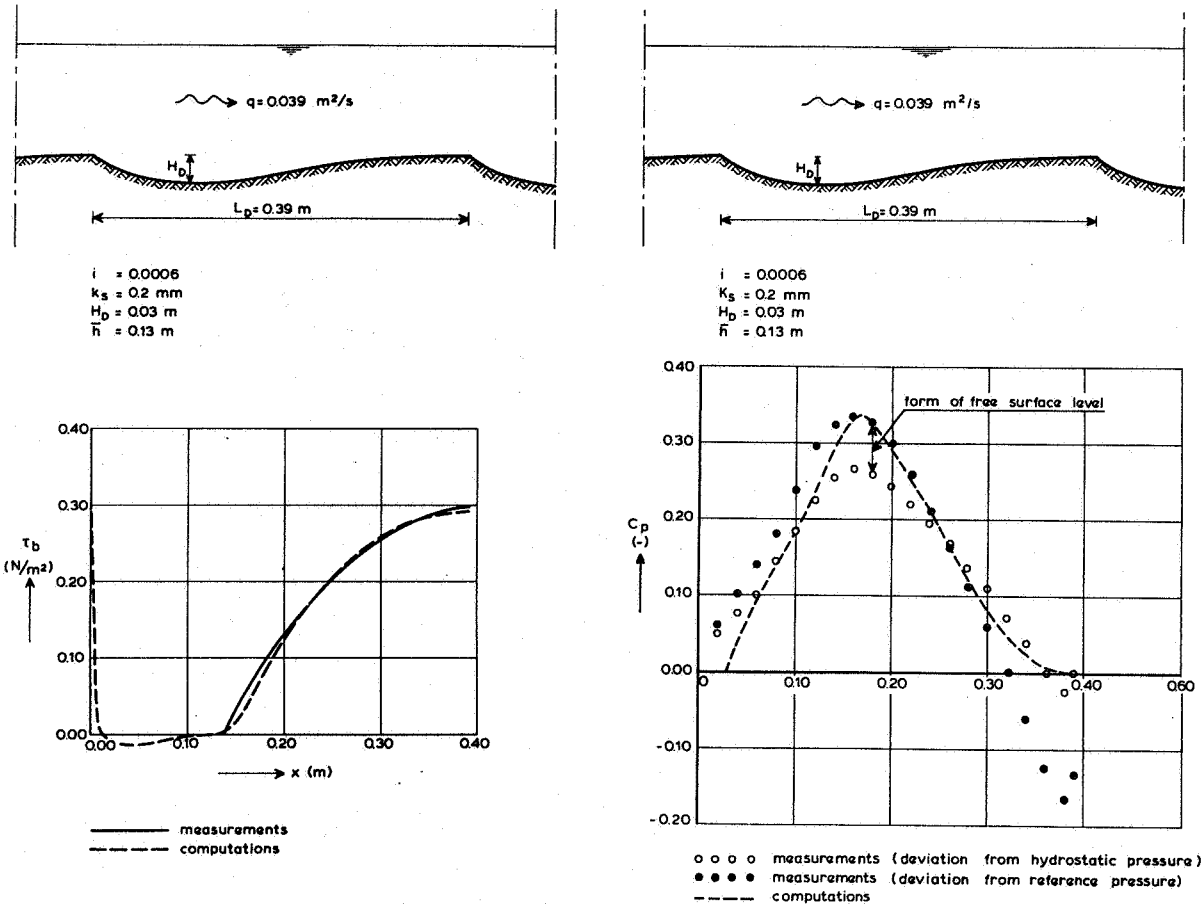
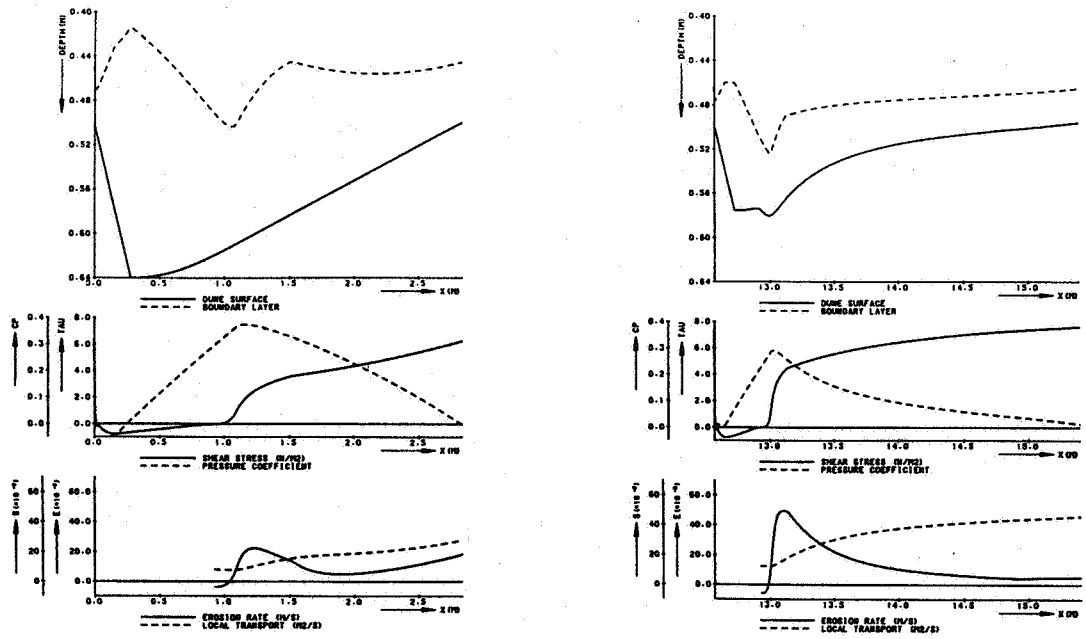


Figure 13 Comparison of measured and computed shear stress and pressure distribution; measurements by Raudkivi (1976)



(a) t = 0 min (b) t = 60 min

Figure 14 Preliminary results of application of DUGRO model for dunes in the DHL sand flume

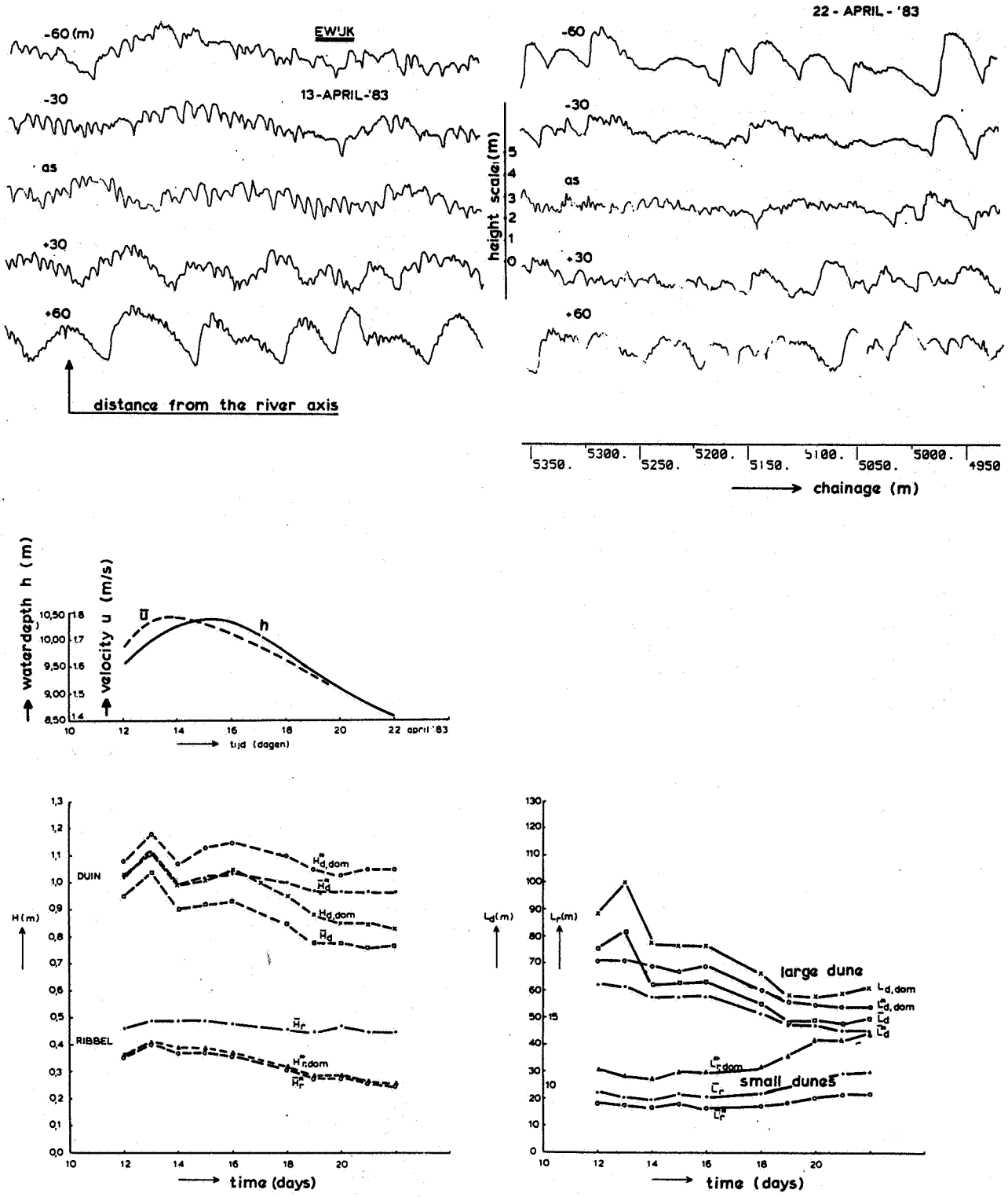
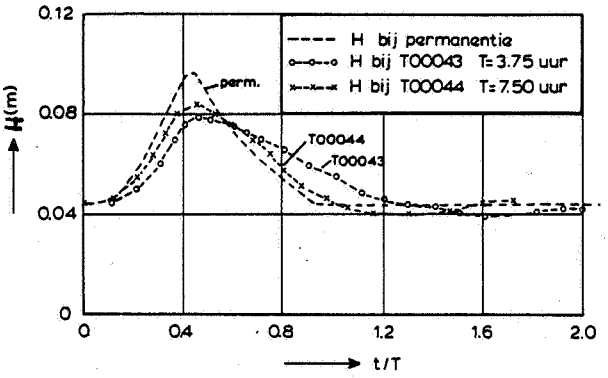
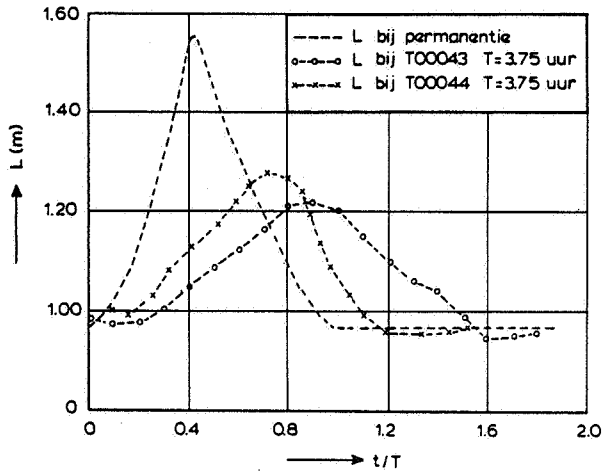


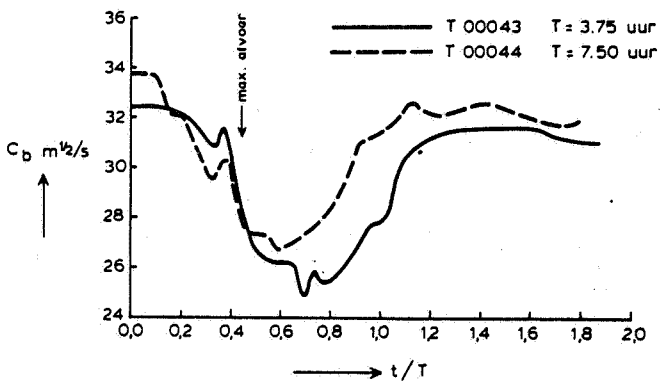
Figure 15 Changes in bedform dimensions in the Waal River near Ewijk during passage of flood (Ogink, 1984)



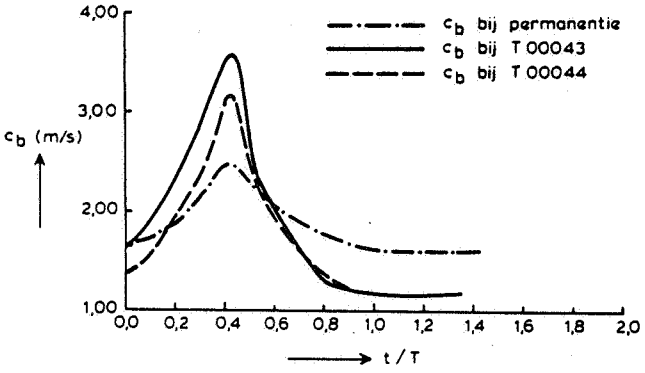
(a) dune height



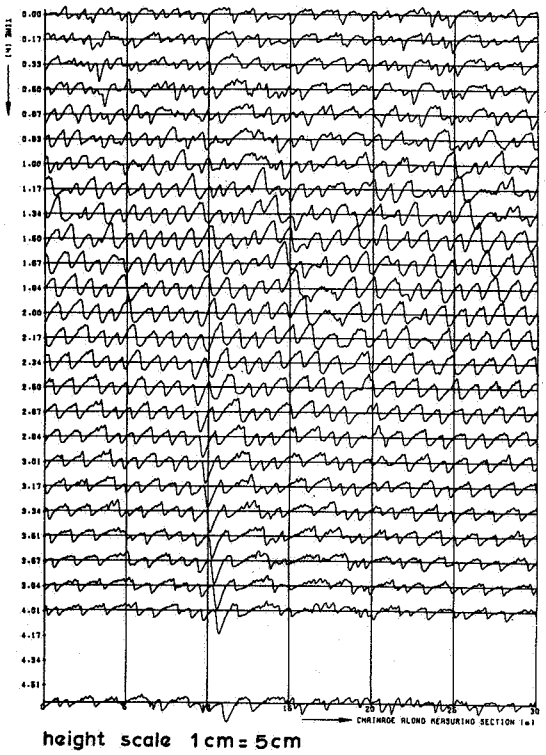
(b) dune height



(c) Chézy coefficient

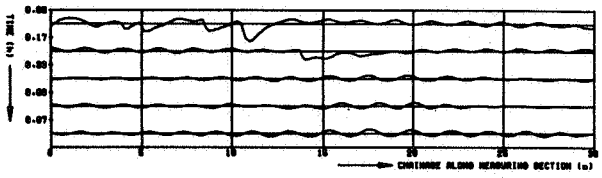


(d) bedform celerity

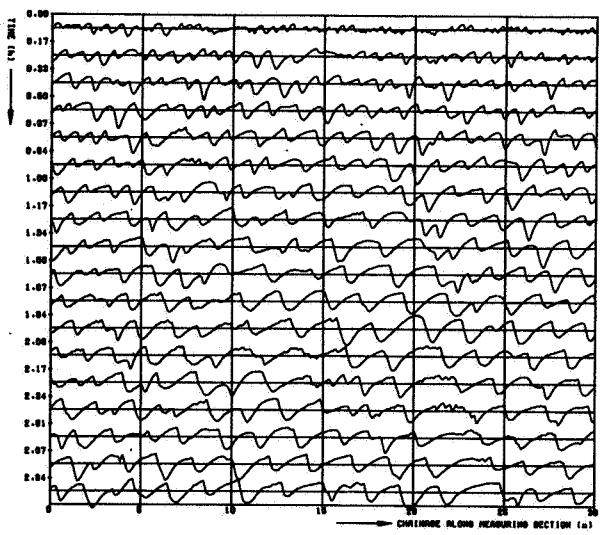


(e) longitudinal soundings middle profile for flood wave with T = 3.75 hours

Figure 16 Changes in bedform dimensions, roughness and bedform celerity during passage of flood waves in DHL sandflume



height scale 1cm = 10cm



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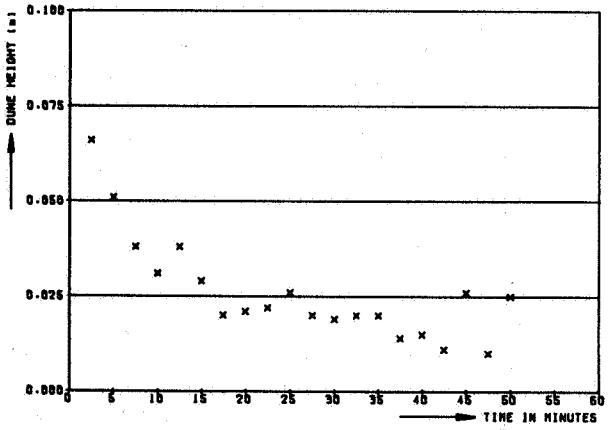
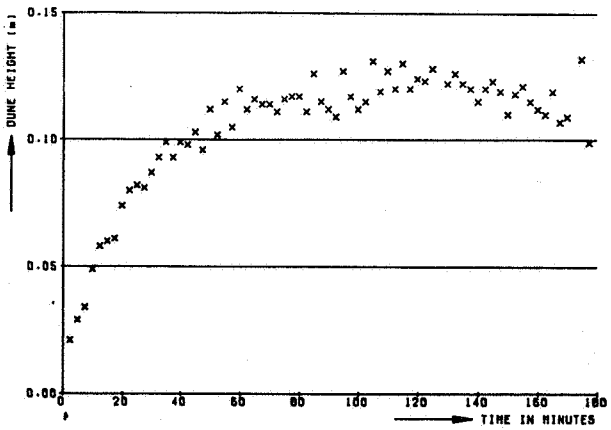
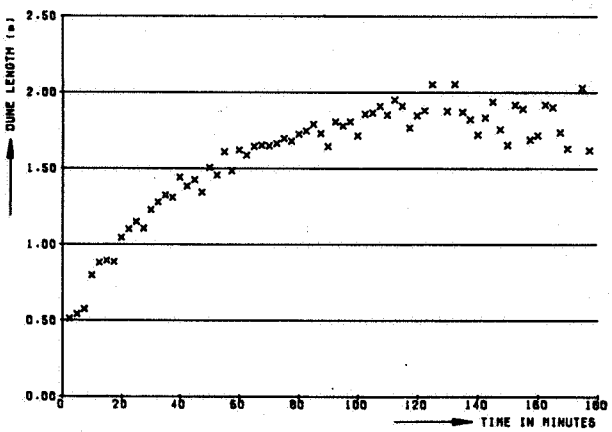






(a) dune-flat bed transition

(b) flat bed-dune transition

Figure 17 Changes in bedform dimensions in DHL sandflume during dune-flat bed (high transport rate) transition and vice versa

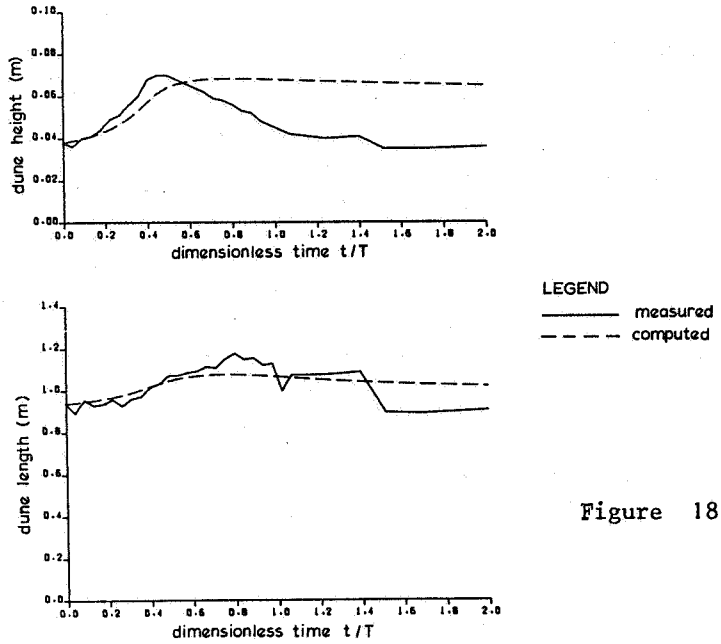


Figure 18 Comparison of measured and computed changes in bedform dimensions during the passage of flood in the DHL sandflume

Based on the simplified approach suggested by Fredsøe (1979) a mathematical model was developed that simulates changes in the height of the dune crest during the passage of flood waves. Although recently this model was compared with measurements in a flume (see Figure 18) and in the field, at present the model is not sufficiently calibrated and verified. Also this model does not yet take into account the effect of suspended load, which according to Fredsøe is essential to predict the dune dimensions at higher transport rates.

5. Resistance to flow

5.1 Resistance to flow of single bedforms

A number of prediction methods proposed earlier (Engelund, 1966; White et al., 1979; Brownlie, 1981; Karim, 1981) can be used to predict the resistance to flow on the basis of slope, bed material characteristics, specific discharge but without explicitly taking into account the occurrence of bedforms. Another possibility is to first predict the bedforms dimensions and, in a second step, to predict the resistance to flow on basis of these bedform dimensions. Such an approach seems anyhow necessary when dealing with unsteady conditions, when the bedforms dimensions are not fully adapted to the actual flow conditions.

The resistance to flow is usually divided in two parts, the first part related to skin friction and the second to additional energy losses due to the presence of bedforms. For the bedform roughness several prediction methods have been proposed, e.g. by Vanoni and Hwang (1967) and Engelund (1977). Within the framework of the research work reviewed here, van Rijn (1984c) proposed the following expressions for the total resistance to flow of dune-covered river beds for $k_s/h < 0.1$:

$$\frac{k_s}{H} = \frac{3D_{90}}{H} + 1.1\ (1 - \exp(-25\ H/L)) \qquad (8)$$

and

$$C = (8g/f)^{\frac{1}{2}} = 18\ \log\ (12\ R_b/k_s) \qquad (9)$$

Equation (8) is based on an analysis of bedform data of both flume and field experiments included in the Extended WFD set. The last term of Equation (8) is plotted in Figure 19 and the expression $3D_{90}$ has been added to arrive at the usually accepted flat bed value of k_s. Equation (8) can be used to predict the total roughness of river bed with all types of bedforms except anti-dunes.

source	d (m)	ū (m/s)	D_{50} (μm)
● Guy et al	0.16-0.32	0.24-0.59	190-930
△ Znamenskaya	0.08	0.49	800
⊘ Ackers	0.17-0.20	0.35-0.43	180
● Stein	0.24-0.30	0.88-1.12	400
⊞ Laursen	0.17-0.23	0.42-0.71	100

source	d (m)	ū (m/s)	D_{50} (μm)
⊠ Barton-Lin	0.14-0.26	0.41-0.58	180
× Japanese Channels	0.11-0.43	0.55-0.73	1260-1440
○ River Lužnic	0.14-0.75	0.35-0.74	2400
▲ Missouri River	4.5	1.5	240

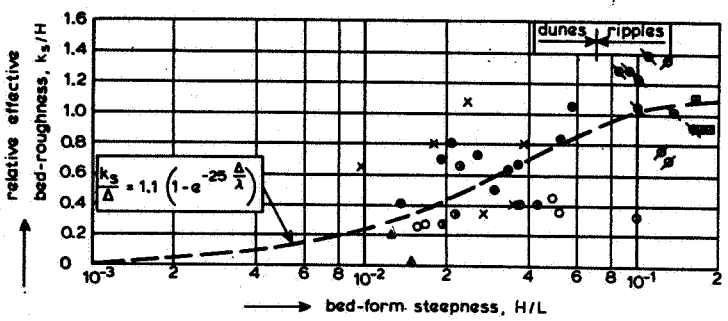


Figure 19 Hydraulic resistance of dunes k_s/H as function of their steepness (van Rijn, 1984c)

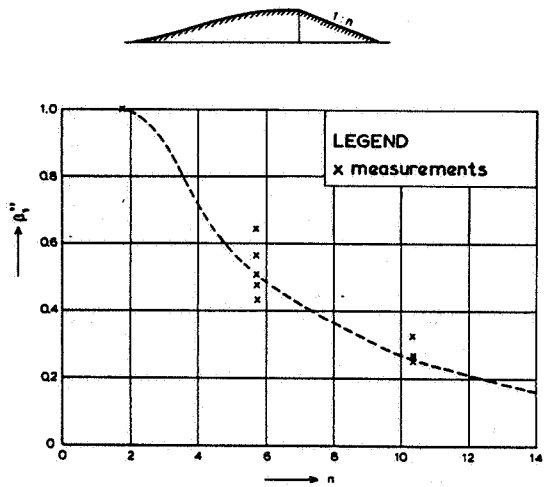


Figure 20 Reduction of form roughness due to the slope of the lee-side of a dune (Ogink, 1984a)

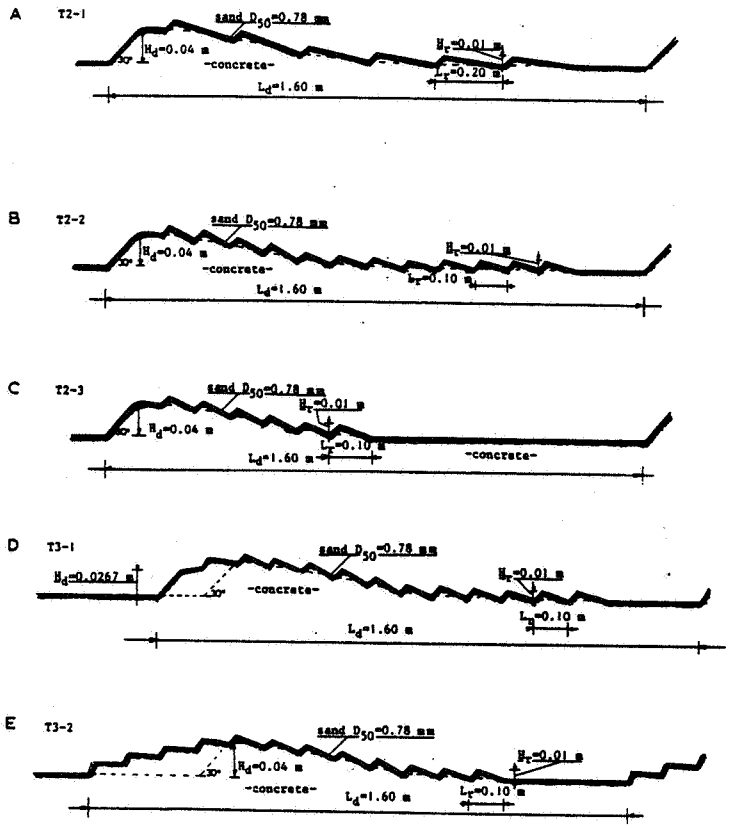


Figure 21 Ripples on dunes studied in the DHL sandflume (Ogink, 1984a)

Klaassen and Van Urk (1986) and Ogink (1984a) made a comparison between prediction methods for the resistance to flow taking the bedform dimensions explicitly into account. From these studies it was concluded that the methods of Vanoni and Hwang (1967) and van Rijn (1984c) were superior to the method of Engelund (1977). For the comparison use was made of the Extended WFD set, field measurements in the Rhine branches and a number of equilibrium tests in the DHL sand flume. It should be remarked that the method of van Rijn (1984c) is partly based on the data, which were used in the comparison. From the analysis it can be concluded that predicted Chezy values can easily differ 10 to 20% from the measured values.

5.2 Effect of lee-side slope

Recently some special tests with fixed dunes were done in the DHL sand flume to study the effect of the slope of the lee-side of bedforms on the resistance to flow (Ogink, 1984a). It was found that the form roughness is significantly affected by this slope. The results of the tests are summarized in Figure 20 (Ogink, 1984a). The form roughness has to be corrected with the factor β''_1, whereby β''_1 is a function of the slope parameter n as indicated in the figure (see Section 5.3). For gentle lee-side slope the form roughness reduces almost to zero. In particular in field conditions often gentle lee-side slopes are found.

5.3 Resistance to flow of composite bedforms

Bedforms in the field but also in laboratory flumes can often be characterized as large dunes on which smaller dunes or (in the case of flumes) ripples are superimposed. This is illustrated by a number of figures in this paper, notably the Figures 7, 15, 16 and 17. These smaller dunes and ripples add to the form roughness. To investigate how their effect should be taken into account, some tests were carried out in the DHL sand flume with fixed dunes on which ripples were superimposed. From the experiments with and without ripples it was concluded that the total resistance to flow f_t of a river bed with composite bedforms can be predicted by the following expression (Ogink, 1984a):

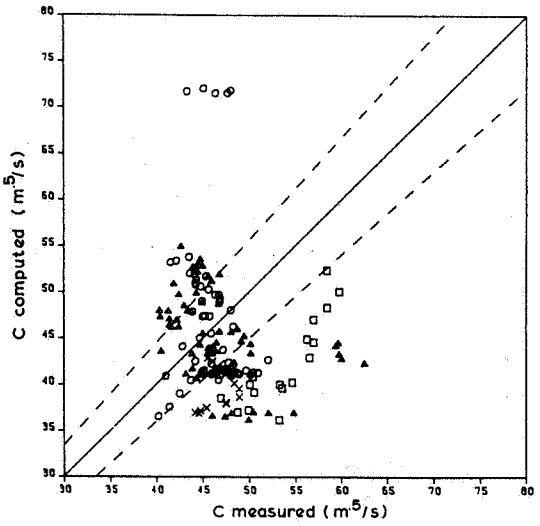
$$f_t = f' + \beta''_1 f''_d + \sum_{i=1}^{N} f''_{ri} \frac{L_{ri}}{L_d} \frac{u_i^2}{u^2} \qquad (10)$$

where f' = particle roughness, β''_1 = correction factor for lee-side slope (see Section 5.2), f''_d = form roughness of large dunes, f''_{ri} = form roughness of i-th superimposed dune or ripple, L_d = length of large dunes, L_{ri} = length of i-th superimposed dune or ripple, u_i = flow velocity above i-th dune.

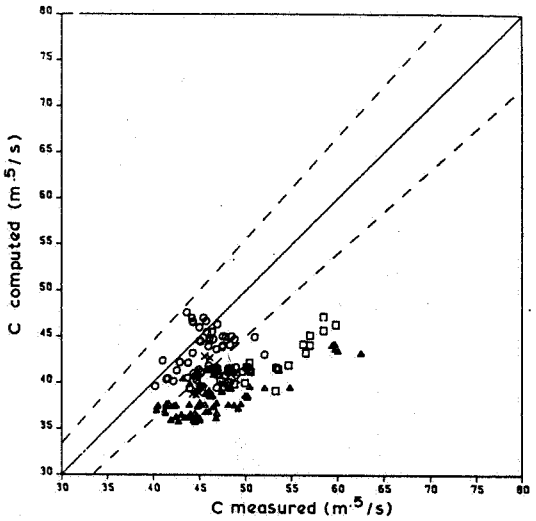
5.4 Comparison of resistance to flow predictions

Figure 22 (Ogink, 1984b) presents some results of the application of resistance to flow predictors to field data from the various branches of the River Rhine in The Netherlands. The field conditions approximated equilibrium. The prediction methods of Brownlie (1981b) using only overall data appears to give the best results. This is, however, a consequence of the limited flow range for which roughness values were available. Brownlie's method leads to a approximately constant C-values for a particular branch irrespective of the flow conditions, so the predictive ability of the method is questionable. The predictors of White et al. (1979) and Karim (1981) systematically predict too low Chézy coefficients. The van Rijn (1984c) method yields on the average fairly good results, but the scatter is rather large. Apparently taking into account the bedform dimensions when predicting resistance to flow does at present not result in better results. In future, however, improved understanding in bedform mechanics may result in better performance of this type of prediction methods.

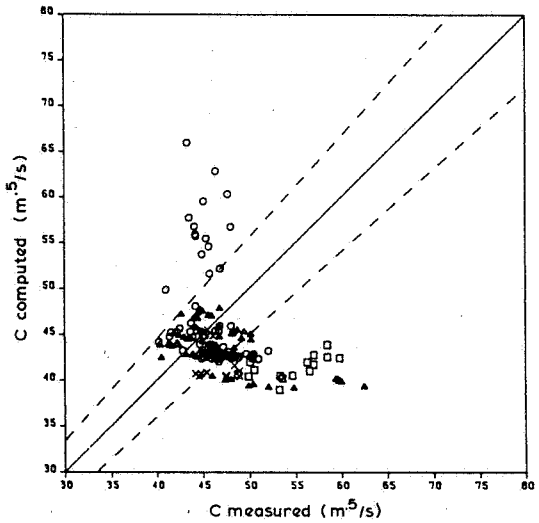
Anyhow, it is for the time being advisable only to use prediction methods when no measurements of resistance to flow of the channels under consideration are available. Whenever measurements are available it is advisable to adapt existing prediction method to these measurements, eventually using the theoretical framework or method of analyzing on which these predictors are based. This is illustrated in Figure 23, where the original Brownlie (1981) predictor and a version based on the same method of analyzing but adapted for the Rhine branches are compared.



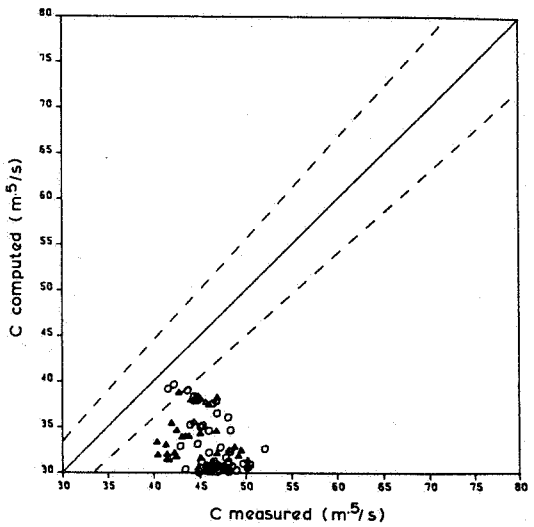
(a) Engelund et al



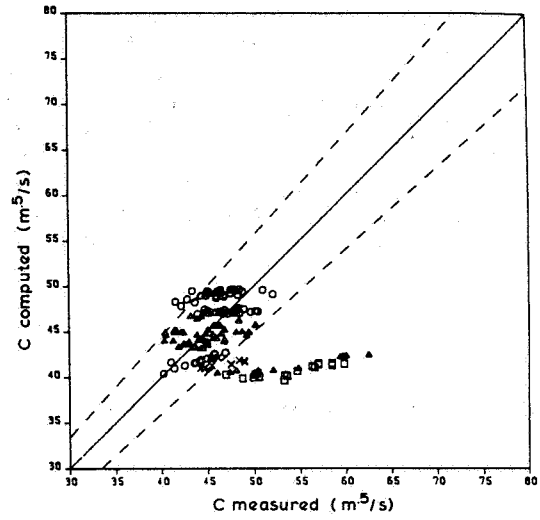
(b) White et al (1979)



(c) van Rijn (1982)



(d) Karim-Kennedy (1981)



(e) Brownlie (1981)

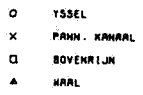


Figure 22 Comparison of measured and computed Chezy coefficients for the branches of the Rhine River (Ogink, 1984b)

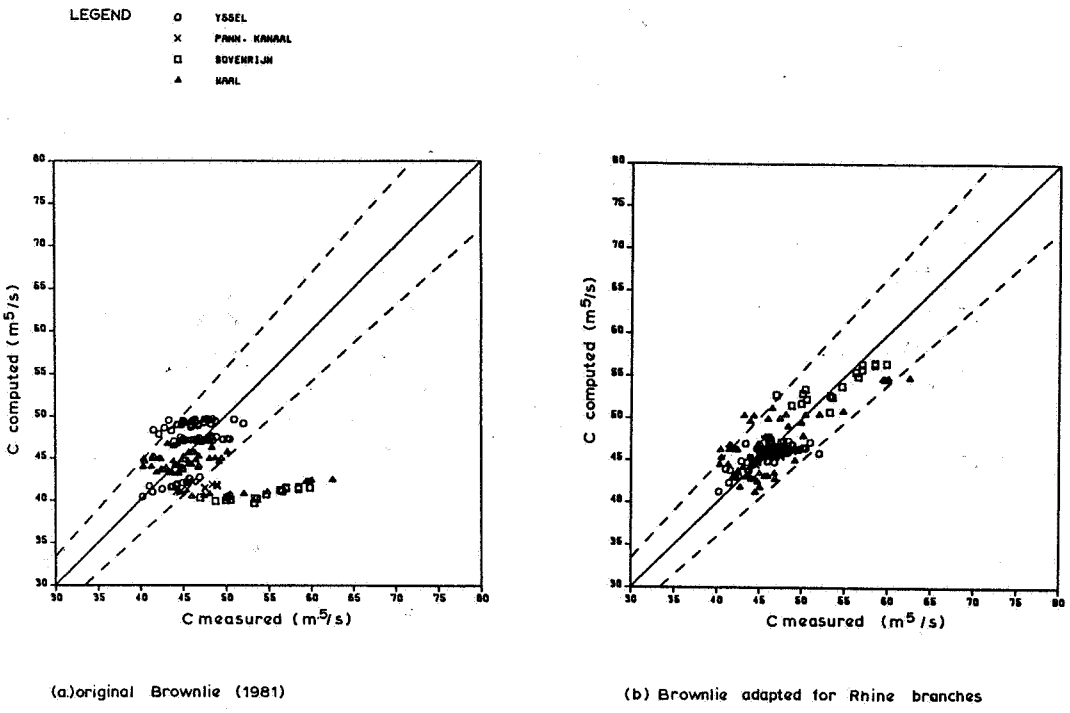


Figure 23 Adaptation of Brownlie (1981) predictor for the Rhine branches (Ogink, 1984b)

Another method would be to base the predicted roughness on measured resistance and dune dimensions for a nearby flow condition and the estimated dune dimensions for the situation to be studied. In this way use is made of bedform and roughness predictors from bedforms in a relative sense, eliminating the empirical constants (Ogink et al., 1986).

6. Sediment transport

6.1 Bed load, suspended load and total load

Van Rijn (1984a and 1984b) has proposed a method for the prediction of the total load in alluvial channels. This method deviates from earlier methods used by DHL in that the suspended load is connected to the bed load via a concentration at a reference level that is related to the bedform height.

The computation of the total load is done in two steps. Firstly, the bed load transport is computed as the product of the saltation height, the particle velocity and the bed-load concentration. The equations of motion for a solitary particle are solved numerically to determine the saltation height and particle velocity. Experiments with gravel particles (transported as bed load) were selected to calibrate the mathematical model using the lift coefficient as a free parameter. The model is used to compute the saltation heights and lengths for a range of flow conditions. The computational results are used to determine simple relationships for the saltation characteristics. Measured transport rates of the bed load are used to compute the sediment concentration bed-load layer. A simple expression specifying the bed-load concentration as a function of the flow and sediment conditions is proposed. This expression reads:

$$\frac{s}{\sqrt{\Delta g D_{50}^3}} = 0.053 \frac{T^{2.1}}{D_*^{0.3}} \qquad (11)$$

where s = sediment transport per unit width (m^2/s), Δ = specific density, defined as $\Delta = (\rho_s - \rho)/\rho$.

In a second step the suspended load is computed as the depth-integration of the product of the local concentration and the flow velocity. The reference concentration near the bed is determined from the computed bed load. It is not attractive to use the bed-load concentration as the reference concentration for the concentration profile because it precribes a concentration at a level equal to the saltation height which may result in large errors for the concentration profile. Furthermore, this approach is rather artificial in the case of bedforms because the bed-load concentration is an estimate for the concentration in the bed-load layer at the upsloping part of the bedforms. Therefore, another approach was introduced with a reference level related to the bedform height. Below the reference level, the transport of all sediment particles is considered as bed-load transport and an effective concentration is defined. In van Rijn (1984b)'s analysis, the reference level was assumed to be equal to half the bedform height (H), or the equivalent roughness height (k_s) if the bedform dimensions are not known. Measured concentration profiles were used for calibration. New relationships were proposed to represent the size gradation of the bed material and the damping of the turbulence by the sediment particles. A verification analysis using about 800 data showed that about 76% of the predicted values are within 0.5 and 2 times the measure values. The method proposed by van Rijn (1984a and 1984b) yields somewhat better results than other total load predictors.

6.2 Mixtures

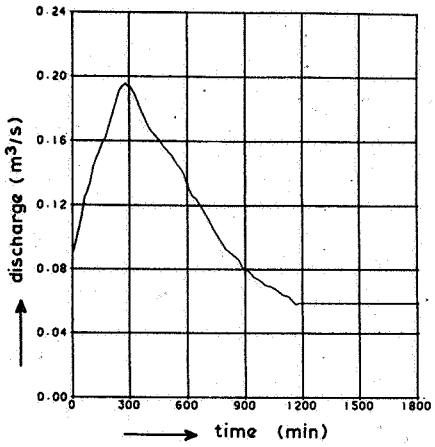
For some applications the fractional transport of mixtures is of interest (Klaassen et al., 1982). Theoretical and experimental research on the sediment transport of mixtures is being carried out at the Delft University of Technology (Ribberink, 1982; Ribberink, 1983). Based on this a one-dimensional mathematical model for morphological changes of rivers with graded bed material, taking into account longitudinal sorting, was developed (Olesen, 1981).Not only longitudinal sorting takes place, but also vertical sorting occurs in the bedforms. The effect is that on the average the bed material at the lower levels is consistently coarser than higher up in the bedforms. This, in combination with the variations in trough height over a whole spectrum of dunes, is responsible for the differences in transport of the different fractions. Based on the above understanding, a method has been developed to predict the fractional transport of mixtures in the dune phase (Klaassen et al., in preparation).

6.3 Armouring

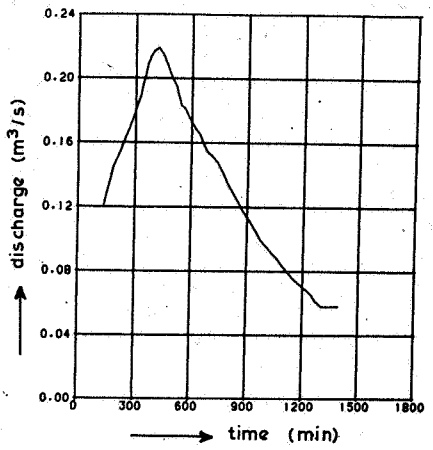
Recently an experimental study was carried out in the DHL sand flume to investigate the destruction and re-formation of armour layers during the passage of floods. The procedure applied was first create an armour layer on top of a well-graded mixture ($D_{50} \cong$ 0.7 mm, $D_{84} \cong$ 2.5 mm). This was done by gradually increasing the discharge in the flume until the coarsest armour layer (corresponding to the critical shear stress of mixtures as defined by Gessler (1971)) was obtained. During this armour layer formation the eroded sediment was removed. Next the armour layer was subjected to two successive flood waves (see Figures 24a and b), while the sediment was recirculated. Some observations made during the tests with the flood waves are summarized below:

- The armour layer collapses locally downstream of small ripples that start to occur for higher discharge. The turbulent bursts downstream of these bedforms are the driving agents.
- The armour layer re-appears again when the bedforms have passed but at a lower level (notably in the troughs of the bedforms where the coarser parts settle).
- The particle distribution of the armour layer present after a flood wave has passed is strongly dependent on the flood wave characteristics. This is in line with the observations of by Milhous (1973).
- The maximum sediment transport lacks considerably behind the maximum flood level (see Figure 24c). The average sediment transport over the whole flood wave, however, is reasonably well predicted by the method of Parker and Klingeman (1982).

So also here a paramount role is played by the bedforms which develop on top of the armour layer during higher stages. For more details reference is made to Klaassen (1986).



(a) flood wave T5



(b) flood wave T6

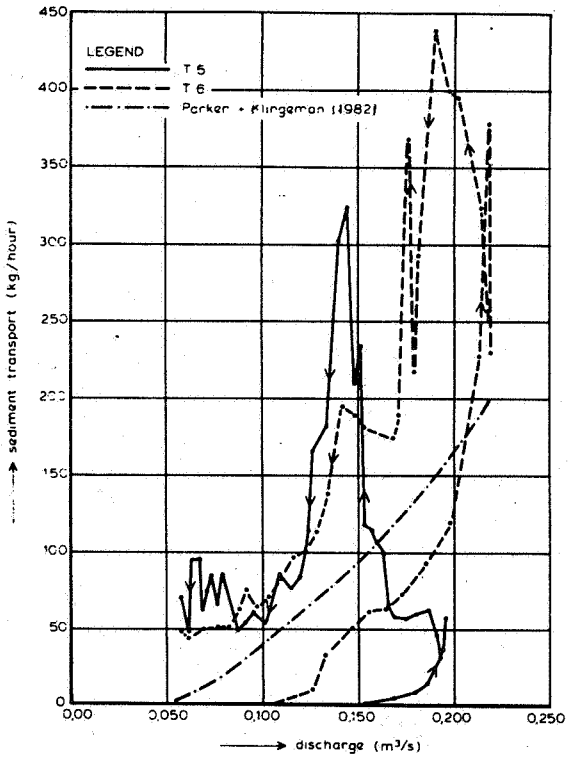


Figure 24 Sediment transport of armoured bed during passage of flood waves according to measurements in DHL flume (Klaassen, 1986)

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