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Experiments with graded sediments in a straight flume

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Experiments with graded sediments in a straight flume

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   b Middle profile
   c Left profile

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<thead>
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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_H$</td>
<td>adaptation coefficient for dune height</td>
<td>$s^{-1}$</td>
</tr>
<tr>
<td>$B$</td>
<td>width of flume</td>
<td>m</td>
</tr>
<tr>
<td>$c_b$</td>
<td>celerity of bedforms</td>
<td>m/s</td>
</tr>
<tr>
<td>$C$</td>
<td>Chézy coefficient</td>
<td>m²/s</td>
</tr>
<tr>
<td>$D$</td>
<td>particle diameter</td>
<td>m</td>
</tr>
<tr>
<td>$D_m$</td>
<td>characteristic particle size of a mixture, according to Meyer-Peter/Mueller</td>
<td>m</td>
</tr>
<tr>
<td>$D_p$</td>
<td>diameter of the particle in the bed material for which p % of the bed material is finer</td>
<td>m</td>
</tr>
<tr>
<td>$h$</td>
<td>water depth</td>
<td>m</td>
</tr>
<tr>
<td>$H$</td>
<td>dune height</td>
<td>m</td>
</tr>
<tr>
<td>$H_o$</td>
<td>average dune height at beginning of transition</td>
<td>m</td>
</tr>
<tr>
<td>$H_e$</td>
<td>average dune height at end of transition</td>
<td>m</td>
</tr>
<tr>
<td>$H_{average}$</td>
<td>average dune height determined from a measurement</td>
<td>m</td>
</tr>
<tr>
<td>$H_{dominant}$</td>
<td>dominant dune height (see Section 3.5 for definition)</td>
<td>m</td>
</tr>
<tr>
<td>$i$</td>
<td>slope</td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>dune length</td>
<td>m</td>
</tr>
<tr>
<td>$L_o$</td>
<td>average dune length at beginning of transition</td>
<td>m</td>
</tr>
<tr>
<td>$L_e$</td>
<td>average dune length at end of transition</td>
<td>m</td>
</tr>
<tr>
<td>$L_{average}$</td>
<td>average dune length determined from a measurement</td>
<td>m</td>
</tr>
<tr>
<td>$L_{dominant}$</td>
<td>dominant dune length (definition conform dominant dune height)</td>
<td>m</td>
</tr>
<tr>
<td>$q$</td>
<td>discharge per unit width</td>
<td>m²/s</td>
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<tr>
<td>$Q$</td>
<td>discharge</td>
<td>m³/s</td>
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<td>Unit</td>
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<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>s</td>
<td>sediment transport per unit width</td>
<td>m²/s</td>
</tr>
<tr>
<td>S</td>
<td>sediment transport (measured under water)</td>
<td>kg/s</td>
</tr>
<tr>
<td>$S$</td>
<td>sediment transport</td>
<td>m²/s</td>
</tr>
<tr>
<td>$T_{d}$</td>
<td>adaptation time</td>
<td>s</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td>s</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>adaptation coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$\beta$</td>
<td>adaptation coefficient for dune height</td>
<td>-</td>
</tr>
<tr>
<td>$\beta$</td>
<td>dune tracking coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>adaptation coefficient for dune length</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>relative density, defined via $\Delta = (\rho_s - \rho)/\rho$</td>
<td>-</td>
</tr>
<tr>
<td>$c$</td>
<td>void ratio (here $c = 0.4$ is used)</td>
<td>-</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density of water</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>density of sediment</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$\sigma_g$</td>
<td>geometric standard deviation of mixture, defined as $\sigma_g = \frac{1}{2} \left( \frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}} \right)$</td>
<td>-</td>
</tr>
<tr>
<td>$\sigma_x$</td>
<td>standard deviation of $x$</td>
<td>variable</td>
</tr>
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</table>
Summary

In a first exploratory study to investigate the effect of the gradation on morphological processes in rivers, experiments were carried out in a straight sandflume with a mixture having the following characteristics:
- \( D_{50} = 0.66 \text{ mm}, \)
- \( \sigma_g = \frac{1}{2} \left( \frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}} \right) = 2.34. \)

The limitations of the study were that the experiments were only done in the dune phase, that the Froude number was low and that during most tests there was active transport (no armour layer formation). The sediment was recirculated.

The experiments were done with the same slope (so adjusting the tail gates automatically), and the discharge was step-wise increased and decreased. During the transition and during the equilibrium phase of the experiments detailed measurements were made of the hydraulic roughness, the bedform dimensions, the sediment transport rates and the composition of the transported sediment and of the bed.

The main objective of the investigation was to obtain insight into the effect of gradation on hydraulic roughness, sorting layer thickness and sediment transport of mixtures. For this comparable experiments were compared mutually and the results of the present series of experiments were compared with a similar series of experiments, but with almost uniform sediment with \( D_{50} = 0.77 \text{ mm}. \)

The following main conclusions were drawn:
- The **hydraulic roughness** of graded sediments is less than that of uniform sediment. This is due to a substantial increase in dune length, and not to a decrease in dune height. Furthermore, there is a significant effect of the history of previous discharges (resulting in the storage of coarse sediments at lower levels in the bed) as the hydraulic roughness.
- **Sorting layer thickness** is slightly larger for graded sediments. The dunes in graded sediment have a different form, characterized by deeper troughs.
- The **sediment transport** rates were larger for the graded sediments, but this was in conformity with earlier observations. Also here the effect of the previous discharges was noticeable.
Recommendations are given for the incorporation of the results of this study into 1-dimensional models, and recommendations are made for additional investigations in the laboratory (both theoretically and experimentally) and in the field.
EXPERIMENTS WITH GRADED SEDIMENTS IN A STRAIGHT FLUME

1. General

1.1 Commission

The experiments described in this report were commissioned to Delft Hydraulics by Rijkswaterstaat, Directie DBW/RIZA in 1987, whereas in its letter of 10 March 1988, reference BX/3348 (see Appendix A), additional funds were made available to conclude both the analysis and the reporting of the study.

1.2 Background of the present investigation

Sediments transported by rivers vary widely in size and composition. Usually sediments observed in the Dutch Rhine branches and the Meuse River consist of gravels, sands, silts and clays. The coarser sediments are transported over or near to the bed, while the finer sediments are usually carried in suspension.

The deposits that occur when the transport capacity in the river decreases in time (after floods) and in space (on flood plains and in reservoirs), are typically made up of a mixture of these elements. The composition of these deposits vary considerably in time and space depending on the hydraulic conditions and on the river reach considered. It may therefore be anticipated that a major difference exists between reaches in the low water bed of the river and the reaches that are located in the floodplain.

In the low water bed of the river no silts and clays can deposit, because the flow velocities and the related turbulence are that high that there will be no opportunity for the finer particles to settle. Nevertheless sorting takes place in the low water bed, thus being the cause that the composition of the bed material in rivers is strongly variable in longitudinal and transversal direction. This phenomena is well known.

Longitudinal sorting, in combination with abrasion (see Parker, 1989a and 1989b), is responsible for the gradual reduction in average diameter of the bed material in rivers in downstream direction. Transversal sorting is causing the sorting phenomena observed in river bends (see e.g. de Vries,
1961). The importance of sorting in the low water bed is increasingly being realized.

Mathematical models are being developed, e.g. Ribberink (1987a), Rahuel (1989), etc., which explore the effect of sorting in 1-dimensional direction. Sorting in 2-dimensional direction is at present being investigated at DELFT HYDRAULICS a.o. for bifurcations (see e.g. de Vries et al., 1989), but for the time being the time-dependent changes in the composition of the bed material cannot be taken into account.

Turning now to the deposition of sediments in floodplains, not only the coarser sands are found there but also deposition of silts and clays takes place during (the recession of) floods. This deposition of finer sediments is of importance because of a number of reasons:

- the deposition of fine sediments in addition to coarser material provides a larger diversity of sedimentological conditions and allows a larger diversity of organisms to live in the floodplain reaches,
- the deposition of finer sediments is of importance for the gradual rise of the floodplain level of the Dutch rivers that are bordered by levees,
- the possible effects of deposition on the hydraulic roughness of the floodplain during floods (see Klaassen and van Urk, 1987),
- the fact that heavy metals and pesticides are very often bonded to silt and clay particles and that as such the finer particles are important modes of transport of pollutions in the riverine environment: knowledge on the deposition and erosion of deposits containing traces of these pollutants is extremely important.

Understanding of the deposition of fine sediments in floodplains is still very limited.

Summarizing, it may therefore be stated that the transport, deposition and (renewed) erosion of sediments of different sizes and the related sorting is a very important phenomena in rivers. The available knowledge on sorting processes, however, is still very limited. It is against this background that the present study should be appreciated

A study of the processes involved should be done in a systematic way and start with relatively "simple" aspects and gradually extend on the knowledge gained. Aspects to be considered are a.o.:

EXPERIMENTS WITH GRADED SEDIMENTS IN A STRAIGHT FLUME 2
- the interaction between coarse and fine sands during the transport process, and the effect on alluvial roughness and sediment transport,
- deposition of fine sediments (silts and clays) between the interstices of larger sediments (gravel),
- 1- and 2-dimensional sorting in the low water bed,
- the effects of the variable discharge, causing the temporary storage of sediments in outer bends and crossings,
- the exchange of sediments between the low water bed and the floodplains,
- the deposition of fine sediments on the floodplain, both on a "flat" floodplain and an irregular floodplain with deeper "natural" channels.

The present study should be considered as a first step towards improved understanding only, as it concerns the investigation of a relatively simple problem, notably the investigation of sorting for the case of graded sediments consisting of a mixture of fine and coarse sands only. Furthermore only 1-dimensional aspects are considered here (although also a comparison is made with results of a three-dimensional model of the Waal River, where the same bed material was used) and the interest is into the hydraulic roughness and the sediment transport of a mixture. A comparison is made with previous tests with almost uniform sediments but similar hydraulic conditions to isolate the effect of the gradation.

1.3 Problem description

For the modelling of morphological changes in rivers it is often required to take into account the gradation of the bed material. This composition affects the river morphology in different ways. Due to be selective transport there will be sorting, and in appropriate cases this has to included in the model. The way to do this, is to extend the morphological model for uniform sediment with sub-models that compute the selective transport and the resulting (changes in) composition of the bed material. Also the composition of layers that are buried due to degradation has to be stored in the program, when subsequent erosion may occur. Ribberink (1987b) and others have developed this type of morphological models and at present Rijkswaterstaat is considering to extend their 1-dimensional morphological model RIJNMOOR (for "uniform" bed material no sorting) with an option for graded sediments.
In the type of morphological models referred to above, a number of relations have to be specified which may in themselves also be influenced by the gradation of the bed material, notably:

(1) the hydraulic roughness of the river bed,
(2) the sediment transport,
(3) the bedform dimensions,
all as function of the hydraulic conditions. These three relations are discussed hereafter in some more detail.

Re(1) **Hydraulic roughness**

The hydraulic roughness is important for the computation of the backwater curve. According to the relatively scarce information available from a limited number of investigations (notably Daranandana (1962)) the effect of the gradation on hydraulic roughness in the dune phase is to reduce the roughness, leading to larger Chézy coefficients. No relationships are known to take the effect of the gradation into account.

Re (2) **Sediment transport**

Some studies have been done to determine to what extent sediment transport predictors can be adopted to take into account the effect of gradation. Examples are Einstein and Nin Chien (1953), Egiazarov (1965) and Day (1979). For a review reference is made to Ribberink (1977). Relationships have been proposed which could be used, but they are limited to the case of moderate gradation. Sediment transport in the case of a wide mixture with large gradation, where during low flows armouring may take place, is rather complex (see Parker and Klingeman (1982) and Klaassen (1986)) and it seems not yet possible to model this type of phenomena accurately.

Re (3) **Bedform dimensions**

The bedform dimensions are important because they determine the vertical exchange of the size fractions of the bed material (see e.g. Ribberink (1987a, 1987b) and Klaassen et al. (1987)). Ribberink (1987b) gives a review of the observations in the dune phase: "The following phenomena were observed:
vertical sorting of size fractions within the bedforms, taking place during sliding and avalanching, of the sediment along the steep lee sides of the dunes and resulting in relatively fine top layers and relatively coarse deeper layers,

- vertical exchange of size fractions between upper and deeper, less frequently moving, bed layers caused by the irregularity of bedforms (varying level of the bedform troughs)."

The vertical exchange is apparently affected by the bedform heights, while the bedform lengths will affect the celerity of the exchange process between the upper and the deeper layer (the two layers in the approach of Ribberink (1987a)). No data are available on the influence of the gradation on bedform dimensions.

The present study is intended to get better understanding of the effect of gradation on (i) the hydraulic roughness and (ii) the bedform dimensions. As a by-product additional data are obtained that can add to the understanding of the sediment transport of mixtures.

1.4 Organization of the study

The study was carried out in the large sandflume that was been constructed in the "De Voorst" research station of DELFT HYDRAULICS within the framework of the applied research programme TOW Rivers. The actual flume tests were carried out in the months March-June 1987. The elaboration of the data, including the sieve analysis of the many samples, was carried out during the remaining part of 1987, and partly in 1988. The interpretation of the data, including additional elaboration as far as the bed samples and the sediment transport samples were concerned, was done in 1988 and 1989. The reporting was done in 1989 and 1990.

The research was carried out by a number of staff members of DELFT HYDRAULICS. Mr. G.J. Klaassen was not only responsible for the overall management of the study, but he also designed the experiments, decided on the data collection, and guided the elaboration of the data. Mr. F. de Groot was in charge of the experiments in the sand flume. The operation of the sand flume, the collection of data, etc. was done by Mr. H. Tukker, with the assistance of Mr. H. Driegen. The elaboration of the data was done by Messrs. S. van der Schoot, J. Ansink, C. Twigt and J. Bremer. The sieving
of the bed and transport samples was done by Mr. H. Driegen. Mr. A.P.P. Terme was responsible for the processing of the transport samples and bed samples. The present report was prepared by Mr. G.J. Klaassen.

On behalf of the Client (Rijkswaterstaat, Dienst Binnenwateren/ RIZA) the investigation was monitored by Mr. R. Cirkel.

1.5 Structure of the report

The present report consists of two volumes, notably:
- Volume A, containing the text, and
- Volume B, with Tables and Figures.

To improve the legibility of the reporting some of the tables and figures have also been included in the volume containing the text. These tables and figures are referenced to with an additional asterix (e.g. Figure 3.1*), the asterix meaning that the figure can be found both in Volume A between the text and in Volume B in numerical order. Figures and tables without asterix can only be found in Volume B.

1.6 Acknowledgements

The investigations discussed in this report, including the experiments with uniform sediments, were carried out within the framework of the applied research project TOW Rivers, that was commissioned to DELFT HYDRAULICS by Rijkswaterstaat, Dienst Binnenwateren/ RIZA. In this project DELFT HYDRAULICS, Delft University of Technology and Rijkswaterstaat worked closely together to improve the understanding of morphological processes in rivers.

The set-up of the present experiments was discussed with Dr. Ir. J.S. Ribberink, at that time still working at Delft University of Technology. He also made valuable comments on an early draft of the report. Prof. Dr. Ir. M. de Vries, also from Delft University of Technology, commented on the preliminary results and reviewed the draft report too. Also the critical comments by Ir. R. Cirkel and Ir. H. Kamphuis, both from Rijkswaterstaat, Dienst Binnenwateren/RIZA, have resulted in substantial improvements of the report.
2. Study approach

2.1 Introduction

In this Chapter the approach is described that was adopted for the experiments reported about here. The present tests were carried out with graded sediments, but it was intended to compare the results of the tests with uniform sediment, which were carried out previously (in the period 1974–1982) in the same straight sand flume. The implication is that the tests conditions for the present tests could not be selected freely, but that they should approximate as much as possible the conditions of the tests with uniform bed material.

In this Chapter the tests conditions of the uniform tests are summarized and based on this summary the decisions regarding the test conditions for the tests with graded sediments are justified. This is done for the selection of the bed material (Section 2.3) and also for the hydraulic conditions (flume width, slope and discharge)(see Section 2.4). The set-up of the experiments is discussed in Section 2.2.

2.2 Set-up of the experiments

The aim of the present experiments was to study the effect of the gradation of the bed material on the alluvial roughness characteristics, the bedform dimensions and the sediment transport of the bed material. According to the experiments of Ribberink (1987), but also from earlier evidence, it was assumed that an important feature in this respect is the vertical sorting of the bed material. This phenomenon causes that, on the average, the bed material near the dune tops is finer than the bed material at the level of the troughs of the dunes. This vertical sorting takes place over a certain depth only, here referred to as the sorting layer (also called mixing layer by Ribberink (1987a) and others). It is felt that the name "mixing layer" is less appropriate because real mixing does not take place. The height of the sorting layer is determined by the lowest level that the dune troughs can reach. See the figure below:

![Diagram](attachment://sorting-layer.png)
In rivers the height of the sorting layer is variable as also the height of the bedforms varies in time, mainly as a result of changes in the discharge. According to many predictors the dune dimensions are a function of the water depth (i.e. the discharge). One may therefore consider the lowest levels of the sorting layer, especially the layers that are only reached by the troughs of the largest dunes during the largest floods, as a reservoir of probably (on the average) the coarsest sediments. This reservoir releases sediments only during the largest floods and it may thus regulate the variation of the bed material size through the year and consequently also affect the alluvial roughness, the bedform dimensions and the sediment transport. It was decided to also study this aspect during the tests with the graded sediments.

Therefore the following set-up of the experiments was selected. At the beginning the bed material was brought in the flume in such a way that sorting was prevented as much as possible. This was done mechanically, because it was estimated that bringing the sediment into the flume hydraulically could create pockets of finer or coarser sediments. The bed material was levelled according to a pre-selected slope.

Then the first test was done with a relatively low but constant discharge (resulting in a depth of approximately 0.2 m). After this test (T 49, see hereafter) was concluded and all the appropriate measurements and observations were done (see Section 3.4), the discharge was increased. The resulting water depth for this new test (T 50) was about 0.3 m. The bedforms were higher too, so the sorting layer reached lower levels. At the end of the second test the discharge was increased again to its highest value, resulting in a water depth of about 0.4 m. During this test (T 51) the bedforms were largest (and consequently the troughs were deepest), and it may be assumed that coarse sediments was predominant at the lowest trough levels.

Then the same sequence of discharges was used again but now in reverse order. After a decrease of the discharge to the value of test T 50, the water depth decreased again. If the above reasoning is correct, then it may be assumed that during the corresponding process of reduction of dune heights, some of the coarsest sediments will have been buried in the lowest troughs present during test T 51, so the average bed material size of this subsequent test (T52) will have been smaller. The same may hold for the next step in discharge in test T 53, corresponding to test T 49. Finally
the discharge was lowered even more and the resulting water depth was about 0.1 m. This corresponded approximately to the average water depth of the model of the Waal River M 1278. This last step was done to allow for a comparison of the 2-dimensional conditions in the sand flume with the 3-dimensional conditions in the movable bed model, especially as far as alluvial roughness and sediment transport are concerned (see also Section 2.3).

The following remarks are made regarding the adopted set-up of the tests:

(i) The adopted set-up with a step-wise increase and later a step-wise decrease of the discharge in the flume had an additional advantage. Over the last decade quite a number of tests have been carried out in the sandflume to study the alluvial roughness and the bedform dimensions for unsteady flow conditions. See e.g. Wijbenga and Klaassen (1983) and a series of reports of DELFT HYDRAULICS, notably Wijbenga and Van Nes (1986a, 1986b, 1986c, 1986d). The set-up of the present tests allowed to observe similar phenomena but then for graded sediments. It should be stressed, however, that according to the experience with the uniform sediments it is required to repeat these unsteady flow tests several times to remove most of the influence of the stochastic behaviour of the bedforms. Here the tests could be carried out only once. It may, therefore, be expected that the results may be obscured partly by stochastic phenomena.

(ii) It should be stressed here that the adopted set-up is appropriate for getting more insight into the effect of gradation under 2-dimensional conditions. In reality, where 3-dimensional phenomena are very important, the effect of the reservoir of coarse sediment on the average bed-material size of the active layer will be different, because the reservoir will not only be formed at the level of the lowest troughs during floods. Also the pool formation during floods and in particular the subsequent filling-in during lower flows may cause coarser sediments to be stored temporarily in a non-active layer.

2.3 Selection of bed material

The tests with "uniform" sediments had been done with bed material with the following characteristic particle sizes:

$$D_{16} = 0.72 \text{ mm},$$
$D_{35} = 0.75 \text{ mm},$
$D_{50} = 0.77 \text{ mm},$
$D_{65} = 0.79 \text{ mm},$
$D_{90} = 0.82 \text{ mm},$

with a gradation of 1.06. The used bed material corresponds with the $\sqrt{2}$ sieve fraction 0.70 - 0.82 mm. The value of $D_m$ is 0.78 mm.

It would have been very expensive to make a special mixture for the present tests via sieving and mixing of the sieve fractions. Therefore it was decided to use sediments that were already available at the laboratory. The sieve curves of the most appropriate available materials, together with the sieving curve of the "uniform" sediments, are plotted in Figure 2.1. One of the curves corresponds to the material used during model investigation M1278, while the other sediment was used during the experiments to study the behaviour of armour layers during floods (Klaassen, 1986; Klaassen, 1987b).

After careful analysis it was decided to use sediment that had also been used for the investigations in the movable-bed model of the Waal River M1278 (see Struiksma, 1977). This material has approximately the same $D_{50}$ as the uniform sediment and the choice of this material allows to compare the results of the (3-dimensional) movable bed model investigation M1278 with the results obtained during the present (straight flume) study (see Section 6.5). The sieving curve of the bed material used during the present tests is presented in Figure 2.2*. The characteristic particle sizes of the used bed material are as follows:

$D_{10} = 0.28 \text{ mm},$
$D_{16} = 0.30 \text{ mm},$
$D_{35} = 0.44 \text{ mm},$
$D_{50} = 0.66 \text{ mm},$
$D_{65} = 0.91 \text{ mm},$
$D_{84} = 1.60 \text{ mm},$
$D_{90} = 2.24 \text{ mm},$

while the gradation of the graded sediment used is 2.34. The value of $D_m = 0.93 \text{ mm}$. As can be observed in Figure 2.2*, the distribution of the particle sizes is not completely normal (otherwise it would have plotted as a straight line on the used probability paper).
Figure 2.2* Particle size distribution of used mixture

2.4 Selection of test conditions

The selection of the test conditions relates to three parameters, notably the width of the flume, the slope of the bed and the discharge in the flume. These are also the independent variables during the previous tests with uniform sediments and the present tests. Most of the tests with uniform sediments were carried out with a slope of 0.0016 (1.6*10^-3), so it was decided to do as well the tests with graded sediments with that slope.

It should be stressed here that during all the tests reported about and used here for comparison, the constant slope system was used. This implies that a feedback system was operational correcting the position of the tail gate, depending on the measured slope of the energy level in the flume. The system used ensures that over the full length of the measuring section uniform flow conditions are always present - it is described more extensively in Bakker (1984) or Van Rijn and Klaassen (1981).
As a consequence of the used procedure, the water depth and the sediment transport (and in the case of the graded sediment also the composition of the transported sediments) are the dependent variables.

To allow for a comparison of the tests with uniform sediments an overview was made of the tests with a slope of about 0.0016 (1.6 x 10^-3) that were carried out with this uniform sediment. This overview is given in the table below:

<table>
<thead>
<tr>
<th>Approximate water depth (m)</th>
<th>Flume width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.50</td>
</tr>
<tr>
<td>0.10</td>
<td>--</td>
</tr>
<tr>
<td>0.20</td>
<td>T 301)</td>
</tr>
<tr>
<td>0.30</td>
<td>T 232)</td>
</tr>
<tr>
<td>0.40</td>
<td>T 263)</td>
</tr>
</tbody>
</table>

Notes:
1) Comparable tests T1, T2, T22, T23-2, T27, T 30
2) Comparable tests T11, T23, T24, T29
3) Comparable tests T34, T36, T38

It appears that most of the tests had been carried out for water depths between 0.2 and 0.4 m, so it was decided to choose the discharges such, that the approximate depth that were obtained, were about 0.2, 0.3 and 0.4 m. The values of the discharges were not fully settled in advance because the alluvial roughness of the graded bed material was not known accurately. So during the carrying out of the tests the final value of the discharge to be imposed was decided upon, based on the experience obtained during the previous tests. This holds only for the tests with increasing discharge. With decreasing discharge the same discharges were used as during the previous tests.

Another important aspect is the width/depth ratio of the tests. This ratio should not be too low because of the possibility of occurrence of alternate bars in the flume, which necessitate elaborate corrections and remaining uncertainties (see Wang, 1987). A too-high ratio, however, causes the wall effects to become too dominant, which should also be prevented. A most favourable choice for this so-called aspect ratio is, according to Wang (1986), a value of about 3 to 5. Assuming that the water depth during the tests with graded sediments will also vary between 0.2 and 0.4 m (with an
average of some 0.3 m), it seems that a most favourable choice for the present tests is about \(4 \times 0.3 = 1.2\) m. Because the earlier tests had been carried out with a flume width of 1.125 m it was decided to accept this value as the width for the present tests with graded sediments. A disadvantage of the use of 1.125 m is that no comparable test was carried out with uniform sediment for a water depth of 0.4 m. It was expected, however, that it would be possible to interpolate between the results of the tests with widths of 1.5 and 0.5 m with sufficient accuracy.

For tests with graded sediments still another decision had to be made that is related to what type of sediment is supplied at the upstream side of the flume. There are two options:

1. to supply sediment with known particle size distribution,
2. to recirculate the sediment: the sediment that settles in the sand trap is immediately introduced at the upstream end.

Option (1) was used by Ribberink (1987a) during his equilibrium tests. Here it was decided to use option (2), because this corresponds best with the conditions in the field. For this option the particle size distribution of the transported sediment is a dependent variable, being determined by the characteristics of the sediment available in the sorting layer.

2.5 Summary of selected test conditions

A summary of the selected test conditions is given below:

- bed material of the Waal model experiments (M 1278),
- flume width 1.125 m,
- constant slope of \(1.6 \times 10^{-3}\);
- water depth of approximately 0.1, 0.2, 0.3 and 0.4 m, to be regulated via the discharge (the imposed variable),
- the following sequence of water depths 0.2 - 0.3 - 0.4 - 0.3 - 0.2 - 0.1 m (see also Figure 3.7*).
Figure 3.7* Experiments carried out as "hydrograph"
3. **Experiments**

3.1 **General**

This chapter gives information about the flume used, its operation, the measurements carried out and the processing of the obtained data. Here only a brief description of the mentioned items is given as far as they are the same as used for the experiments with uniform sediments. For more details on these items, the reader is referred to Chapter 4 of Report R 657-XV (Bakker, 1984), which provides an extensive description of the sandflume and its facilities. A detailed description is provided for those measurements that were done additionally for the present tests with graded sediments.

3.2 **Used facility**

3.2.1 **General layout**

The tests were carried out in a sandflume which had been built especially for fundamental research into sediment transport and resistance to flow (Struiksma and Van der Zwaard, 1971). The flume can reproduce, generally, the conditions experienced in major Dutch rivers. Tests can be performed with:

- low Froude numbers, in the lower flow regime,
- predominant bed-load transport,
- dunes as the main bedforms,
- relatively low sediment transport rates,
- discharge varying in time,
- constant water temperature.

The sand flume is constructed in reinforced concrete, with a measuring section consisting of a steel frame with glass windows. The main dimensions of the flume (see Figure 3.1*) are:

- overall length 98 m,
- length of section with glass windows 50 m, containing a measuring length for bed-level measurements of 30 m,
- width of the measuring section variable between 0.30 to 1.50 m,
- maximum water depth without sediment 1.00 m.
Figure 3.1* Planform and longitudinal section of the sandflume

In the subsequent part of this Section 3.2 the "normal" operation and control devices of the sand flume are described. How these were used during the present tests and which additional data were collected for the graded sediments, is described in Section 3.4.

Water circuit

The discharge in the water circuit can be varied from 0.02 to 0.80 m /s. Four pumps are provided at the upstream end of the sand flume to pump water from an underground storage tank to a reservoir where a constant level is maintained. Water flows from the constant head reservoir through a Romijn weir into a stilling basin and then through the flume. At the end of the flume the water passes over a sandtrap and falls over a tailgate, and then returns to the underground storage tank via a second flume, located beneath the sand flume. A heating and cooling system in the return flume maintains the water at a constant temperature.
Sediment circuit

The sediment circuit can be set up in two ways:
- with sediment recirculation
- without sediment recirculation.

At the upstream end of the flume, immediately upstream of the glass window section, there is a hydrocyclone (hydrocyclone A, see Figure 3.1b), through which sediment is dropped when required into the flume. A V-shaped sand trap is constructed at the downstream end of the flume, immediately upstream of the tailgate in which the transported material settles. The material is pumped to one of the two hydrocyclones installed in the facility. When sediment is being recirculated it is pumped to Hydrocyclone A installed at the upstream end of the flume, thus providing a closed circuit.

When sediment is not being recirculated it is pumped to a second hydrocyclone (hydrocyclone B on the same figure), installed above a sediment storage reservoir. The sediment from the sand flume is weighed in either hydrocyclone (see Figure 3.1b), enabling the difference between the sediment rate supplied via the first hydrocyclone and that transported through the flume to be determined. In this way the weighing of sediment supplied and sediment transported through the flume is separated. The sediment required for a particular test is pumped from the sand reservoir to Hydrocyclone A at the upstream end of the flume.

3.2.2 Operation of the flume

Water circuit

The discharge in the flume can be regulated by means of the pumps and the Romijn weir. There are four pumps, each with a maximum capacity of 0.2 m/s, which are generally operated automatically, depending on the discharge variation required in the flume. The discharge in the flume can be varied between 0.02 and 0.80 m/s. The Romijn weir is an adaptation of the original type, being a combination of an undershot gate and a movable weir, as illustrated in Figure 3.2. The rounded bottom edge of the top section of the upstream face is fixed at an arbitrary level below the upstream water level. The lower section is formed by the adjustable plate of the original Romijn weir, and is always above the downstream water level. With this arrangement the discharge is less dependent on the upstream water level, and the discharge can be controlled accurately.
The discharge through the Romijn weir depends on the size of the gate opening and the upstream water level. Since the upstream water level is almost constant, the discharge is varied by changing the gate opening, by adjusting the lower section.

**Sediment circuit**

The sediment can be supplied at rates up to 800 kg/h submerged weight. The sediment is pumped either from the sediment reservoir or from the sand trap, as discussed in Section 2.1, to Hydrocyclone A at the upstream end of the sand flume (see Figure 3.1b and 3.3). Here the water and sediment are separated, the sediment remaining in a small storage tank below the hydrocyclone. The increase in weight due to the sediment is recorded on a balance. When the increase in weight reaches a certain preset value one of two things can happen. If sediment is being recirculated the stopcock under the storage tank automatically opens and the sediment is flushed into the flume via a separate pump. After 30 seconds the flushing pump stops and the stopcock is closed. If sediment is not being recirculated the supply of sediment is stopped until the hydrocyclone has been emptied at a preset time interval.

When sediment is being recirculated, the sediment supply depends on the amount of sediment caught in the sand trap. This amount is directly related to the bedform immediately upstream of the sandtrap. If this is a dune crest the amount of sediment caught in the following period will be higher than when there is a trough. As a result the time interval between successive injections from the hydrocyclone will vary in order to give the injection rate required. When sediment is not being recirculated the supply is more regular. In both cases the sediment transport adjusts itself to the flow regime in the first few metres downstream of the supply point.

**Energy slope/water depth**

The energy slope is maintained constant by adjusting the discharge and sediment supply accordingly, or by using an automatic slope control system. During tests with automatic slope control the sediment is recirculated directly.

When the energy slope is not being controlled automatically the supply of sediment is related to the present water discharge. This is calculated from
previously measured discharge and sediment transport values in such a way that hardly any change in surface/bed slope occurs during the tests.

**Temperature control**

The temperature of the water in the flume is kept more or less constant at 18 degrees Celsius by a heating and cooling system, installed in the pumping cellar.

3.2.3 **Measuring and control devices**

**Discharge**

A Rehbock weir is installed in the return flume to measure and control the discharge constantly. Furthermore a Romeijn weir is present in the return flume to check the discharge.

**Sediment**

The bed-load sediment transport is equal to the amount pumped from the sandtrap and is measured in a hydrocyclone, installed either at the upstream end of the flume or above a sediment reservoir. The measurement of the weight of sediment transport is determined from the submerged weight of the sediments in the hydrocyclone and the frequency of the droppings. In the recirculation mode, the time of the droppings and thus the number of droppings per unit time is registered and this provides the sediment transport per unit time.

**Energy slope**

Energy levels are measured at two locations in the flume, 35 m apart. The water level is also measured at the downstream location. Pitot tubes have been installed in the flume for these measurements. These tubes are connected to barrels alongside the flume, where the water level can be measured. The water level is measured immediately before and after the instrument carriage has made a water depth measuring traverse along the flume as described.
Automatic slope control

During tests an automatic slope control system was operating. This regulates the tailgate level in such a way that the actual slope in the flume is equal within narrow limits to a pre-set value. The difference in pressure between the Pitot tubes, 35 m apart, is measured continuously and compared with pre-set values. If the difference is too large the tailgate is regulated. During the tests with automatic slope control the sediment is recirculated.

Water depth

Rails are mounted above the glass window section for an instrument carriage. Three profile indicators and a water-level indicator are installed upon the carriage. 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. The mean water depth in the measuring section is taken as the difference between the average of all water levels and the three bed levels in the longitudinal sections (see Section 3.2.4).

Bedform dimensions

With additional data processing, see Section 3.4, the bed-level profiles measured in the way described above can be analysed to yield bedform dimensions.

Temperature

The temperature of the water in the flume is measured in the underground water-storage tank.

Time

The time is recorded in the computer which automatically processes the recorded data.

Alarm system

Several measuring and control devices have been connected to an alarm system. If something goes wrong this alarm system is activated and a bell
starts to ring or, after working hours, a staff member is warned by telephone. Emergencies activating the alarm system include:
- water level in constant head reservoir too low
- malfunctioning of Romijn weir
- exceedance of one of the discharge limits
- malfunctioning of the slope control system
- water level in the flume too high
- tail gate malfunctioning
- exceedance of one of the tail gate limits
- malfunctioning of hydrocyclone stopcocks
- malfunctioning of sand pumps
- malfunctioning of flushing pumps.

3.2.4 Data processing

The sandflume is equipped with a minicomputer for data acquisition and processing. Furthermore, a microprocessor is present that can be used for imposing time-dependent boundary conditions. The combined system of minicomputer and the microprocessor enable data to be acquired automatically and also enable the boundary conditions, such as the discharge to be varied automatically as a function of time.

Initially the data recorded and collected by the minicomputer are stored in a disk memory, and a number of simple calculations are made to check the operation of the instruments and the progress of the test. The results of these computations are presented in the operating room of the flume. Regularly the data stored on disk are transferred to magnetic tape to be used for more complicated calculations at a later stage.

3.3 Testing programme

For reasons already discussed in Section 2.4, the experiments carried out can be schematized as a type of hydrograph, consisting of a succession of experiments with gradually increasing and later on gradually decreasing discharge. After a step-wise increase or decrease in discharge, the experiments were run sufficiently long with this new discharge to allow for equilibrium conditions to establish. This made it possible to determine equilibrium sediment transport, hydraulic roughness and bedform dimensions. A
sudden increase or decrease of the discharge in the flume (step function) was selected:
- to enable the method of Fredsoe (1979, 1981, 1982) for bedform adjustment to be verified;
- to check whether or not dunes adapt to a sudden change in discharge according to a first-order system;
- to verify the results of Gee (1973) and Bishop (1977) who also carried out measurements for a sudden change in discharge.

So the test procedure was in two stages:
(1) The discharge was kept constant and the sediment was recirculated until equilibrium conditions were reached. Once this equilibrium had been reached, the water depth, energy slope, bed slope, bed level and bedform celerity were measured a number of times.
(2) The discharge was then suddenly changed, the energy slope being kept constant by means of the automatic slope control. The sediment was recirculated too, the sediment transport being only measured at the upstream end of the flume. The definition of equilibrium (sediment transport at upstream end of the flume = sediment transport at downstream end of the flume) used previously (when the sediment was not recirculated), was not applicable under these conditions of recirculation. In this series of tests equilibrium was characterized by negligible changes of the (average) water depth, dune height and dune length.

The phase between the two equilibrium stages is called the transition stage. During the transition and during the following equilibrium the hydraulic roughness, the sediment transport and the bedform characteristics were measured. The anticipated pattern of changes in the hydraulic roughness (expressed in terms of the Chézy coefficient), water depth and dune height during the transition period after a sudden increase in discharge are indicated in Figure 3.5 left. For a sudden decrease in discharge the opposite can be expected (see Figure 3.5 right).

A schematic summary of the experiments reported about in the present report is given in Figure 3.5 and in Table 3.1. Roughly speaking, the water depth varied in the tests T49 - T50 - T51 - T52 - T53 - T54 as 0.2m - 0.3m - 0.4m - 0.3m - 0.2m - 0.1m. Because the water depth was a dependent variable, the above indication of the changes in water depths is only approximate.
In general a transition is preceded by the equilibrium stage of the previous test and followed by the equilibrium stage of the test under consideration. As an example the following sequence can be cited: Equilibrium T50 - Transition T51 - Equilibrium T51 - Transition T52. So each test consisted of a transitional part and an equilibrium part.

3.4 Measurements

3.4.1 General

The measurements performed can be distinguished in the measurements performed in the test with uniform sediments too, and the measurements which were special for the experiments with graded sediments. These are discussed hereafter as the "standard" measurements (Subsection 3.4.2) and the "additional" measurements (Subsection 3.4.3).

3.4.2 Standard measurements

The hydraulic and bedform characteristics were measured during the initial equilibrium stage, the transition stage and during the following equilibrium stage. Each measurement consisted of the following observations:
- the energy slope, by using two Pitot tubes located 35 m apart;
- the bed level in three longitudinal profiles at every centimetre of the 30 m long measuring section;
- the water level in the middle profile at every centimetre of the measuring section.

During the equilibrium stage about twenty such measurements were carried out, at intervals of two hours, a period sufficiently large to guarantee statistical independence. During the transitions the time interval between two measurements was about six minutes, which is the minimum that can be taken with the present data collection system.

Measurements were also taken with a time interval of about ten minutes, referred to as "high-frequency measurements". A set of high-frequency measurements was also carried out during the equilibrium phases. These were aimed at collecting data on the celerity of bedforms.

The discharge, sediment transport and water temperature were measured continuously, as described in Section 3.2.
Basic parameters assumed to be constant during each experiment were:

- the distance between the points used for determining the difference in energy head (L);
- the width of the flume (B);
- the wall roughness (see Wijbenga, 1979);
- the porosity of the sediment.

After the operation of the flume had been checked, the data were stored on magnetic tape for computer processing.

Measurements were mainly taken to check the test conditions, the bed level and the water level and, in addition, to obtain all other data necessary for calculating:

- water depth;
- bedforms;
- resistance to flow;
- celerity of change in bedform dimensions.

3.4.3 Additional measurements

For the experiments with graded sediments additional measurements were carried out. These were related to the size distribution of the transported sediments and the vertical sorting (the size distribution in the sorting layer) of the bed material.

Size distribution of transported sediments

The transported sediments were sampled during the transition and during the equilibrium stage. These samples were taken in the following way (comparable to the samples taken during the experiments with armour layers (see Klaassen, 1986)). Samples were taken from the droppings of the upstream hydrocyclone: the whole contents of one dropping was diverted into a container, and from this container a sample of sufficient weight (see De Vries (1970)) was taken (after thorough mixing!). This sample was put in a plastic bag and labelled (test number, sample number, date and time). These samples were sent to the sieving laboratory for further analysis. The remaining part of the sample, often more than 95% of the dropping, was dropped into the flume after the sample was taken, to prevent that in the upstream end too-little sediment was entering.
During the transition the samples were taken from all droppings during the first hours of the experiments. In the equilibrium stage samples were only taken during the high frequency measurements. The reasoning behind this was that it was assumed that a fair relationship existed between the local sediment transport on the dune and the size distribution of the sample (as postulated by Klaassen et al (1987)). So it was assumed that, once this relationship was established, it would be possible to compute the average particle size during a particular experiment from the recorded variation of the sediment transport during each particular test.

**Vertical sorting**

At the end of each experiment the bed material in the flume was sampled. This was done in seven sections in the flume. At some sections sampling was done in three locations (left, middle and right), in some others only in the middle of the flume. An overview of the locations of the samples is given below:

<table>
<thead>
<tr>
<th>Approximate chainage of sample (m)</th>
<th>Location of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
</tr>
<tr>
<td>15</td>
<td>x</td>
</tr>
<tr>
<td>20</td>
<td>x</td>
</tr>
<tr>
<td>25</td>
<td>x</td>
</tr>
<tr>
<td>30</td>
<td>x</td>
</tr>
<tr>
<td>35</td>
<td>x</td>
</tr>
<tr>
<td>40</td>
<td>x</td>
</tr>
<tr>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

In the above table it is indicated "approximate chainage" because the sampling was not done at the precise chainage, but the nearest dune top was selected and there a sample was taken. The actual sampling location was registered. "Left" and "right" means 1.125/6 m (which equals to about 0.2 m) from the left and from the right wall. Essentially the same bed-sampling technique was applied as developed by Ribberink (1987a). This means that a cylinder with a diameter of 0.05 m is sunk into the bed and that near by sucking layers with a thickness of 0.5 mm were removed. The exact height of the samples relating to the zero-level of the flume (corresponding to the steel floor), was also determined. Also these samples were sufficiently labelled and sent to the laboratory for later analysis. Different from the procedure used by Ribberink (1987a), here the holes originating from the sampling were not refilled with the samples after analysis, but they were
filled with the original material. This may have caused some minor distur-
bances, but the alternative of accepting the procedure of Ribberink (1987a) 
would have resulted in an unacceptable extension of the flume tests.

3.5 Data processing

3.5.1 General

For the experiments with uniform sediment the data processing comprised the 
calculation of, in particular:
- water depth,
- Chézy coefficient,
- average height and length of the dunes,
- bedform celerity.

For the experiments with graded sediments the analysis of the samples from 
the transport and from the bed had to be done additionally. Furthermore the 
probability density function of the bed levels was computed.

3.5.2 Standard data processing

The TABELLEN Program was used for calculating the water depth, the resis-
tance to flow and the dune dimensions. Only one out of five sets of initial 
data, taken at intervals of 1 cm along the longitudinal section, was consi-
dered in the program. TABELLEN is part of a more extensive program known as 
the BOGIRSKI computer program. A description of this program is given in 
Informatie R 657-III (Bakker, 1977).

The average water depth is calculated using:

\[
h(x) = z_w(x) - z_b(x)
\]  

(3.1)

and

\[
\bar{h}(x) = \frac{1}{n} \sum_{x=1}^{n} \left[ (z_w(x) - z_b(x)) \right]
\]  

(3.2)

in which:

- \( x \) = location of measuring points along the longitudinal profile
- \( h(x) \) = water depth (m)
- \( z_w(x) \) = water level (m)
- \( z_b(x) \) = bed level (m)
\( \bar{h} \) = average water depth along the flume (m), average of the three values
\( n \) = number of measuring points along longitudinal profile

The resistance to flow is defined as the Chézy coefficient \( (C_b) \) related to the bed, in the formula:

\[
C_b = \frac{\bar{u}}{\sqrt{(R_b i)}} \tag{3.3}
\]

in which:
\( \bar{u} \) = average velocity (m/s)
\( Q \) = discharge (m³/s)
\( B \) = flume width (m)
\( \bar{h} \) = average water depth (m)
\( R \) = hydraulic radius of the bed (m)
\( i \) = energy slope

The hydraulic radius of the bed \( R_b \) is determined using the hypothesis of Einstein (1934), as given in "Note R 657-VI" (Wijbenga, 1979) using the formulas:

\[
C_w = \frac{\bar{u}}{\sqrt{(R_w i)}} \tag{3.4}
\]

\[
C_w = 18 \log \left\{ 12 \frac{R_w}{(k_w + \delta_w/3.5)} \right\} \tag{3.5}
\]

\[
A_t = B \bar{h} = 2 A_w + A_b = 2 R_w h + R_b B \tag{3.6}
\]

\[
R_b = h - 2 R_w h/B \tag{3.7}
\]

in which:
\( C_w \) = Chézy coefficient of the wall
\( R_w \) = hydraulic radius of the wall, to be determined from Equations (3.4) and (3.5)
\( k_w \) = roughness coefficient of the wall
\( \delta_w \) = thickness of sublayer (m), defined via
\[
\delta_w = 11.6 \sqrt{\nu (g R_w i)}
\]
\( \nu \) = kinematic viscosity of water (m²/s)
\( A_w, A_b \) = sub-areas, related to channel depth and width proportions (m²)
\( A_t \) = total cross-sectional area (m²)
The TABELLEN Program was used for calculating bedform dimensions. In this program first the mean bed level is determined, being a straight regression curve. The location of the zero crossings are then determined, a distinction being made between up-crossings and down-crossings; the maximum distances between the bed level to the regression curve between two successive up-crossings is then determined. A dune is defined as being between two zero up-crossings. The dune length is the distance between those two up-crossing. The dune height is the sum of the distances between the bed level and the regression curve at the crest and between regression curve and the bed level at the next trough of the dune.

Some of the zero crossings are caused by small ripples on the dunes. The VLAK subroutine defines ripples as dunes in the sense of BOGIRSKI, but with a dune height of less than 25% of the average dune height, and filters their signal out of the calculation. A description of this subroutine is given in "Informatie R 657-XLV" (Bakker 1981).

Bed levels have been measured along the length profile at an interval of 1 cm, thus giving 3001 measuring points. One out of five successive measuring points has been taken into consideration for the calculations.

The DULOC Program is another method of calculating bedform dimensions. This method is described in "Informatie R 657-XLV" (Bakker 1982). The procedure is to follow the bed level along the length profile and record the location and level of all maximums and minimums. One dune is defined as lying between two successive minimums. The dune length is the distance between these two minimums. The dune height is the difference in level between the crest and the trough of the dune. In this procedure more dunes are counted since the dunes which do not cross the regression line are also taken into consideration. The result is, in general, a lower value for dune height and dune length than those obtained with the TABELLEN Program, but the values are nearer to those estimated by eye. As with the TABELLEN Program ripples with a height of less than 25% of the average dune height are filtered out.

A slightly modified version of TABELLEN is the DULOC-II Program. In this version the VLAK subroutine is not used, but the dunes with a height lower than a pre-set value (usually 0.020 m) are filtered out. The program also evaluates the dominant dune height and dune length, using the dune length as a weighting factor. The dominant dune height and dune length are defined as
\[ H_{d, dom} = \frac{1}{L_{d, tot}} \sum_{i=1}^{N} H_d(i) \cdot L_d(i) \tag{3.8} \]

\[ L_{d, dom} = \frac{1}{L_{d, tot}} \sum_{i=1}^{N} L_d(i) \tag{3.9} \]

in which:
- \( H_{d, dom}, L_{d, dom} \) = dominant dune height and dune length
- \( H_d(i), L_d(i) \) = original dune height and dune length
- \( L_{d, tot} \) = distance between first and last dune crest
- \( N \) = total number of dune crests

The bedform celerity was determined with the DUKO computer program. A description of this program is given in "Informatie R657-XV" (Bakker, 1978). The determination of the bedform celerity is based on a cross-correlation technique of two successive measurements separated by a relative short time interval. The time interval between two successive bed level measurements in a longitudinal section is considered to be relatively short if the changes in the bed levels are relatively small. With a short time interval there is a distinct peak in the cross-correlation function:

\[ C_{z_{b1}z_{b2}}(\chi) = \frac{1}{K} \int_{0}^{L} z_{b2}(x) z_{b1}(x+\chi) \, dx \tag{3.10} \]

in which:
- \( C_{z_{b1}z_{b2}}(\chi) \) = cross-correlation function of bed level measurements \( z_{b1}(x) \) and \( z_{b2}(x) \)
- \( L \) = length over which bed level measurements are being considered
- \( \chi \) = shift in \( x \) position of particular bedform = lag

In the DUKO program the cross-correlation function is normalized using the value of the auto covariance of each measurement:

\[ \rho_{z_{b1}z_{b2}}(\chi) = C_{z_{b1}z_{b2}}(\chi) / \sqrt{C_{z_{b1}}(0) \cdot C_{z_{b2}}(0)} \tag{3.11} \]

in which:
- \( C_{z_{b1}}(0), C_{z_{b2}}(0) \) = auto covariance of bed level measurements \( z_{b1}(x) \) and \( z_{b2}(x) \)
\[ \rho_{b_1 b_2}(x) = \text{cross-correlation coefficient} \]

The bedform celerity can then be calculated from the position of the peak in the cross-correlation coefficient with respect to the \(x=0\) position, divided by the time between the two measurements being considered. The bedform celerities given in this report are based on the average celerities for the three profiles.

3.5.3 Additional data processing

In addition to the standard data processing also used for the uniform sediment, for the present experiments data processing was carried out to determine:
- the probability density function of the bed levels,
- the composition of the transported sediment,
- the composition of the bed.

The probability density function was determined by extending the TABELLEN program. The deviations of the bed from the average bed levels were determined by using the averaged bed slope and level obtained with the TABELLEN program. The probability of occurrence of a certain deviation was computed per profile and per measurement (for every cm). The results are presented in Figures.

The samples that were taken from the transported sediment and from the bed of the flume were sieved and from each sample a sieving curve was determined. From these sieving curves characteristic particle sizes were determined, such as \(D_{10}\), \(D_{50}\) and \(D_{90}\), and the gradation. Furthermore the probability density function was prepared with the \(\phi\)-scale as basis, where \(\phi\) is defined via:

\[ \phi = - \log_2 D \]  \(\text{(3.12)}\)

where \(D = \text{diameter in mm}\) (for details see e.g. Briggs, 1977).

For the transported sediments these characteristic particle sizes were introduced in a spreadsheet program (SUPERCALC). With this program time series of the particle sizes and any other processing of the data could be done easily.

The analysis of the bed samples was much more complicated. Use was made of the regression line of the bed levels (see Subsection 3.5.2). The height of
all samples with respect to the zero-level of the flume was transferred to a depth above or below this regression line. So for all sections a different correction had to be carried out. Next the average size distribution as a function of the depth above or below the regression level was determined. These average size distributions were based on seven samples per level in the middle of the flume, but in the left and right profile only on three samples per level. Furthermore interpolation had to be applied, because the samples were not taken at the same level with respect to the (initially unknown) average bed level.

3.5.4 Accuracy

An estimation of the errors involved in the "standard" processing of the basic parameters and the computer derivation of other parameters was made by Wijbenga (1979). A summary of the main results from this study is given in Report R 657-XV (Bakker, 1984). Some information from the study is given below.

In principle the errors can be divided into stochastical and systematic errors. The relative error is the sum of these errors divided by the average value of the parameter. Systematic errors are mostly related to the instrument or to the incorrect setting up of the measuring equipment and are constant during a test. In most cases these errors can be eliminated by correct experimental procedure. Stochastic errors are caused by incorrect reading of the measuring equipment by man, and/or the stochastic character of the parameter being measured. The scale and the sign of these errors can vary from measurement to measurement.

A reduction of the effect of stochastic errors on the accuracy of derived parameters can be obtained by averaging several observations of the same conditions. In general it has been found that at least eight observations are required to obtain a reasonable accuracy. More than twenty observations do not give significantly more accurate results.
4. Results for equilibrium conditions

4.1 General

In this Chapter the results are given of the experiments with graded sediments, as far as the equilibrium conditions are concerned. Immediately after a change in discharge a transition takes place, in which the bedform dimensions and the sediment transport are being adapted to the new hydraulic conditions. During the present tests this transition required a few days only, because (thanks to the constant slope feedback system) only an adaptation of the bedform dimensions was required. In the first tests with uniform sediments also the bed slope was changed and then it took substantially more time to obtain equilibrium conditions (Bakker, 1984). Once equilibrium conditions had been established, the average water depth, sediment transport, hydraulic roughness, and so on did not change any more.

The results of the experiments are presented in this report in tables and figures. Although the equilibrium conditions and the transitions are described in separate Chapters (in this Chapter the equilibrium conditions and in Chapter 5 the transitions) the tables and figures are presented in Volume B in a different order. There a chronological order is used, which means that the transition of a certain test is followed by the equilibrium conditions of the same test.

In the next Sections the six experiments which were performed with the graded sediments, are discussed. The imposed variables are given and the obtained results are given per experiment. For a further analysis of the results obtained, a mutual comparison of the different experiments and a comparison with the previous experiments with uniform sediments, reference is made to Chapter 6.

4.2 Experiment T49

Experiment T49 was the first experiment in this series of experiments with graded sediments. Before the beginning of the test the bed material was brought into the flume. That was done mechanically and manually (so not hydraulically!), while extreme care was taken that, initially, the sediment was fully mixed. At the same time the bed was shaped according to the pre-determined slope of $1.6 \times 10^{-3}$. Furthermore is was attempted to smooth the bed
levels as much as possible. To check that, the way the sediment was brought into the flume had not caused segregation and pockets of finer and coarser sediments, the bed material of the flume was sampled in the way described in Subsection 3.4.3. The initial conditions are given in the Figures 4.1 and 4.2, where Figure 4.1 pertains to the composition of the bed and Figure 4.2 to soundings of the middle, the right and the left longitudinal profiles. From Figure 4.1 it was concluded that initially segregation was negligible. Figure 4.2 shows that the bed was not completely smooth, but the slope of the bed in the flume is uniform. The first measurement in Table 4.1 (so the top row) also pertains to the initial conditions. It can be concluded that the average bed-level variation ("dune height") is about 0.04 m, which is substantially smaller than the bedform height expected in Experiment T49. The computed bed slopes in the three profiles were indeed about 1.6 * 10^{-3}.

The imposed variables of Experiment T49 can be divided in (i) variables that were constant for all experiments in this series of experiments with graded sediment, notably:
- slope of energy level 1.6 * 10^{-3},
- flume width 1.125 m,
- mixture used,
- sediment being recirculated,
and (ii) variables that were selected for this particular experiment. For the latter only the discharge still had to be selected. Because the water depth is a dependent variable and a water depth of approximately 0.2 m was required, the discharge could not be established in advance but had to be estimated, too. Changing of the discharge during the experiment was not considered as a possibility because also transitions would be studied. For T49 the following choice was made:
- discharge 0.110 m³/s.

Experiment T49 was carried out in the period 1987.04.02 ... 1987.04.08. Equilibrium had established by 1987.04.06. In total twenty equilibrium measurements were made, spread over a period of three days, from 1987.04.06 ... 1987.04.08. Two series of frequent measurements of thirteen measurements each were done on 1987.04.06. The bed composition was sampled on 1987.04.09.
From the measurements made in the equilibrium stage the following main results were obtained as to the most important dependent variables (average value and standard deviation):

- **water depth:**
  - average water depth 0.178 m,
  - standard deviation 0.004 m;

- **flow velocity:**
  - average flow velocity 0.56 m/s,
  - standard deviation 0.01 m/s;

- **hydraulic radius:**
  - average hydraulic radius 0.159 m,
  - standard deviation 0.004 m;

- **Chézy coefficient:**
  - average Chézy coefficient \(35.1 \text{ m}^{1/2}/\text{s},\)
  - standard deviation \(1.0 \text{ m}^{1/2}/\text{s};\)

- **sediment transport:**
  - average sediment transport 85 kg/s,

- **average dune height:**
  - average average dune height 0.075 m,
  - standard deviation 0.006 m;

- **average dune length:**
  - average average dune length 1.72 m,
  - standard deviation 0.14 m;

- **dune steepness based on average dune dimensions:**
  - average steepness 0.044,
  - standard deviation 0.003;

- **dominant dune height:**
  - average dominant dune height 0.080 m,
  - standard deviation 0.007 m;

- **dominant dune length:**
  - average dominant dune length 2.08 m,
  - standard deviation 0.17 m;

- **dune steepness based on dominant dune dimensions:**
  - average steepness 0.038,
  - standard deviation 0.003.

Although the energy slope and the water temperature were in principle controlled variables, they also fluctuated slightly. The following values are representative for the equilibrium conditions:
- energy slope:
  - average energy slope \( 1.61 \times 10^{-3} \)
  - standard deviation \( 0.11 \times 10^{-3} \)
- water temperature:
  - average water temperature \( 17.6 \text{ deg C} \)
  - standard deviation \( 0.3 \text{ deg C} \)

More detailed results of the measurements during equilibrium are presented in the following tables and figures:

**Tables:**

4.2 Summary of results of the measurements during equilibrium
4.3 Dune heights per profile during equilibrium
4.4 Dune lengths per profile during equilibrium
4.5 Average dune dimensions and steepness during equilibrium
4.6 Dominant dune dimensions and steepness during equilibrium
4.7 Summary of results of the frequent measurements during equilibrium
4.8 Dune heights per profile during frequent equilibrium measurements
4.9 Dune lengths per profile during frequent equilibrium measurements
4.10 Average dune dimensions and steepness during frequent equilibrium measurements
4.11 Dominant dune dimensions and steepness during frequent equilibrium measurements

**Figures:**

4.10 Example of bed and water level profiles during equilibrium
4.11 Statistics of bed levels
4.12 Sediment transport versus time
4.13 Sediment transport and \( D_{50} \) of transported sediment during equilibrium
4.14 Water depth versus time during frequent equilibrium measurements
4.15 Energy slope and temperature versus time during frequent equilibrium measurements
4.16 Time series of longitudinal soundings of middle profile during frequent equilibrium measurements
4.17 Average dune heights versus time during frequent equilibrium measurements

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4.18 Average dune lengths versus time during frequent equilibrium measurements

4.19 Celerities of bedforms versus time during frequent equilibrium measurements

4.20 Particle size versus sediment transport during equilibrium

4.21 Composition of transported sediment during equilibrium

4.22 Bed composition at the end of the test
  a  $D_{10}$
  b  $D_{50}$
  c  $D_{90}$

4.23 Average $D_{10}$, $D_{50}$, $D_{90}$ and sigma
  a  Right profile
  b  Middle profile
  c  Left profile

4.3 **Experiment T50**

The imposed variables of Experiment T50 can be divided in (i) variables that were constant for all experiments in this series of experiments with graded sediment, notably:
- slope of energy level $1.6 \times 10^{-3}$,
- flume width 1.125 m,
- mixture used,
- sediment being recirculated,
and (ii) variables that were selected for this particular experiment. For the latter only the discharge still had to be selected. Because a water depth of approximately 0.3 m was required, for T50 the following value for the discharge was selected:
- discharge $0.240 \text{ m}^3/\text{s}$.

Experiment T50 was carried out in the period 1987.04.09 ... 1987.04.15. Equilibrium had established by 1987.04.13. In total twenty equilibrium measurements were made spread over a period of three days, from 1987.04.13 ... 1987.04.15. Two series of frequent measurements of thirteen measurements each were done on 1987.04.14. The bed composition was sampled on 1987.04.16.
From the measurements made in the equilibrium stage the following main results were obtained as to the most important dependent variables (average value and standard deviation):

- water depth:
  - average water depth 0.337 m,
  - standard deviation 0.009 m;

- flow velocity:
  - average flow velocity 0.64 m/s,
  - standard deviation 0.02 m/s;

- hydraulic radius:
  - average hydraulic radius 0.293 m,
  - standard deviation 0.008 m;

- Chézy coefficient:
  - average Chézy coefficient $\frac{29.5}{\frac{1}{2}}$ m$^{\frac{1}{2}}$/s,
  - standard deviation $\frac{1.2}{\frac{1}{2}}$ m$^{\frac{1}{2}}$/s;

- sediment transport:
  - average sediment transport 170 kg/s;

- dune height:
  - average average dune height 0.109 m,
  - standard deviation 0.009 m;

- dune length:
  - average average dune length 1.80 m,
  - standard deviation 0.17 m;

- dune steepness based on average dune dimensions:
  - average steepness 0.060,
  - standard deviation 0.004;

- dominant dune height:
  - average dominant dune height 0.115 m,
  - standard deviation 0.010 m;

- dominant dune length:
  - average dominant dune length 2.11 m,
  - standard deviation 0.19 m;

- dune steepness based on dominant dune dimensions:
  - average steepness 0.055,
  - standard deviation 0.005.

From the above it has to be concluded that the selected value for the discharge was definitely too high as the actual water depth during equilibrium (about 0.34 m) was substantially higher than the target value (0.30 m).
Although the energy slope and the water temperature were in principle controlled variables, they also did fluctuate slightly. The following values are representative for the equilibrium conditions:

- energy slope:
  - average energy slope \(1.61 \times 10^{-3}\),
  - standard deviation \(0.13 \times 10^{-3}\);

- water temperature:
  - average water temperature \(17.8\) deg C,
  - standard deviation \(0.1\) deg C.

More detailed results of the measurements during equilibrium are presented in the following tables and figures:

Tables:

4.13 Summary of results of the measurements during equilibrium
4.14 Dune heights per profile during equilibrium
4.15 Dune lengths per profile during equilibrium
4.16 Average dune dimensions and steepness during equilibrium
4.17 Dominant dune dimensions and steepness during equilibrium
4.18 Summary of results of the frequent measurements during equilibrium
4.19 Dune heights per profile during frequent equilibrium measurements
4.20 Dune lengths per profile during frequent equilibrium measurements
4.21 Average dune dimensions and steepness during frequent equilibrium measurements
4.22 Dominant dune dimensions and steepness during frequent equilibrium measurements

Figures:

4.31 Example of bed and water level profiles during equilibrium
4.32 Statistics of bed levels
4.33 Sediment transport versus time
4.34 Sediment transport and \(D_{50}\) of transported sediment during equilibrium
4.35 Water depth versus time during frequent equilibrium measurements
4.36 Energy slope and temperature versus time during frequent equilibrium measurements
4.37 Time series of longitudinal soundings of middle profile during frequent equilibrium measurements
4.38 Average dune heights versus time during frequent equilibrium measurements
4.39 Average dune lengths versus time during frequent equilibrium measurements
4.40 Celerities of bedforms versus time during frequent equilibrium measurements
4.41 Particle size versus sediment transport during equilibrium
4.42 Composition of transported sediment during equilibrium
4.43 Bed composition at the end of the test
   a $D_{10}$
   b $D_{50}$
   c $D_{90}$
4.44 Average $D_{10}$, $D_{50}$, $D_{90}$ and sigma
   a Right profile
   b Middle profile
   c Left profile

4.4 Experiment T51

The imposed variables of Experiment T51 can be divided in (i) variables that were constant for all experiments in this series of experiments with graded sediment, notably:
- slope of energy level $1.6 \times 10^{-3}$,
- flume width 1.125 m,
- mixture used,
- sediment being recirculated,
and (ii) variables that were selected for this particular experiment. For the latter only the discharge still had to be selected. Because a water depth of approximately 0.4 m was required, for T51 the following value for the discharge was selected:
- discharge 0.300 m$^3$/s.

Experiment T51 was carried out in the period 1987.04.17 ... 1987.04.29. Equilibrium had established by 1987.04.25. In total twenty equilibrium measurements were made spread over a period of four days, from 1987.04.29 ... 1987.04.29. Two series of frequent measurements of thirteen measurements each were done on 1987.04.27. The bed composition was sampled on 1987.04.30.
From the measurements made in the equilibrium stage the following main results were obtained as to the most important dependent variables (average value and standard deviation):

- water depth:
  - average water depth 0.402 m,
  - standard deviation 0.013 m;

- flow velocity:
  - average flow velocity 0.66 m/s,
  - standard deviation 0.02 m/s;

- hydraulic radius:
  - average hydraulic radius 0.346 m,
  - standard deviation 0.015 m;

- Chézy coefficient:
  - average Chézy coefficient $\frac{1}{2} 28.1 \frac{m}{s}$,
  - standard deviation $\frac{1}{2} 1.9 \frac{m}{s}$;

- sediment transport:
  - average sediment transport 196 kg/s,

- average dune height:
  - average average dune height 0.117 m,
  - standard deviation 0.012 m;

- average dune length:
  - average average dune length 1.83 m,
  - standard deviation 0.14 m;

- dune steepness based on average dune dimensions:
  - average steepness 0.064,
  - standard deviation 0.005;

- dominant dune height:
  - average dominant dune height 0.123 m,
  - standard deviation 0.011 m;

- dominant dune length:
  - average dominant dune length 2.13 m,
  - standard deviation 0.16 m;

- dune steepness based on dominant dune dimensions:
  - average steepness 0.058,
  - standard deviation 0.006.

From the above it may be concluded that for experiment T51 the difference between the actual value of the water depth and the target value was much smaller than for experiment T50.
Although the energy slope and the water temperature were in principle controlled variables, they also did fluctuate slightly. The following values are representative for the equilibrium conditions:

- energy slope:
  - average energy slope \(1.62 \times 10^{-3}\),
  - standard deviation \(0.11 \times 10^{-3}\);

- water temperature:
  - average water temperature \(18.0\) degr Celsius,
  - standard deviation \(0.1\) degr Celsius.

More detailed results of the measurements during equilibrium are presented in the following tables and figures:

**Tables:**

4.24 Summary of results of the measurements during equilibrium
4.25 Dune heights per profile during equilibrium
4.26 Dune lengths per profile during equilibrium
4.27 Average dune dimensions and steepness during equilibrium
4.28 Dominant dune dimensions and steepness during equilibrium
4.29 Summary of results of the frequent measurements during equilibrium
4.30 Dune heights per profile during frequent equilibrium measurements
4.31 Dune lengths per profile during frequent equilibrium measurements
4.32 Average dune dimensions and steepness during frequent equilibrium measurements
4.33 Dominant dune dimensions and steepness during frequent equilibrium measurements

**Figures:**

4.52 Example of bed and water level profiles during equilibrium
4.53 Statistics of bed levels
4.54 Sediment transport versus time
4.55 Sediment transport and \(D_{50}\) of transported sediment during equilibrium
4.56 Water depth versus time during frequent equilibrium measurements
4.57 Energy slope and temperature versus time during frequent equilibrium measurements
4.58 Time series of longitudinal soundings of middle profile during frequent equilibrium measurements
4.59 Average dune heights versus time during frequent equilibrium measurements
4.60 Average dune lengths versus time during frequent equilibrium measurements
4.61 Celerities of bedforms versus time during frequent equilibrium measurements
4.62 Particle size versus sediment transport during equilibrium
4.63 Composition of transported sediment during equilibrium
4.64 Bed composition at the end of the test
   a $D_{10}$
   b $D_{50}$
   c $D_{90}$
4.65 Average $D_{10}$, $D_{50}$, $D_{90}$ and sigma
   a Right profile
   b Middle profile
   c Left profile

4.5 Experiment T52

The imposed variables of Experiment T52 can be divided in (i) variables that were constant for all experiments in this series of experiments with graded sediment, notably:
- slope of energy level $1.6 \times 10^{-3}$,
- flume width 1.125 m,
- mixture used,
- sediment being recirculated,
and (ii) variables that were selected for this particular experiment. For the latter only the discharge still had to be selected. Because it was intended to compare experiment T52 with T50, the same value for the discharge was selected as in experiment T50, notably:
- discharge 0.240 m$^3$/s.
The actual value of the discharge was however slightly larger, notably 0.241 m$^3$/s.

Experiment T52 was carried out in the period 1987.05.07 ... 1987.05.18. Equilibrium had established by 1987.05.11. In total twenty-three equilibrium measurements were made spread over a period of four days, from 1987.05.11 ... 1987.05.18. Two series of frequent measurements of thirteen measurements each were done on 1987.05.11. The bed composition was sampled on 1987.05.18.
From the measurements made in the equilibrium stage the following main results were obtained as to the most important dependent variables (average value and standard deviation):

- water depth:
  - average water depth 0.349 m,
  - standard deviation 0.014 m;

- flow velocity:
  - average flow velocity 0.62 m/s,
  - standard deviation 0.01 m/s;

- hydraulic radius:
  - average hydraulic radius 0.306 m,
  - standard deviation 0.014 m;

- Chézy coefficient:
  - average Chézy coefficient $^{3/2} \frac{m}{s}$, 27.8 $^{3/2} \frac{m}{s}$,
  - standard deviation $^{3/2} \frac{m}{s}$, 2.0 $^{3/2} \frac{m}{s}$;

- sediment transport:
  - average sediment transport 146 kg/s;

- average dune height:
  - average average dune height 0.109 m,
  - standard deviation 0.014 m;

- average dune length:
  - average average dune length 1.71 m,
  - standard deviation 0.12 m;

- dune steepness based on average dune dimensions:
  - average steepness 0.064,
  - standard deviation 0.005;

- dominant dune height:
  - average dominant dune height 0.113 m,
  - standard deviation 0.015 m;

- dominant dune length:
  - average dominant dune length 1.97 m,
  - standard deviation 0.08 m;

- dune steepness based on dominant dune dimensions:
  - average steepness 0.057,
  - standard deviation 0.008.
Although the energy slope and the water temperature were in principle controlled variables, they also fluctuated slightly. The following values are representative for the equilibrium conditions:

- energy slope: 
  - average energy slope: $1.61 \times 10^{-3}$, 
  - standard deviation: $0.14 \times 10^{-3}$;

- water temperature: 
  - average water temperature: 17.7 degr Celsius, 
  - standard deviation: 0.1 degr Celsius.

More detailed results of the measurements during equilibrium are presented in the following tables and figures:

Tables:

4.35 Summary of results of the measurements during equilibrium
4.36 Dune heights per profile during equilibrium
4.37 Dune lengths per profile during equilibrium
4.38 Average dune dimensions and steepness during equilibrium
4.39 Dominant dune dimensions and steepness during equilibrium
4.40 Summary of results of the frequent measurements during equilibrium
4.41 Dune heights per profile during frequent equilibrium measurements
4.42 Dune lengths per profile during frequent equilibrium measurements
4.43 Average dune dimensions and steepness during frequent equilibrium measurements
4.44 Dominant dune dimensions and steepness during frequent equilibrium measurements

Figures:

4.73 Example of bed and water level profiles during equilibrium
4.74 Statistics of bed levels
4.75 Sediment transport versus time
4.76 Sediment transport and $D_{50}$ of transported sediment during equilibrium
4.77 Water depth versus time during frequent equilibrium measurements
4.78 Energy slope and temperature versus time during frequent equilibrium measurements
4.79 Time series of longitudinal soundings of middle profile during frequent equilibrium measurements
4.80 Average dune heights versus time during frequent equilibrium measurements
4.81 Average dune lengths versus time during frequent equilibrium measurements
4.82 Celerities of bedforms versus time during frequent equilibrium measurements
4.83 Particle size versus sediment transport during equilibrium
4.84 Composition of transported sediment during equilibrium
4.85 Bed composition at the end of the test
   a $D_{10}$
   b $D_{50}$
   c $D_{90}$
4.86 Average $D_{10}$, $D_{50}$, $D_{90}$ and sigma
   a Right profile
   b Middle profile
   c Left profile

4.6 Experiment T53

The imposed variables of Experiment T53 can be divided in (i) variables that were constant for all experiments in this series of experiments with graded sediment, notably:
   - slope of energy level $1.6 \times 10^{-3}$,
   - flume width 1.125 m,
   - mixture used,
   - sediment being recirculated,
and (ii) variables that were selected for this particular experiment. For the latter only the discharge still had to be selected. Because it was intended to compare experiment T53 with T49, the same value for the discharge was selected as in experiment T49, notably:
   - discharge 0.110 m$^3$/s.

The actual value of the discharge was however slightly larger, notably 0.111 m$^3$/s.

Experiment T53 was carried out in the period 1987.05.19 ... 1987.05.27. Equilibrium had established by 1987.05.22. In total twenty-four equilibrium measurements were made spread over a period of six days, from 1987.05.22 ... 1987.05.27. Two series of frequent measurements of thirteen measurements each were done on 1987.05.22. The bed composition was sampled on 1987.05.28.
From the measurements made in the equilibrium stage the following main results were obtained as to the most important dependent variables (average value and standard deviation):

- **water depth:**
  - average water depth 0.189 m,
  - standard deviation 0.004 m;

- **flow velocity:**
  - average flow velocity 0.52 m/s,
  - standard deviation 0.01 m/s;

- **hydraulic radius:**
  - average hydraulic radius 0.171 m,
  - standard deviation 0.004 m;

- **Chézy coefficient:**
  - average Chézy coefficient \( \frac{1}{2} \) \( \frac{m}{s} \),
  - standard deviation 1.0 \( \frac{m}{s} \);

- **sediment transport:**
  - average sediment transport 69 kg/s;

- **average dune height:**
  - average average dune height 0.073 m,
  - standard deviation 0.004 m;

- **average dune length:**
  - average average dune length 1.55 m,
  - standard deviation 0.10 m;

- **dune steepness based on average dune dimensions:**
  - average steepness 0.047,
  - standard deviation 0.003;

- **dominant dune height:**
  - average dominant dune height 0.077 m,
  - standard deviation 0.005 m;

- **dominant dune length:**
  - average dominant dune length 1.86 m,
  - standard deviation 0.14 m;

- **dune steepness based on dominant dune dimensions:**
  - average steepness 0.042,
  - standard deviation 0.003.
Although the energy slope and the water temperature were in principle controlled variables, they also fluctuated slightly. The following values are representative for the equilibrium conditions:

- energy slope:
  - average energy slope \( 1.56 \times 10^{-3} \),
  - standard deviation \( 0.14 \times 10^{-3} \);

- water temperature:
  - average water temperature 17.9 deg C,
  - standard deviation 0.0 deg C.

More detailed results of the measurements during equilibrium are presented in the following tables and figures:

**Tables:**

4.46 Summary of results of the measurements during equilibrium
4.47 Dune heights per profile during equilibrium
4.48 Dune lengths per profile during equilibrium
4.49 Average dune dimensions and steepness during equilibrium
4.50 Dominant dune dimensions and steepness during equilibrium
4.51 Summary of results of the frequent measurements during equilibrium
4.52 Dune heights per profile during frequent equilibrium measurements
4.53 Dune lengths per profile during frequent equilibrium measurements
4.54 Average dune dimensions and steepness during frequent equilibrium measurements
4.55 Dominant dune dimensions and steepness during frequent equilibrium measurements

**Figures:**

4.94 Example of bed and water level profiles during equilibrium
4.95 Statistics of bed levels
4.96 Sediment transport versus time
4.97 Sediment transport and \( D_{50} \) of transported sediment during equilibrium
4.98 Water depth versus time during frequent equilibrium measurements
4.99 Energy slope and temperature versus time during frequent equilibrium measurements
4.100 Time series of longitudinal soundings of middle profile during frequent equilibrium measurements
4.101 Average dune heights versus time during frequent equilibrium measurements

4.102 Average dune lengths versus time during frequent equilibrium measurements

4.103 Celerities of bedforms versus time during frequent equilibrium measurements

4.104 Particle size versus sediment transport during equilibrium

4.105 Composition of transported sediment during equilibrium

4.106 Bed composition at the end of the test
   a $D_{10}$
   b $D_{50}$
   c $D_{90}$

4.107 Average $D_{10}$, $D_{50}$, $D_{90}$ and sigma
   a Right profile
   b Middle profile
   c Left profile

4.7 Experiment T54

The imposed variables of Experiment T54 can be divided in (i) variables that were constant for all experiments in this series of experiments with graded sediment, notably:
- slope of energy level $1.6 \times 10^{-3}$,
- flume width 1.125 m,
- mixture used,
- sediment being recirculated,

and (ii) variables that were selected for this particular experiment. For the latter only the discharge still had to be selected. Because a water depth of approximately 0.3 m was required, for T50 the following value for the discharge was selected:
- discharge 0.050 m³/s.

Experiment T50 was carried out in the period 1987.05.27 ... 1987.06.04. Equilibrium had established by 1987.05.31. In total twenty equilibrium measurements were made spread over a period of four days, from 1987.05.31 ... 1987.06.03. Two series of frequent measurements of thirteen measurements each were done on 1987.06.01. The bed composition was sampled on 1987.06.02.
From the measurements made in the equilibrium stage the following main results were obtained as to the most important dependent variables (average value and standard deviation):

- **water depth**:
  - average water depth 0.091 m,
  - standard deviation 0.001 m;

- **flow velocity**:
  - average flow velocity 0.50 m/s,
  - standard deviation 0.01 m/s;

- **hydraulic radius**:
  - average hydraulic radius 0.083 m,
  - standard deviation 0.010 m;

- **Chézy coefficient**:
  - average Chézy coefficient 43.4 $\frac{m}{s}$,
  - standard deviation 1.0 $\frac{m}{s}$;

- **sediment transport**:
  - average sediment transport 30 kg/s;

- **average dune height**:
  - average average dune height 0.040 m,
  - standard deviation 0.002 m;

- **average dune length**:
  - average average dune length 1.92 m,
  - standard deviation 0.23 m;

- **dune steepness based on average dune dimensions**:
  - average steepness 0.021,
  - standard deviation 0.002;

- **dominant dune height**:
  - average dominant dune height 0.042 m,
  - standard deviation 0.003 m;

- **dominant dune length**:
  - average dominant dune length 2.40 m,
  - standard deviation 0.32 m;

- **dune steepness based on dominant dune dimensions**:
  - average steepness 0.018,
  - standard deviation 0.002.
Although the energy slope and the water temperature were in principle controlled variables, they also fluctuated slightly. The following values are representative for the equilibrium conditions:

- **energy slope:**
  - average energy slope: $1.60 \times 10^{-3}$
  - standard deviation: $0.08 \times 10^{-3}$

- **water temperature:**
  - average water temperature: 18.2 degrees Celsius
  - standard deviation: 0.0 degrees Celsius

More detailed results of the measurements during equilibrium are presented in the following tables and figures:

**Tables:**

4.57 Summary of results of the measurements during equilibrium
4.58 Dune heights per profile during equilibrium
4.59 Dune lengths per profile during equilibrium
4.60 Average dune dimensions and steepness during equilibrium
4.61 Dominant dune dimensions and steepness during equilibrium
4.62 Summary of results of the frequent measurements during equilibrium
4.63 Dune heights per profile during frequent equilibrium measurements
4.64 Dune lengths per profile during frequent equilibrium measurements
4.65 Average dune dimensions and steepness during frequent equilibrium measurements
4.66 Dominant dune dimensions and steepness during frequent equilibrium measurements

**Figures:**

4.115 Example of bed and water level profiles during equilibrium
4.116 Statistics of bed levels
4.117 Sediment transport versus time
4.118 Sediment transport and $D_{50}$ of transported sediment during equilibrium
4.119 Water depth versus time during frequent equilibrium measurements
4.120 Energy slope and temperature versus time during frequent equilibrium measurements
4.121 Time series of longitudinal soundings of middle profile during frequent equilibrium measurements
4.122 Average dune heights versus time during frequent equilibrium measurements
4.123 Average dune lengths versus time during frequent equilibrium measurements
4.124 Celerities of bedforms versus time during frequent equilibrium measurements
4.125 Particle size versus sediment transport during equilibrium
4.126 Composition of transported sediment during equilibrium
4.127 Bed composition at the end of the test
   a. $D_{10}$
   b. $D_{50}$
   c. $D_{90}$

4.128 Average $D_{10}$, $D_{50}$, $D_{90}$ and sigma
   a. Right profile
   b. Middle profile
   c. Left profile

4.8 Summary of results for equilibrium conditions

In the preceding Sections results were presented for the different experiments with graded sediments reported upon here. A summary of the main results is given in this last Subsection.

Table 4.67* presents the main characteristics of experiments with graded sediments as far as the imposed variables are concerned. Table 4.68* gives a summary of results of equilibrium measurements of experiments with graded sediments, as far as the dependent variables are concerned.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Discharge (m³/s)</th>
<th>Flume width (m)</th>
<th>Slope $i$ (10⁻³)</th>
<th>Sediment characteristics</th>
<th>Water temperature ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>B</td>
<td></td>
<td>$D_{50}$ (mm)</td>
<td>$D_{90}$ (mm)</td>
<td>$\sigma_g$ (-)</td>
</tr>
<tr>
<td>T49</td>
<td>0.110</td>
<td>1.125</td>
<td>1.61</td>
<td>0.66</td>
<td>2.24</td>
</tr>
<tr>
<td>T50</td>
<td>0.240</td>
<td>1.125</td>
<td>1.61</td>
<td>0.66</td>
<td>2.24</td>
</tr>
<tr>
<td>T51</td>
<td>0.300</td>
<td>1.125</td>
<td>1.67</td>
<td>0.66</td>
<td>2.24</td>
</tr>
<tr>
<td>T52</td>
<td>0.240</td>
<td>1.125</td>
<td>1.61</td>
<td>0.66</td>
<td>2.24</td>
</tr>
<tr>
<td>T53</td>
<td>0.110</td>
<td>1.125</td>
<td>1.56</td>
<td>0.66</td>
<td>2.24</td>
</tr>
<tr>
<td>T54</td>
<td>0.050</td>
<td>1.125</td>
<td>1.60</td>
<td>0.66</td>
<td>2.24</td>
</tr>
</tbody>
</table>

Table 4.67* Characteristics of experiments with graded sediments
<table>
<thead>
<tr>
<th>Test number</th>
<th>Water depth (m)</th>
<th>Hydraulic radius (m)</th>
<th>Chézy coefficient (m²/s)</th>
<th>Roughness coefficient (m)</th>
<th>Sediment transport (weighted submerged) (kg/h)</th>
<th>Bedform characteristic H (m)</th>
<th>L (m)</th>
<th>(c_b) (m/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T49</td>
<td>0.178</td>
<td>0.159</td>
<td>35.1</td>
<td>0.021</td>
<td>85.0</td>
<td>0.075</td>
<td>1.716</td>
<td>1.69</td>
</tr>
<tr>
<td>T50</td>
<td>0.337</td>
<td>0.293</td>
<td>29.5</td>
<td>0.081</td>
<td>170.2</td>
<td>0.109</td>
<td>1.799</td>
<td>2.22</td>
</tr>
<tr>
<td>T51</td>
<td>0.402</td>
<td>0.346</td>
<td>28.1</td>
<td>0.114</td>
<td>195.8</td>
<td>0.117</td>
<td>1.829</td>
<td>2.16</td>
</tr>
<tr>
<td>T52</td>
<td>0.349</td>
<td>0.306</td>
<td>27.8</td>
<td>0.104</td>
<td>146.2</td>
<td>0.109</td>
<td>1.709</td>
<td>1.97</td>
</tr>
<tr>
<td>T53</td>
<td>0.189</td>
<td>0.171</td>
<td>32.0</td>
<td>0.034</td>
<td>69.2</td>
<td>0.073</td>
<td>1.552</td>
<td>1.58</td>
</tr>
<tr>
<td>T54</td>
<td>0.091</td>
<td>0.079</td>
<td>43.4</td>
<td>0.004</td>
<td>30.0</td>
<td>0.035</td>
<td>1.534</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Table 4.68* Summary of results of equilibrium measurements of experiments with graded sediment

The same results are presented in the Figures 4.129, 4.130* ... 4.137* and 4.138. In these figures the dependent variables are plotted against the only varying imposed variable, notably the discharge. The legend to these figures is as follows:

- Figure 4.129 Water depth versus discharge
- Figure 4.130* Flow velocity versus discharge
- Figure 4.131* Hydraulic radius versus discharge
- Figure 4.132* Chézy coefficient versus discharge
- Figure 4.133* Sediment transport versus discharge
- Figure 4.134* Dune height versus discharge
- Figure 4.135* Dune length versus discharge
- Figure 4.136* Dune steepness versus discharge
- Figure 4.137* Dune celerity versus discharge
- Figure 4.138* Characteristic particle sizes versus discharge
Figure 3.130* Flow velocity versus discharge

Figure 4.131* Hydraulic radius versus discharge

Figure 4.132* Chézy coefficient versus discharge

Figure 4.133* Sediment transport versus discharge

EXPERIMENTS WITH GRADED SEDIMENTS IN A STRAIGHT FLUME 53
Figure 4.134* Dune height versus discharge

Figure 4.135* Dune length versus discharge

Figure 4.136* Dune steepness versus discharge

Figure 4.137* Dune celerity versus discharge
5. Results for transitional conditions

5.1 General

In this Chapter the results are presented that were obtained during the transitional stages of the tests with graded sediments that are described in the present report. As explained in Section 4.1 the results obtained during the present tests are presented as tables and figures in approximately a chronological order. That means that the tables and figures in which data are given regarding the transitions are included in the numbering as if they are part of Chapter 4.

It should be stressed here that the data gathered during the transitions should be considered, at least to some extent, as by-products only. The main aim of the present study was to investigate equilibrium conditions. The implication is that the data gathered during the transitions described here, are possibly of limited value only. A major drawback in this respect is that all transitions occurred only once. From previous experience with the study of transitions (see e.g. Wijbenga and Klaassen (1983)), it is known that this could introduce substantial "scatter" because of the limited number of bedforms in the flume. It is nevertheless of interest to report on the data obtained, because (i) they are the first data known to the author of transitions for so widely graded bed material, and (ii) it is worthwhile to try to compare the results with the transitions studied previously for uniform material, to see whether the behaviour of graded sediments is different from uniform material.

The different transitions are described briefly in the subsequent Sections. A discussion of the results and a comparison with the experiments with uniform sediments is provided in Section 6.9.

5.2 Experiment T49

The transition T49 was slightly different from all the other transitions reported about in this Chapter: the initial condition of T49 was not a bed with fully developed bedforms, but T49 started from an artificially flattened bed where segregation had been prevented as much as possible. Nevertheless, the bed in the flume was not completely flat. In Section 4.2 it was already indicated that small disturbances were still present in the bed with a "bedform..."
height" of some 0.04 m. This implies that the transition T49 had better be characterized as a test of the initiation and growth of bedforms than as a dune-dune transition.

The final condition of transition T49 was of course the equilibrium conditions of T49. The main characteristics of the "initial" and the final conditions for the transition T49 are listed below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
</tr>
<tr>
<td>Test number</td>
<td>---</td>
</tr>
<tr>
<td>Dune height (m):</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>0.04</td>
</tr>
<tr>
<td>- Dominant</td>
<td>0.04</td>
</tr>
<tr>
<td>Dune length (m):</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>---</td>
</tr>
<tr>
<td>- Dominant</td>
<td>---</td>
</tr>
<tr>
<td>Dune steepness (−)</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>---</td>
</tr>
<tr>
<td>- Dominant</td>
<td>---</td>
</tr>
</tbody>
</table>

Detailed data on the transition are provided in the following tables and figures:

Tables:

4.1 Summary of results of the measurements during the transition

Figures:

4.3 Energy slope and temperature versus time during the transition
4.4 Water depth versus time during the transition
4.5 Chézy coefficient versus time during the transition
4.6 Sediment transport versus time during the transition
4.7 Longitudinal profiles of middle section during the transition
4.8 Average dune height of each longitudinal profile during the transition
4.9 Average dune length of each longitudinal profile during the transition
5.3 Experiment T50

The initial conditions for transition T50 were the equilibrium conditions for T49, whereas the final condition of this transition was of course the equilibrium conditions of T50. The main characteristics of the "initial" and the final conditions for the transition T50 are listed below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
</tr>
<tr>
<td>Test number</td>
<td>T49</td>
</tr>
<tr>
<td>Dune height (m):</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>0.075</td>
</tr>
<tr>
<td>- Dominant</td>
<td>0.080</td>
</tr>
<tr>
<td>Dune length (m):</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>1.72</td>
</tr>
<tr>
<td>- Dominant</td>
<td>2.08</td>
</tr>
<tr>
<td>Dune steepness (-):</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>0.044</td>
</tr>
<tr>
<td>- Dominant</td>
<td>0.038</td>
</tr>
</tbody>
</table>

Detailed data on the transition are provided in the following tables and figures:

Tables:

4.12 Summary of results of the measurements during the transition

Figures:

4.24 Energy slope and temperature versus time during the transition
4.25 Water depth versus time during the transition
4.26 Chézy coefficient versus time during the transition
4.27 Sediment transport versus time during the transition
4.28 Longitudinal profiles of middle section during the transition
4.29 Average dune height of each longitudinal profile during the transition
4.30 Average dune length of each longitudinal profile during the transition
5.4 Experiment T51

The initial conditions for transition T51 were the equilibrium conditions for T50, while the final condition of this transition was of course the equilibrium conditions of T51. The main characteristics of the "initial" and the final conditions for the transition T51 are listed below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
</tr>
<tr>
<td>Test number</td>
<td>T50</td>
</tr>
<tr>
<td>Dune height (m):</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>0.109</td>
</tr>
<tr>
<td>- Dominant</td>
<td>0.115</td>
</tr>
<tr>
<td>Dune length (m):</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>1.80</td>
</tr>
<tr>
<td>- Dominant</td>
<td>2.11</td>
</tr>
<tr>
<td>Dune steepness (-)</td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td>0.060</td>
</tr>
<tr>
<td>- Dominant</td>
<td>0.055</td>
</tr>
</tbody>
</table>

Detailed data on the transition are provided in the following tables and figures:

Tables:

4.23 Summary of results of the measurements during the transition

Figures:

4.45 Energy slope and temperature versus time during the transition
4.46 Water depth versus time during the transition
4.47 Chézy coefficient versus time during the transition
4.48 Sediment transport versus time during the transition
4.49 Longitudinal profiles of middle section during the transition
4.50 Average dune height of each longitudinal profile during the transition
4.51 Average dune length of each longitudinal profile during the transition
5.5 Experiment T52

The initial conditions for transition T52 were the equilibrium conditions for T51, while the final condition of this transition was of course the equilibrium conditions of T52. The main characteristics of the "initial" and the final conditions for the transition T52 are listed below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Initial</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test number</td>
<td></td>
<td>T51</td>
<td>T52</td>
</tr>
<tr>
<td>Dune height (m):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td></td>
<td>0.117</td>
<td>0.109</td>
</tr>
<tr>
<td>- Dominant</td>
<td></td>
<td>0.123</td>
<td>0.113</td>
</tr>
<tr>
<td>Dune length (m):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td></td>
<td>1.83</td>
<td>1.71</td>
</tr>
<tr>
<td>- Dominant</td>
<td></td>
<td>2.13</td>
<td>1.97</td>
</tr>
<tr>
<td>Dune steepness (-)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td></td>
<td>0.064</td>
<td>0.064</td>
</tr>
<tr>
<td>- Dominant</td>
<td></td>
<td>0.058</td>
<td>0.057</td>
</tr>
</tbody>
</table>

Detailed data on the transition are provided in the following tables and figures:

Tables:

4.34 Summary of results of the measurements during the transition

Figures:

4.66 Energy slope and temperature versus time during the transition
4.67 Water depth versus time during the transition
4.68 Chézy coefficient versus time during the transition
4.69 Sediment transport versus time during the transition
4.70 Longitudinal profiles of middle section during the transition
4.71 Average dune height of each longitudinal profile during the transition
4.72 Average dune length of each longitudinal profile during the transition
5.6 Experiment T53

The initial conditions for transition T53 were the equilibrium conditions for T52, while the final condition of this transition T49 was of course the equilibrium conditions of T53. The main characteristics of the "initial" and the final conditions for the transition T53 are listed below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Initial</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test number</td>
<td></td>
<td>T52</td>
<td>T53</td>
</tr>
<tr>
<td>Dune height (m):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td></td>
<td>0.109</td>
<td>0.073</td>
</tr>
<tr>
<td>- Dominant</td>
<td></td>
<td>0.113</td>
<td>0.077</td>
</tr>
<tr>
<td>Dune length (m):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td></td>
<td>1.71</td>
<td>1.55</td>
</tr>
<tr>
<td>- Dominant</td>
<td></td>
<td>1.97</td>
<td>1.86</td>
</tr>
<tr>
<td>Dune steepness (-)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td></td>
<td>0.064</td>
<td>0.047</td>
</tr>
<tr>
<td>- Dominant</td>
<td></td>
<td>0.057</td>
<td>0.042</td>
</tr>
</tbody>
</table>

Detailed data on the transition are provided in the following tables and figures:

Tables:

4.45 Summary of results of the measurements during the transition

Figures:

4.87 Energy slope and temperature versus time during the transition
4.88 Water depth versus time during the transition
4.89 Chézy coefficient versus time during the transition
4.90 Sediment transport versus time during the transition
4.91 Longitudinal profiles of middle section during the transition
4.92 Average dune height of each longitudinal profile during the transition
4.93 Average dune length of each longitudinal profile during the transition
5.7 Experiment T54

The initial conditions for transition T54 were the equilibrium conditions for T53, while the final condition of this transition T49 was of course the equilibrium conditions of T54. The main characteristics of the "initial" and the final conditions for the transition T54 are listed below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Initial</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test number</td>
<td></td>
<td>T53</td>
<td>T54</td>
</tr>
<tr>
<td>Dune height (m):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td></td>
<td>0.073</td>
<td>0.040</td>
</tr>
<tr>
<td>- Dominant</td>
<td></td>
<td>0.077</td>
<td>0.042</td>
</tr>
<tr>
<td>Dune length (m):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td></td>
<td>1.55</td>
<td>1.92</td>
</tr>
<tr>
<td>- Dominant</td>
<td></td>
<td>1.86</td>
<td>2.40</td>
</tr>
<tr>
<td>Dune steepness (-)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Average</td>
<td></td>
<td>0.047</td>
<td>0.021</td>
</tr>
<tr>
<td>- Dominant</td>
<td></td>
<td>0.042</td>
<td>0.018</td>
</tr>
</tbody>
</table>

Detailed data on the transition are provided in the following tables and figures:

Tables:

4.56 Summary of results of the measurements during the transition

Figures:

4.108 Energy slope and temperature versus time during the transition
4.109 Water depth versus time during the transition
4.110 Chézy coefficient versus time during the transition
4.111 Sediment transport versus time during the transition
4.112 Longitudinal profiles of middle section during the transition
4.113 Average dune height of each longitudinal profile during the transition
4.114 Average dune length of each longitudinal profile during the transition
6. **Analysis and discussion of results**

6.1 **General**

In the previous Chapters 4 and 5 the results of the experiments with graded sediments were presented, both for the equilibrium conditions and for the transitions. In this Chapter these results are analysed in some detail and the obtained results are discussed.

The analyses and the discussions to follow should be appreciated in the light of the problem description given in Section 1.3. This means that the emphasis will be on improving the understanding of the morphological behaviour of graded sediments and that the possible influence of the gradation is investigated.

The latter is done by comparing the results obtained during the present studies with the results obtained during the experiments with uniform bed material, that have been carried out in the sand flume previously. An overview of these experiments is given in Section 2.4. In Table 6.1* the characteristics of these tests, as far as the imposed boundary conditions are concerned, are given. These should be compared with the characteristics of the present tests, see Table 4.67*. Most of the results for these tests with uniform sediments are presented in Bakker(1986), and some are presented together with the corresponding results of the present tests with mixtures, in Table 6.2*. For the present analysis some additional data processing of those tests with uniform sediments was required, and the results of this processing will be discussed (and the results presented) in the appropriate Sections.

The comparison with the experiments with uniform bed material is done per subject. That means that e.g. for the hydraulic roughness (Section 6.4) not only the results of the graded sediment experiments are discussed but also a comparison is made with the tests with uniform sediments.

In the subsequent Sections the following aspects are discussed:
- vertical sorting (Section 6.3);
- hydraulic roughness (Section 6.4);
- bedform dimensions (Section 6.5);
- sediment transport (Section 6.6), including the analysis of the composition of the transported sediments;

EXPERIMENTS WITH GRADED SEDIMENTS IN A STRAIGHT FLUME
<table>
<thead>
<tr>
<th>Test number</th>
<th>Discharge Q (m$^3$/s)</th>
<th>Flume width B (m)</th>
<th>Slope i ($10^{-3}$)</th>
<th>Sediment characteristics</th>
<th>Water temperature T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T23</td>
<td>0.265</td>
<td>1.500</td>
<td>1.69</td>
<td>0.77 0.82 1.06</td>
<td>18.0</td>
</tr>
<tr>
<td>T26</td>
<td>0.401</td>
<td>1.500</td>
<td>1.56</td>
<td>0.77 0.82 1.06</td>
<td>18.0</td>
</tr>
<tr>
<td>T30</td>
<td>0.148</td>
<td>1.500</td>
<td>1.64</td>
<td>0.77 0.82 1.06</td>
<td>17.8</td>
</tr>
<tr>
<td>T31</td>
<td>0.116</td>
<td>1.125</td>
<td>1.60</td>
<td>0.77 0.82 1.06</td>
<td>17.9</td>
</tr>
<tr>
<td>T33</td>
<td>0.200</td>
<td>1.125</td>
<td>1.52</td>
<td>0.77 0.82 1.06</td>
<td>17.9</td>
</tr>
<tr>
<td>T35</td>
<td>0.089</td>
<td>0.500</td>
<td>1.63</td>
<td>0.77 0.82 1.06</td>
<td>18.0</td>
</tr>
<tr>
<td>T38</td>
<td>0.048</td>
<td>0.500</td>
<td>1.58</td>
<td>0.77 0.82 1.06</td>
<td>18.0</td>
</tr>
<tr>
<td>T39</td>
<td>0.133</td>
<td>0.500</td>
<td>1.51</td>
<td>0.77 0.82 1.06</td>
<td>18.0</td>
</tr>
<tr>
<td>T49</td>
<td>0.110</td>
<td>1.125</td>
<td>1.61</td>
<td>0.66 2.24 2.34</td>
<td>17.6</td>
</tr>
<tr>
<td>T50</td>
<td>0.240</td>
<td>1.125</td>
<td>1.61</td>
<td>0.66 2.24 2.34</td>
<td>17.8</td>
</tr>
<tr>
<td>T51</td>
<td>0.300</td>
<td>1.125</td>
<td>1.67</td>
<td>0.66 2.24 2.34</td>
<td>18.0</td>
</tr>
<tr>
<td>T52</td>
<td>0.240</td>
<td>1.125</td>
<td>1.61</td>
<td>0.66 2.24 2.34</td>
<td>17.7</td>
</tr>
<tr>
<td>T53</td>
<td>0.110</td>
<td>1.125</td>
<td>1.56</td>
<td>0.66 2.24 2.34</td>
<td>17.9</td>
</tr>
<tr>
<td>T54</td>
<td>0.050</td>
<td>1.125</td>
<td>1.60</td>
<td>0.66 2.24 2.34</td>
<td>18.2</td>
</tr>
</tbody>
</table>

Table 6.1 Characteristics of selected experiments for study of effect of gradation

<table>
<thead>
<tr>
<th>Test number</th>
<th>Water depth h (m)</th>
<th>Hydraulic radius $R_b$ (m)</th>
<th>Chezy coeff. $C_b$ ($m^1/2/s$)</th>
<th>Roughness coeff. $k_s$ (m)</th>
<th>Sediment transport (weighed submerged) S (kg/h)</th>
<th>Bedform characteristics $H$ (m)</th>
<th>$L$ (m)</th>
<th>$C_b$ (m/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T23</td>
<td>0.302</td>
<td>0.295</td>
<td>27.1</td>
<td>0.111</td>
<td>130.4</td>
<td>0.080</td>
<td>1.112</td>
<td>2.06</td>
</tr>
<tr>
<td>T26</td>
<td>0.405</td>
<td>0.361</td>
<td>28.1</td>
<td>0.119</td>
<td>179.1</td>
<td>0.096</td>
<td>1.323</td>
<td>2.71</td>
</tr>
<tr>
<td>T30</td>
<td>0.200</td>
<td>0.187</td>
<td>28.2</td>
<td>0.061</td>
<td>64.4</td>
<td>0.070</td>
<td>1.168</td>
<td>1.33</td>
</tr>
<tr>
<td>T31</td>
<td>0.208</td>
<td>0.189</td>
<td>28.5</td>
<td>0.059</td>
<td>48.4</td>
<td>0.068</td>
<td>1.187</td>
<td>1.45</td>
</tr>
<tr>
<td>T33</td>
<td>0.306</td>
<td>0.271</td>
<td>27.2</td>
<td>0.100</td>
<td>93.1</td>
<td>0.081</td>
<td>1.202</td>
<td>-</td>
</tr>
<tr>
<td>T35</td>
<td>0.328</td>
<td>0.256</td>
<td>26.1</td>
<td>0.109</td>
<td>35.6</td>
<td>0.079</td>
<td>1.212</td>
<td>2.10</td>
</tr>
<tr>
<td>T38</td>
<td>0.209</td>
<td>0.172</td>
<td>27.5</td>
<td>0.061</td>
<td>23.3</td>
<td>0.056</td>
<td>1.131</td>
<td>1.80</td>
</tr>
<tr>
<td>T39</td>
<td>0.436</td>
<td>0.321</td>
<td>25.9</td>
<td>0.140</td>
<td>47.4</td>
<td>0.092</td>
<td>1.287</td>
<td>2.39</td>
</tr>
<tr>
<td>T49</td>
<td>0.178</td>
<td>0.159</td>
<td>35.1</td>
<td>0.021</td>
<td>85.0</td>
<td>0.075</td>
<td>1.716</td>
<td>1.69</td>
</tr>
<tr>
<td>T50</td>
<td>0.337</td>
<td>0.293</td>
<td>29.5</td>
<td>0.081</td>
<td>170.2</td>
<td>0.109</td>
<td>1.799</td>
<td>2.22</td>
</tr>
<tr>
<td>T51</td>
<td>0.402</td>
<td>0.346</td>
<td>28.1</td>
<td>0.114</td>
<td>195.8</td>
<td>0.117</td>
<td>1.829</td>
<td>2.16</td>
</tr>
<tr>
<td>T52</td>
<td>0.349</td>
<td>0.306</td>
<td>27.8</td>
<td>0.104</td>
<td>146.2</td>
<td>0.109</td>
<td>1.709</td>
<td>1.97</td>
</tr>
<tr>
<td>T53</td>
<td>0.189</td>
<td>0.171</td>
<td>32.0</td>
<td>0.034</td>
<td>69.2</td>
<td>0.073</td>
<td>1.552</td>
<td>1.58</td>
</tr>
<tr>
<td>T54</td>
<td>0.091</td>
<td>0.083</td>
<td>43.4</td>
<td>0.004</td>
<td>30.0</td>
<td>0.040</td>
<td>1.924</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Table 6.2 Results of selected experiments for study of effect of gradation
- influence of gradation (Section 6.7), where those aspects which are related to the comparison between the graded and the uniform sediments see below figure and which are discussed in the Sections 6.3...6.6, are summarized;

![Graph showing particle size distribution](image)

- the influence of three-dimensional phenomena (Section 6.8), where a comparison is made between the present experiments and the results of the Waal model, where the same bed material was used;

- transitions (Section 6.9).

Because an important part of this analysis deals with the comparison of results of experiments, it is important to see how significant a possible difference between two observed values is. Therefore Section 6.2 deals with the accuracy of the data obtained and discusses possibilities and limitations of checking whether results obtained are significantly different.
The Sections 6.10 and 6.11 deal with the implications of the results obtained during the present studies for respectively morphological models of graded sediments and for field conditions and investigations in prototype.

6.2 Accuracy and the significance of observed differences

All parameters that are linked to sediment transport processes are stochastic. This starts with the size and density of the sediments that are being transported and with the flow velocity, even when the discharge is constant. But also the discharge is usually variable, subject as it is to external factors like the climate and the weather which are reflected in the rainfall and the temperature, but also like the geological and soil conditions of the catchment, which combined determine e.g. the vegetation cover and the permeability of the subsoil. Also the amounts of sediment per unit time delivered to the river are quite variable. Furthermore, also the dimensions of the minor bed and of the floodplains are variable, at least in space. Finally, the turbulence of the water induces stochastic elements.

This variability in time and space of the external factors is also present during flume experiments, although at a smaller scale. It is reflected in the different dependent variables like the sediment transport itself, the dune dimensions, the water depth, the hydraulic roughness, etc. This implies that all these parameters are characterized by an average value and a fluctuation around this average.

This fluctuation is present at different time scales. Small-scale fluctuations are related to the turbulence of the water and typically have a period in the order of minutes. Larger-scale phenomena are the irregular dune pattern, persisting several hours (see Wijbenga and Klaassen, 1983), and three-dimensional phenomena which may even last much longer. There may even be larger time scales, as discussed by Ribberink (1987a): the deepest troughs occur only seldom, so the material that is deposited at the lowest levels of the sorting layers is only moved after a very long time.

The reason to discuss this aspect at length is that during the experiments discussed here many measurements were done and from these measurements e.g. the average dune height or the average vertical composition of the sorting layer were determined. All these averages are subject to errors due to a number of reasons:
(i) the measurement was done only a limited number of times, so the true average was certainly not obtained;
(ii) the measurements were carried out only over a limited period, so it may be that fluctuations with a large period were present having caused that the estimate of the average was biased;
(iii) the measurements were only done at a limited number of locations, so the true average was certainly not obtained;
(iv) the measurements were done with a limited accuracy only.

The implication is that the computed average for a certain parameter may be quite different from the true average, but also that the standard deviation of the individual measurements may not be a good basis for the estimation of the error involved in the computed average. Nevertheless, it has been assumed, for the time being, that the standard deviation of the individual measurements can be used for the computation of the possible variation in the computed average. So the following statement can be made:

If n measurements have been made of a certain parameter $X$ and these measurements are $X_1, X_2, \ldots, X_n$, and the average and the standard deviation of this series are $\bar{X}$ and $\sigma_X$, then there is a probability of 67% that the true average lies between the following boundaries:

- lower boundary: $\bar{X} - \frac{\sigma_X}{\sqrt{n}}$
- upper boundary: $\bar{X} + \frac{\sigma_X}{\sqrt{n}}$

Based on this assumption it is possible to use e.g. the Student-t test (see e.g. Hald, 1967) to check whether two computed averages are significantly different at a certain probability level. In appropriate cases this technique was used in this study.

More generally all discussions hereafter should be appreciated, keeping in mind the stochastic behaviour of most of the parameters involved, so identified tendencies may or may not be significant. For many aspects more and more detailed investigations may be needed to ascertain the true nature of the different phenomena.
6.3 Vertical sorting

According to Ribberink (1987a) and some other authors vertical sorting is an important aspect of sediment transport phenomena of mixtures in the dune phase. This aspect was one of the most important items studied in the present investigation. It was expected that as a consequence of this phenomena some of the coarsest material would be stored in a "reservoir" at the level of the lowest troughs during the test with the largest bedforms (T51). As a consequence the composition of the sorting layer during the subsequent tests (T52, T53 and T54) with smaller discharges (and consequently lower bedforms) would be finer.

This supposed behaviour was checked on the basis of the measurements made. In particular the following Figures should be considered:

- Test 49: Initial: Figure 4.1
- Test 49: Final: Figure 4.23
- Test 50: Final: Figure 4.44
- Test 51: Final: Figure 4.65
- Test 52: Final: Figure 4.86
- Test 53: Final: Figure 4.107
- Test 54: Final: Figure 4.128

From all tests for the final conditions it is clear that vertical sorting had occurred. This can be concluded by comparing the "final" figures with Figure 4.1. From the latter it was concluded, that initially segregation played only a negligible role. Furthermore, it is of interest to see that the gradation of the bed material in the upper layers is much smaller than the gradation of the initial material. Of the initial material the gradation is about 2.3, while in the upper layers the gradation has fallen back to about 1.5, implying that this material is better sorted. Also this can be interpreted as the result of the coarser sediments deposited at the level of the troughs.

In the figures mentioned above also the initial D_{50} and D_{90} were drawn, and furthermore the approximate thickness and level of the sorting layer was indicated. The level of the sorting layer was inferred from the figures with the "Statistics of the bed levels" (notably the Figures 4.11 (T49), 4.32 (T50), 4.53 (T51), 4.74 (T52), 4.95 (T53) and 4.116 (T54)). The thickness of the sorting layer was defined as the distance between the 2.5% upper level and the 2.5% lower level (whereas Ribberink (1987a) used 5%).

EXPERIMENTS WITH GRADED SEDIMENTS IN A STRAIGHT FLUME

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distinction was made between the sorting layer thickness of the middle profile and the side profiles, see Table 6.3. A number of interesting observations can be made:

1. There is a considerable scatter: compare e.g. the Figures 4.23a (right profile) and 4-23c (left profile). It is assumed that the difference is due to the limited sampling in the side profiles, but also the middle profile can be subject to considerable errors.

2. Even for the tests T49, T50 and T51 the coarsest sediments are found below the lower level of the sorting layer. This may be due to several causes, notably:
   - data processing: the use of 2.5% in stead of 0%;
   - the possible sinking away of the coarsest sediments in the finer sediments due to local erosion around these coarsest grains.

3. The composition of the sorting layer of T54 is definitely finer than the initial material. This is less evident for the other tests.

4. The sorting layer thickness in the side profiles is substantially larger than in the middle profile.

Furthermore, it is of interest to compare mutually (i) the test T49 and T53 and (ii) the tests T50 and T52, because these tests were carried out with the same imposed boundary conditions. The only difference between the tests is their different "history": the tests T52 and T53 were preceded by the test with the highest discharge (Test T51), while the tests T49 and T50 were in the rising limb of the "hydrograph" (see Figure 3.7*).

The Figures 6.1* and 6.2* were prepared especially to allow to make a comparison between T49 and T53 and between T50 and T52, respectively. To reduce the scatter the data from the left and the right profile were combined to "the" side profile. From an inspection of the Figures 6.1* and 6.2* it must be concluded that no significant differences exists between experiments before and after the peak discharge of T51. So the above assumption regarding the storing of coarse sediments in a "reservoir" is not supported by the measured vertical sorting. The scatter does however also not allow to state that this vertical sorting is absent.

A comparison with the experiments with uniform sediments is of course not possible because in those experiments no vertical sorting was present.
Figure 6.1* Comparison of vertical sorting at the end of the tests T49 and T54

Figure 6.2* Comparison of vertical sorting at the end of the tests T50 and T52
6.4 Hydraulic roughness

The Chézy coefficients observed during the tests with graded sediments under equilibrium conditions are listed in Table 4.68*. Figure 4.132* presents the same information. The Chézy coefficients varied during the sequence of experiments T49 - T50 - T51 - T52 - T53 - T54 as 35.1 - 29.9 - 28.1 - 27.8 - 32.0 - 43.4 m²/s.

It is of interest to have a closer look at the observed hydraulic roughness of the two sets of experiments with comparable discharge, but before and after the "flood" of T51. As can be observed in Figure 4.132* after the T51 the Chézy coefficients are lower, but it should be checked whether this is a significant difference. The average values and standard deviation of the Chézy coefficients of the two sets of experiments are given below:

<table>
<thead>
<tr>
<th>Test number</th>
<th>Chézy coefficient (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>T49</td>
<td>35.1</td>
</tr>
<tr>
<td>T53</td>
<td>32.0</td>
</tr>
<tr>
<td>T50</td>
<td>29.5</td>
</tr>
<tr>
<td>T52</td>
<td>27.8</td>
</tr>
</tbody>
</table>

On these data the Student-t test was applied and it could be shown that the Chézy coefficients of both sets of experiments are significantly different at a 95% confidence level. This means that there is apparently a significant effect of the vertical sorting on the roughness coefficients. Apparently, the Chézy coefficient of graded sediments can be substantially different before and after the passage of a flood. This is the more interesting because in the previous Section a difference in composition of the bed before and after the flood could not be identified at a significant level.

The question is of course, whether this difference in hydraulic roughness is due to the fining of the sorting layer material due to the storage of coarse sediments at a lower level in the bed. The effect of this fining was studied by applying the Engelund-Hansen roughness predictor to some hypothetical "cases". These cases are only different in the size of the bed material, all the other parameters are the same. The cases were applied to the two sets of comparable experiments to study how a change in bed material size would affect the Chézy coefficients. The characteristic sizes.
(D$_{50}$) of the sediment considered below are (1) the initial D$_{50}$ of the bed material used (so neglecting vertical sorting) and corresponding to 0.66 mm, and (2) the D$_{50}$ of the sorting layer during the "recession" of the hydrograph (so during the tests T52 and T53), for which a value of D$_{50} = 0.50$ mm is a fair estimate (see e.g. the Figures 4.85 and 4.106).

(1) Comparison T49 and T53

<table>
<thead>
<tr>
<th>Case</th>
<th>no vertical sorting</th>
<th>after vertical sorting</th>
</tr>
</thead>
<tbody>
<tr>
<td>slope</td>
<td>1.6$\times$10$^{-3}$</td>
<td>1.6$\times$10$^{-3}$</td>
</tr>
<tr>
<td>unit dischrg(m$^3$/s)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>D$_{50}$ (mm)</td>
<td>0.66</td>
<td>0.50</td>
</tr>
<tr>
<td>Predicted h (m)</td>
<td>0.203</td>
<td>0.201</td>
</tr>
<tr>
<td>Predicted C (m$^3$.s$^{-1}$/s)</td>
<td>27.3</td>
<td>27.8</td>
</tr>
</tbody>
</table>

(2) Comparison T50 and T52

<table>
<thead>
<tr>
<th>Case</th>
<th>no vertical sorting</th>
<th>after vertical sorting</th>
</tr>
</thead>
<tbody>
<tr>
<td>slope</td>
<td>1.6$\times$10$^{-3}$</td>
<td>1.6$\times$10$^{-3}$</td>
</tr>
<tr>
<td>unit dischrg(m$^3$/s)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>D$_{50}$ (mm)</td>
<td>0.66</td>
<td>0.50</td>
</tr>
<tr>
<td>Predicted h (m)</td>
<td>0.313</td>
<td>0.296</td>
</tr>
<tr>
<td>Predicted C (m$^3$.s$^{-1}$/s)</td>
<td>28.6</td>
<td>31.0</td>
</tr>
</tbody>
</table>

From the result it may be concluded that a fining of the bed material would result in an increase of the Chézy coefficient (and not a decrease), so probably the fining due to vertical sorting is not causing the observed difference in hydraulic roughness. Consequently, no explanation can be offered for the reduction in hydraulic roughness. 

Furthermore, a comparison can be made with the experiments with uniform sediments. This is done in Figure 6.3* where, apart from the results of the tests with graded sediments, also the observed Chézy coefficients for the experiments with uniform sediments are plotted. From the Figure 6.3 it can be concluded that for uniform sediments smaller values for the Chézy coefficients are found than for the graded sediments. Because the D$_{50}$ of the uniform sediment is even larger than the D$_{50}$ of the graded sediment, this can not be due to the difference in D$_{50}$ (because that would even result in
a different behaviour, see before). So it must be due to the gradation of the sediment. It can be remarked here that the observed difference due to the gradation is in line with Daranandana (1962), who also found a reduction of the roughness with an increase of the gradation.

6.5 Bedform dimensions

The dimensions of the bedforms observed during the experiments with graded sediments are presented in the Figures 4.134* (dune height) and 4.135* (dune length). From Figure 4.134* it may be concluded that there is hardly any difference between the dune heights before and after the flood of T51. A different behaviour is found for the dune lengths. During the tests T52 and T53 the dune lengths are shorter than during the tests T50 and T49. Also this was investigated with the Student-\( t \) test using the following data:

<table>
<thead>
<tr>
<th>Test number</th>
<th>Average dune length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>T49</td>
<td>1.72</td>
</tr>
<tr>
<td>T53</td>
<td>1.55</td>
</tr>
<tr>
<td>T50</td>
<td>1.80</td>
</tr>
<tr>
<td>T52</td>
<td>1.71</td>
</tr>
</tbody>
</table>

Application of the Student-\( t \) test yielded as a result that the dune lengths are indeed significantly different at a 95% confidence level for the tests T49 and T53. For the tests T50 and T52 this was only the case at a 67% confidence level.

It is furthermore of interest to note that the shorter dune lengths for the tests T52 and T53 are in line with the observed smaller values for the Chézy coefficients (see Section 6.4). With the same dune height the energy losses due to the expansion downstream of the dune crests is the same too, but for the tests T52 and T53 there are more expansion losses per unit length (because there are more dune crests per unit length). A tentative conclusion may therefore be that the smaller Chézy coefficients are probably due to increased form roughness. Considering the vertical sorting in the dunes it is even probable that the grain roughness for the tests T52
Figure 6.3* Comparison of observed Chézy coefficients for graded and of uniform sediments

Figure 6.4* Comparison of observed dune heights for graded and of uniform sediments

Figure 6.5* Comparison of observed dune lengths for graded and of uniform sediments

Figure 6.18* Comparison of observed sediment transport rates for graded and of uniform sediments
and T53 is smaller, but apparently this is more than compensated for by the increased form roughness.

In the Figures 6.4* and 6.5* a comparison is made between the dune heights and dune lengths for the graded sediments and for the uniform sediments. In Figure 6.4* it is observed that the dune heights for the graded sediments are larger than for the uniform sediments, on the average about 25%. The dune lengths, however, are about 50% larger. This means that for the graded sediments probably the energy loss per dune crest is larger (Carnot losses), but that the number of losses per unit length is substantially lower. In addition also the grain roughness is larger for the uniform sediments ($D_{50}$ about 0.77 mm) than for the graded sediments ($D_{50}$ after vertical sorting about 0.5 mm, see e.g. the Figures 4.107 and 4.128). This combined effect is the explanation for the observed larger Chézy coefficients for the graded sediments.

Special attention is drawn to the apparently important role of the dune length. Until now no systematic research has been carried out into the dune length as a function of the hydraulic and sedimentological parameters. Van Rijn (1984c) proposed the following formula:

\[
L = 7.3 \, h
\]  
(6.1)

and this relation (using the hydraulic radius instead of the water depth) is drawn into Figure 6.5*. It is seen that this relation provides a poor estimate of the average dune length.

A matter of special interest is the thickness of the sorting layer and the relation of it to the dune height. The thickness of the sorting layer was determined from the probability distribution of the bed levels. This was done for the tests with graded sediments as well as for the tests with uniform sediments. For the experiments with the uniform sediments the distribution functions had not been computed before and within the framework of the present study this was done after all. The computed probability distributions for the uniform sediments (together with the associated probability density function) are given in the Figures 6.6 ... 6.13. From these figures and from similar figures for the graded sediments the thickness of the sorting layer was determined. For the upper and lower level of the sorting layer a probability of 2.5% was used, which means that 95% of the bed levels fall within the so defined sorting layer thickness. The results of the analysis is presented in Tables 6.1. Furthermore, reference is made to Figure 6.14*, where the relative thickness of the sorting layer (by dividing it by the average dune height) is plotted versus the hydraulic radius.
both for the graded and for the uniform sediment. The following observations are made:

1. The relative thickness of the sorting layer varies between about 1.5 to 2.0 times the average dune height (relative thickness 1.5 to 2.0).
2. There is no significant difference in relative sorting layer thickness between the experiments with graded sediments and with uniform bed material.
3. Deviations are present for the tests T39. Experiment T39 was an experiment with an aspect ratio (width/depth) of 1.25 only, so it may be assumed that the wall roughness had an overriding effect on the phenomena. For the time being the results of this test can be discarded.

In Figure 6.15* some more detailed results of the above analysis are given, notably the upper levels and the lower levels of the sorting layers in absolute values. Also here some observations can be made:

1. The upper level of the sorting layer is not significantly different for the graded and for the uniform sediments.

---

Figure 6.14* Relative sorting layer thickness

Figure 6.15* Upper and lower levels of sorting layer

---

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(2) A significant difference exists for the lower level. For the graded sediments the trough levels are apparently lower than for the uniform sediment.

It can be concluded that the larger dune heights for the graded sediments are mainly due to deeper troughs and that the dune crest levels for the graded sediments are not significantly different from the uniform bed material. There is no ready explanation for these observed phenomena. Especially the fact that the trough levels are lower, whereas the bed material in the troughs is coarser, seems to be contradictory.

Furthermore, it is possible to make a comparison of the observed Nikurade roughness parameter and the predictor of Van Rijn (1982). The Nikuradse "equivalent sand roughness" is defined via:

\[ C = 18 \log \frac{12 \ h}{k_s} \]  

(6.2)

where \( k_s \) = equivalent sand roughness. Van Rijn (1982) gave the following expression for this equivalent roughness:

\[ k_s = 1.1 \ H \ (1-e^{-25 \ H/L}) \]  

(6.3)

This relation is presented in Figure 6.16. The observed values of \( k_s/H \) are plotted in this Figure 6.16 too at the appropriate value of \( H/L \), both for the graded sediments and for the uniform sediments. It is observed that major deviations occur between the observations and the prediction. It seems that for a particular data set especially the sensitivity of \( k_s \) on \( H/L \) is much larger than suggested by the predictor of Van Rijn (1982).

Since 1982, Equation (6.3) was refined by Van Rijn (1984c) by including the particle roughness (in addition to the form roughness) via:

\[ k_s = 3 \ D_{90} + 1.1 \ H \ (1-e^{-25 \ H/L}) \]  

(6.4)

The above Equation (6.4) cannot be tested easily via a figure comparable to Figure 6.16. It is obvious that inclusion of the term \( 3 \ D_{90} \) is only relevant when \( k_s \approx 3 \ D_{90} \). For the present tests this is only the case for test T54 \( (k_s = 0.004 \ m, 3 \ D_{90} \approx 0.007) \). That for this test \( 3 \ D_{90} > k_s \) shows at the same time that inclusion of \( 3 \ D_{90} \) is only an approximate way of dealing with particle roughness.
Finally the celerities of the dunes are considered. Some data are given in Figure 6.17. The dune celerities are not significantly different for the graded sediments (apart from test T54 with some armouring) compared to the uniform sediments.

6.6 Sediment transport

The sediment transport rates were quite variable, even during equilibrium conditions. This is illustrated in the Figure 4.12, 4.33, 4.54, 4.75, 4.96 and 4.117 for the six tests considered here. These fluctuations are in line with earlier theoretical models (Hamamori, 1962) and experimental data (for recent information, see Gomez et al (1989). The sediment transport rates follow a skewed distribution, and that is the reason that in Chapter 4 only the average sediment transport and not the standard deviation was given.

The fluctuation in the transport rates is closely connected to the migration of dunes. The "local" sediment transport at the dune crest is according to Hamamori about 4 times the average sediment transport. Below the maximum transport rates and the average transport rates during equilibrium are listed per test:

<table>
<thead>
<tr>
<th>Test number</th>
<th>Maximum transport rate (kg/h)</th>
<th>Average sediment transport rate (kg/h)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>T49</td>
<td>200 - 450</td>
<td>85.0</td>
<td>2.3 - 5.3</td>
</tr>
<tr>
<td>T50</td>
<td>450 - 800</td>
<td>170.2</td>
<td>2.6 - 4.7</td>
</tr>
<tr>
<td>T51</td>
<td>500 - 1250</td>
<td>195.8</td>
<td>2.5 - 6.4</td>
</tr>
<tr>
<td>T52</td>
<td>300 - 550</td>
<td>146.2</td>
<td>2.5 - 6.4</td>
</tr>
<tr>
<td>T53</td>
<td>150 - 350</td>
<td>69.2</td>
<td>2.1 - 3.8</td>
</tr>
<tr>
<td>T54</td>
<td>80 - 190</td>
<td>30.0</td>
<td>2.7 - 6.3</td>
</tr>
</tbody>
</table>

The above data support the findings of Hamamori (1962). Although the available data do allow a more detailed analysis, including a comparison between the tests with mixtures and with uniform sediment (e.g. conform Gomez et al, 1989), this was outside the scope of the present study, so it was not pursued.

The average sediment transport rates that were measured during the experiments with graded sediments under equilibrium conditions are listed in
Table 4.68* and they are plotted against the discharge in the flume in Figure 4.133*. From an inspection of the plotted points in this figure it is clear that also in the sediment transport rates a loop-type of behaviour is present. The sediment transport rates during the tests T49 and T50 (before the flood of T51) are substantially larger than during the later experiments T52 and T53. A possible explanation is the increased roughness (lower Chézy coefficients) in the later tests. This was studied on the basis of the Engelund/Hansen (1967) sediment transport predictor. This predictor can be written in the following form:

\[ S = D^{-1} Q^{5/3} i^{5/3} C^{1/3} \]  \hspace{1cm} (6.5)

For the present tests the slope i was kept constant. For a comparison between the two tests like T49 and T53 also the discharge was the same. Assuming that the bed-material size (so implicitly also the vertical sorting) played a minor role for the sediment transport (so also D constant), the sediment transport is dependent on the roughness via:

\[ S = C^{1/3} \]  \hspace{1cm} (6.6)

The above relationship implies that the larger the Chézy coefficient, the larger the sediment transport will be. The dependence of S on C is very weak, because of the power of 1/3. So it is concluded that the difference in roughness can explain only a small part of the observed differences. It should be noted that also the vertical sorting cannot explain the decrease in sediment transport either. According to Equation (6.5) a decrease of particle size of the sorting layer could lead to an increased sediment transport.

Another aspect to consider is the composition of the transported sediments. This was computed on the basis of the samples that were taken during the frequent equilibrium measurements. Initially it was attempted to correlate the average size of the transported sediments to the sediment transport rate. According to Klaassen et al (1987), for a mixture there should be a negative correlation between the sediment transport rate and the average particle size of the transported sediments. This negative correlation was obtained by considering the continuity equation of the sediment over a bedform and assuming that vertical sorting was present. During the derivation of an expression for the particle distribution of the transported sediments it was assumed that selective transport on the stoss side of the dunes was
negligible. For more details on the proposed relationship, reference is made to Klaassen et al. (1987). During the present tests this was studied by plotting the average size of the particles \( D_m \) against the sediment transport rate, see the Figures 4.20, 4.41, 4.62, 4.83, 4.104 and 4.125. From an inspection of these figures it follows that even if such a relation does exist, it is completely obscured by the scatter in the observations. In this respect it should be realized that analysis by Klaassen et al. (1987) was based on regular dunes, while:

- in reality the dunes are irregular,
- also the vertical sorting is not resulting in "ideal" separation,
- in the dunes cross-bedding and pockets of sand can be observed that will also cause substantial scatter.

A consequence of the above is that it was not possible to determine the composition of the transported sediment according to the method initially intended to be used see Section 3.4.3. Therefore a slightly different method had to be used: from all samples taken during the equilibrium phase of the tests a weighed average was taken by taking into account the sediment transport rate. The result per experiment is presented in the Figures 4.21, 4.42, 4.63, 4.84, 4.105 and 4.126. In Figure 6.19 the results are summarized via the cumulative probability distributions. In the Figures 6.20 and 6.21 a comparison is made between the experiments with the same discharge T49/T53 and T50/T52). A thorough inspection of these three figures lead to the conclusion that the results presented are subject to a considerable scatter. It had to be concluded that the presented particle size distributions are poor estimators of the particle size distributions during equilibrium conditions and that no further conclusions can be drawn from them. See for additional data and discussion also Section 6.8.

Although the data in the Figures 4.20, 4.41, 4.62, 4.83, 4.104 and 4.125 provide a poor estimate of the particle distribution of the transported sediments, it is nevertheless worthwhile to inspect these figures more carefully. For this a line was added indicating the \( D_m \) of the bed material. It may concluded that on the average the characteristic particle size of the transported sediments is smaller than this characteristic particle size of the bed material. This fact contradicts Parker and Klingeman (1982), see also Section 6.8.

Next a comparison is made between the sediment transport rates of the present tests with mixtures and the previous ones with uniform sediments. This
is done in Figure 6.18. The sediment transport rates for the graded sediment is about 50% larger than for the uniform sediments. Regarding the possible cause of this difference the following remarks are made:

(1) The first possibility may be the smaller $D_{50}$ of the graded sediments. This was investigated by doing a number of sediment transport computations with the Engelund-Hansen (1967) predictor for different values of $D_{50}$ and with the Meyer-Peter/Müller (1948) predictor for different values of $D_m$. The results (per unit width) are summarized below (whereby it is assumed that 1 l (pores included) corresponds to 1 kg submerged weight):

<table>
<thead>
<tr>
<th>Test number</th>
<th>Sediment transport rate (kg/h/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
</tr>
<tr>
<td></td>
<td>Engelund/Hansen</td>
</tr>
<tr>
<td></td>
<td>graded $D_{50} = 0.66$ mm</td>
</tr>
<tr>
<td></td>
<td>$D_m = 0.93$ mm</td>
</tr>
<tr>
<td>T49</td>
<td>75.6</td>
</tr>
<tr>
<td>T50</td>
<td>151.3</td>
</tr>
<tr>
<td>T51</td>
<td>174.1</td>
</tr>
</tbody>
</table>

According to the predictor of Engelund/Hansen (based on $D_{50}$) the predicted sediment transport rate for the mixture is about 13% larger than for the uniform material. Also the predicted value for the mixture using the method of Meyer-Peter/Müller is larger, some 40%, and at first sight this seems strange. A more refined analysis shows that the reduction is Shield parameter is compensated by an increase in ripple factor $\mu$. This is not logic, but may be due to the extreme low gradation of the uniform sediment and consequently not realistic. It seems safe to state that the difference in $D_{50}$ may cause a larger transport rate of at least some 15%. The conclusion from the above is that taking into account the effect of the difference in $D_{50}$ and $D_m$ may partly explain the difference.

(2) A second cause may be the difference in hydraulic roughness. According to the above:

$$S : = C^{\frac{1}{3}}$$  \hspace{1cm} (6.6)

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The Chézy coefficient of the graded sediment experiments is about 10% larger than for the uniform sediment. So there is some effect, but this effect is almost negligible (some 3%).

(3) A third cause may be the nonlinearity between the sediment transport and the Shields parameter. Often the sediment transport of a mixture is computed via:

\[ S_{\text{total}} = \sum_{i=1}^{n} p_i \cdot S_i \] (6.7)

where \( p_i \) = percentage of bed material of the class characterized by \( D_i \), \( S_i \) = sediment transport rate when only particle with \( D_i \) as characteristic size would be present. When the non-linearity is taken into account, this may result in a substantial increase in predicted sediment transport. See the table below:

<table>
<thead>
<tr>
<th>Test number</th>
<th>Sediment transport according to Engelund/Hansen (1967)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( S (10^{-5} \text{ m}^2/\text{s}) )</td>
</tr>
<tr>
<td></td>
<td>based on ( D_{50} = 0.66 \text{ mm} )</td>
</tr>
<tr>
<td>T49</td>
<td>1.89</td>
</tr>
<tr>
<td>T50</td>
<td>6.19</td>
</tr>
<tr>
<td>T51</td>
<td>7.16</td>
</tr>
</tbody>
</table>

For the above computation the mixture was split up in 10 fractions. An increase of some 20% is found when so many individual fractions are distinguished. Taking into account the hiding effect (Egiazorov, 1965), only possible for the Meyer-Peter/Müller (1948) predictor and similar equations because the Egiazorov correction applies to the "initiation of motion", again reduces the difference.

Summarizing it is concluded that the observed differences between the sediment transport rates for the graded sediment compared to the uniform sediment can be explained by a combination of the possible causes mentioned above.

Finally, the attention is drawn to the relation between bedform height and celerity and sediment transport. Assuming steady flow conditions and undisturbed bed-form migration, the bed-load transport rate can be computed as (Engel and Lau, 1980, 1981):

EXPERIMENTS WITH GRADED SEDIMENTS IN A STRAIGHT FLUME
\[ s_b = \beta (1-\varepsilon) \rho_s H c_b \]  

(6.8)

in which:

- \( s_b \) = bed-load transport  
- \( \beta \) = dune tracking coefficient  
- \( \varepsilon \) = porosity  
- \( \rho_s \) = density of sediment  
- \( c_b \) = average migration velocity  
- \( H \) = average bedform height

According to Engel and Lau (1980, 1981) and Havinga (1982) the dune tracking coefficient \( \beta \) varies between 0.5 and 0.6. The results of the present tests (both for the uniform sediments and for the mixture) can be used to study the value of \( \beta \). The results of the application of Equation (6.8) to these data are provided in Table 6.6*). For this analysis it was assumed that \( \varepsilon = 0.4 \) and \( \rho_s = 2,650 \text{ kg/m}^3 \).

<table>
<thead>
<tr>
<th>Test number</th>
<th>Flume width (m)</th>
<th>Dune characteristics</th>
<th>Sediment transport (kg/h)</th>
<th>Dune tracking coefficient (( \beta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dune height (m)</td>
<td>Dune celerity (m/h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T23</td>
<td>1.500</td>
<td>0.080</td>
<td>2.06</td>
<td>130.4</td>
</tr>
<tr>
<td>T26</td>
<td>1.500</td>
<td>0.096</td>
<td>2.71</td>
<td>179.1</td>
</tr>
<tr>
<td>T30</td>
<td>1.500</td>
<td>0.070</td>
<td>1.33</td>
<td>64.4</td>
</tr>
<tr>
<td>T31</td>
<td>1.125</td>
<td>0.068</td>
<td>1.45</td>
<td>48.4</td>
</tr>
<tr>
<td>T33</td>
<td>1.125</td>
<td>0.081</td>
<td>----</td>
<td>93.1</td>
</tr>
<tr>
<td>T35</td>
<td>0.500</td>
<td>0.079</td>
<td>2.10</td>
<td>35.6</td>
</tr>
<tr>
<td>T38</td>
<td>0.500</td>
<td>0.056</td>
<td>1.80</td>
<td>23.3</td>
</tr>
<tr>
<td>T39</td>
<td>0.500</td>
<td>0.092</td>
<td>2.39</td>
<td>47.3</td>
</tr>
<tr>
<td>T49</td>
<td>1.125</td>
<td>0.075</td>
<td>1.69</td>
<td>85.0</td>
</tr>
<tr>
<td>T50</td>
<td>1.125</td>
<td>0.109</td>
<td>2.22</td>
<td>170.2</td>
</tr>
<tr>
<td>T51</td>
<td>1.125</td>
<td>0.117</td>
<td>2.16</td>
<td>195.8</td>
</tr>
<tr>
<td>T52</td>
<td>1.125</td>
<td>0.109</td>
<td>1.97</td>
<td>146.2</td>
</tr>
<tr>
<td>T53</td>
<td>1.125</td>
<td>0.070</td>
<td>1.58</td>
<td>69.2</td>
</tr>
<tr>
<td>T54</td>
<td>1.125</td>
<td>0.035</td>
<td>1.68</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Table 6.6 Determination of dune tracking coefficient \( \beta \)

The following observations can be made regarding Table 6.6*:

1. The computed values of \( \beta \) vary between 0.43 and 0.69.
2. The coefficients of \( \beta \) for graded sediments are substantially larger (average of 0.59) than for the uniform sediment (average 0.46).
3. The value of \( \beta \) for test T54 (partial armouring) is relatively low.

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For the time being no explanation can be proposed for the latter two observations.

6.7 **Influence of gradation**

In the previous Sections a number of aspects are discussed which are of relevance for an investigation of the influence of the gradation on "one-dimensional" (width averaged) morphological processes. In this Section the earlier observations are summarized to get a complete picture of this influence.

In advance, however, it should be stressed here that also this investigation suffers from the fact that it is difficult to design a series of experiments that lead to unique conclusions as to the influence of gradation. The main problem is the definition of the "characteristic particle size" of a mixture. For this characteristic particle size different authors have used different "assumptions". A limited overview is given below:

- Meyer-Peter/Mueller: \( D_m \) (for definition see Section 2.3; a first estimate is often made via \( D_m = D_{65} \))
- Engelund/Hansen: \( D_{50} \)
- Ackers/White: \( D_{35} \)
- Van Rijn: \( D_{50} \)

The problem is clearly shown by comparing the "characteristic particle sizes" of the present experiments with that of the uniform sediments:

<table>
<thead>
<tr>
<th>Characteristic particle size (mm)</th>
<th>Uniform sediment</th>
<th>Graded Sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_{35} )</td>
<td>0.75</td>
<td>0.44</td>
</tr>
<tr>
<td>( D_{50} )</td>
<td>0.77</td>
<td>0.66</td>
</tr>
<tr>
<td>( D_m )</td>
<td>0.78</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Using either \( D_{35} \) or \( D_{50} \) as characteristic particle size, not only the influence of gradation is studied, but also the effect of a decrease in sediment size. On the contrary, in addition to the foregoing, the use of \( D_m \) is instrumental in studying the effect of an increase in characteristic particle size!

In the present investigation this was partly compensated for by doing (if and when possible) computations to explore the influence of changes in the...
particle size too. This allowed to separate, to some extent, the effect of the gradation.

Summarizing the previous Sections, the following statements can be made. 
(1) The gradation causes a reduction in hydraulic roughness. This is due to a substantial increase in average dune lengths, which overcompensates for the slight increase of the dune heights of the graded sediments compared with the uniform sediments.
(2) There is a clear influence of the "history", which implies that not only the actual discharge is of importance but also the previous hydrograph. It should be realized, however, that due to the fact that initially no sorting was present, here an extreme case was considered. In reality the observed difference will be less because vertical sorting will always be present in the field due to previous floods.
(3) The relative thickness of the sorting layer (after dividing it by the dune height) is not significantly different, but because the average dune height is larger for the graded sediments also the absolute sorting layer thickness is larger. The shape of the dunes is affected by the gradation: the troughs become deeper. The heights of the crests are approximately the same for uniform and for graded sediments.
(4) Sediment transport rates (per unit width) are also larger for the graded sediments, but this may be due to (a combination of) the difference in hydraulic roughness, the different characteristic particle size (see above) or the non-linearity of the sediment transport and the Shields parameter (or the velocity).

It should be stressed here that all conclusions drawn are restricted to the conditions studied in the flume tests. These conditions can be summarized as:
- dune phase,
- active transport for all sediment sizes (only during experiment T54 there was a tendency of partial armouring),
- low Froude numbers.

6.8 Comparison with results Waal model

In the present tests the same bed material was used as had been applied previously in a movable-bed model of the Waal bend near Nijmegen (M 1278, see Struiksma, 1981). Most of that model investigation was done with one
single discharge (notably 0.121 m³/s), but some tests were carried out in which the discharge in the model was either smaller or larger than the "dominant discharge" used. The results of these tests are described by Struiksma (1983) and these results, in combination with additional information provided by Struiksma, can be used for comparison with the results of the present flume study.

The interesting aspect of this comparison is that it may allow to get some insight into the effect of 3-dimensional aspects, notably the outer bend and pointbar formation and the crossings) on the average sediment transport and hydraulic roughness of a river reach.

Obviously, a model of a river reach is different from a flume. In reality the width of a river is not constant but it changes with the discharge and also in longitudinal direction. The Waal model results can nevertheless be considered as if they were from a flume, because the width is approximately constant due to the presence of groynes.

Regarding the similarities and the differences between the two investigations the following remarks are made:

(1) In the Waal model the slope was slightly less than the slope in the sandflume (1.4 x 10⁻³ versus 1.6x10⁻³).

(2) The width of the model was much larger, notably 2.60 m compared with the 1.125 m of the sandflume. The effects of the bank roughness were probably limited.

(3) The investigations in the Waal model were done for the new alignment, so only in the lower and upper reaches were groynes present; in the middle reach the width of the river was 260 m.

(4) The bed material was the same.

(5) In the model investigation the sediment was being recirculated by taking special measures (see Struiksma, 1983).

(6) The periods with smaller and larger discharge than 0.121 m³/s lasted only for about 8 hours.

(7) Sediment transport rates could only be measured in an approximate way and this was done for two model discharges only.

(8) Only for a discharge of 0.121 m³/s the slope was measured. For the other two discharges it could be assumed that the slope was the same.

(9) Bedform dimensions were not explicitly measured but a good indication of the average dune heights could be obtained from the probability distribution of the bed levels. See Section 6.5.
Observations from the Waal model are summarized in Table 6.7*. Data are available for three model discharges. Expressed per unit width these discharges are 0.022, 0.046 and 0.074 m³/s/m. This implies that the data can be compared with the experiments T54 (discharge per unit width 0.044 m³/s/m) and the experiments T49/T53 (discharge per unit width 0.098 m³/s/m).

<table>
<thead>
<tr>
<th>Test number</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model discharge (m³/s)</td>
<td>0.058</td>
<td>0.121</td>
<td>0.194</td>
</tr>
<tr>
<td>Model width (m)</td>
<td>2.60</td>
<td>2.60</td>
<td>2.60</td>
</tr>
<tr>
<td>Slope (-)</td>
<td>1.4*10⁻³</td>
<td>1.4*10⁻³</td>
<td>1.4*10⁻³</td>
</tr>
<tr>
<td>Water depth (m)</td>
<td>0.0625</td>
<td>0.1125</td>
<td>0.156</td>
</tr>
<tr>
<td>Sediment transport (m³/day)</td>
<td>0.4</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Chézy coefficient (m²/s)</td>
<td>32</td>
<td>33</td>
<td>32</td>
</tr>
<tr>
<td>Average velocity (m/s)</td>
<td>0.30</td>
<td>0.41</td>
<td>0.47</td>
</tr>
<tr>
<td>Estimated dune height (m)</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 6.7* Selected results from Waal River model investigation

To get insight into the effect of 3-dimensional phenomena the results provided in Table 6.7* should be compared with the results of the appropriate experiments, listed in Table 4.68* (but per unit width). For this purpose three figures were prepared, notably:

- Figure 6.22*, providing the hydraulic roughness of the flume tests compared to the Waal river model;
- Figure 6.23*, comparable to the previously mentioned figure, but relating to sediment transport rates;
- Figure 6.24*, showing the average dune heights during the flume tests compared to the dune heights inferred from the bed level sounding in the Waal River model.

From an inspection of these figures, the following conclusions are drawn:

(1) The Chézy coefficients of the Waal model are substantially lower than for the straight flume tests, so apparently the effect of the 3-dimensional effects on the hydraulic roughness is considerable. In this respect it should be stressed that in the Waal model every where dunes of substantial dimensions were present, whereas in the straight flume tests the dune dimensions diminished considerably and the dune lengths increased (tendency to armouring).
**Figure 6.22** Hydraulic roughness of flume tests compared to Waal model

**Figure 6.23** Sediment transport during flume tests compared to Waal model results

**Figure 6.24** Average dune heights during flume tests compared to Waal model results

**Figure 6.26** Variation of characteristic particle sizes sediment transport with discharge
(2) The sediment transport rates in the Waal model are smaller than in the straight flume experiments. It can be shown that the following relationship holds (assuming that the Engelund/Hansen transport predictor is applicable):

\[ S : = i^{5/3} \]

The smaller slope accounts for a reduction in sediment transport of about 25%, but the actual reduction is more.

(3) Average bedform dimensions in the Waal model are smaller than in the straight flume. This seems to contradict the statement made under (1). It must, therefore, be concluded that the observed increase in dune length during the straight flume tests (see also Klaassen, 1987b) was the more important phenomena.

Tentatively it is concluded that (i) the effect of the 3-dimensional effects on the hydraulic roughness is considerable, and that (ii) the influence on the sediment transport is minor. This conclusion is tentative only, because the data from the Waal model are not so accurate (see before).

In addition to the information provided above, Figure 6.25 was reproduced from the report of Struiksma (1983). It provides the composition of the transported sediment as a function of the discharge. This data were combined with the estimates of the composition of the transported sediments as provided in the Figures 6.19 through 6.21. The result is presented in Figure 6.26*. Although there is still a considerable scatter for the larger values of the unit discharge, nevertheless the following observations can be made:

(1) For lower unit discharges the data of the Waal River model and the straight flume tests corresponds nicely.

(2) For low unit discharges the composition of the transported sediment is substantially finer than the original bed material. This is especially reflected in the values of \( D_{90} \).

(3) It seems that even during the highest discharges the coarsest fractions are not transported in the same partition as they are represented in the bed. This is not in line with the statements of Parker and Klingeman (1982).
6.9 Transitions

In the present experiments not only equilibrium conditions were studied, but also transitions. The results of the transitions are provided in Chapter 5. The transitions studied are schematically indicated in Figure 6.27*.

**Figure 6.27** Schematic summary of the transitions studies during the present tests

Here a limited analysis of the transitional part of the experiments is made. This analysis is limited for two reasons: first of all, a more detailed analysis is beyond the scope (and assignment) of the present study; secondly, all transitions were done only once and the experience from the transitions studied for uniform sediments (see e.g. Wijbenga and Klaassen, 1983) has shown that single events may exhibit a considerable scatter, thus complicating the analysis.

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The analysis is limited to the changes in dune height in time during the initial stage of the transition. Data on these changes in dune height are provided in the Figures 4.8, 4.29, 4.50, 4.71, 4.92 and 4.113. From these figures \( \frac{dH}{dt} \) was determined and the results are listed in Table 6.8. Only for the transition T51 no clear increase in dune height could be identified.

The analysis of the change in dune height versus time is done using the first-order relation proposed by Wijbenga and Klaassen (1983):

\[
\frac{dH(t)}{dt} = A_H (H_\infty - H(t))
\]  

(6.9)

For the present experiments also \( A_H \) was computed, see Table 6.8. In conformity with Wijbenga and Klaassen (1983) this coefficient was plotted against the ultimate change in dune height (being the difference between the ultimate dune height and the initial dune height). Figure 6.29 provides the results. In this graph also the results of the experiments with uniform sediments, which are schematically indicated in Figure 6.28, are plotted.

It may be concluded that the results for the graded sediments do not differ significantly from the results with the uniform sediments. Also for the graded sediments experiment T52, an experiment with a reduction of the water depth and still high sediment transport rates, yields a very high value for the adaptation coefficient \( A_H \), in conformity with what was observed for the uniform sediment experiments. This is not predicted by existing theories. A gradual increase of the dune heights is apparently reasonably well predicted by the method of Fredsoe (1982).

An alternative method of analysis of transitions was suggested by Van Rijn (1989). The dune transition period \( T_d \), during which the dune dimensions change from those of stage 1 to those of stage 2, is related to the ratio of the change in cross-sectional area of the dune and the average bed load transport in the transition period. Thus,

\[
T_d = \alpha \frac{(1-c) (H_2L_2 - H_1L_1)}{s_1 + s_2}
\]

(6.10)

Assuming a first order adjustment process, the changes in dune height and dune length can be expressed as:
\[
\frac{H_2 - H_t}{H_2 - H_1} = e^{-\beta t/T_d}
\] (6.11)

and

\[
\frac{L_2 - L_t}{L_2 - L_1} = e^{-\gamma t/T_d}
\] (6.12)

in which:

- \(H_t, L_t\) = dune height, length at time \(t\)
- \(H_1, L_1\) = equilibrium dune height, length at stage 1
- \(H_2, L_2\) = equilibrium dune height, length at stage 2
- \(s_1, s_2\) = equilibrium bed load transport rates at stage 1, 2
- \(\varepsilon\) = porosity of bed material
- \(T_d\) = dune transition period
- \(\alpha, \beta, \gamma\) = coefficients.

Van Rijn (1989) applied the above method to one of the transitions described by Wijbenga and Klaassen (1983) (notably to T26 and not to T27, as is erroneously stated in Van Rijn (1989)) and found the following coefficients:

- \(\alpha = 4\)
- \(\beta = 3\)
- \(\gamma = 1\)

The same method was used in the analysis of the present tests. The value of \(T_d\) was derived from the measured value of \(dH/dt\), in conformity with the below figure:

![Diagram showing time, dune height, and derivative](image)

The thus obtained values of \(T_d\) were used to establish \(\alpha\). The procedure used is indicated in Table 6.9. From this table it is concluded that the coefficient \(\alpha\) is not constant (as implicitly suggested by Van Rijn (1989)), but is variable. In Figure 6.30* the different transitions (both for uniform

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sediments and for the mixtures studied here) are plotted by their initial and ultimate for each point. A tentative conclusion is that $\alpha$ is low for large changes in water depth (rapid adaptation) and large for small changes in water depth (slow adaptation). It was not attempted to determine values for $\beta$ and $\gamma$. It seems, however, that here is a field wide open for further study.

![Graph showing transition coefficients $\alpha$ for different transitions](image)

**Figure 6.30** Transition coefficients $\alpha$ for different transitions

### 6.10 Implications for 1-dimensional morphological modelling

In the present study it was attempted to study the influence of the gradation on the morphological processes. The results as far as the hydraulic roughness, the thickness of the sorting layer and the sediment transport are concerned, are listed in Section 6.7. These conclusions, together with the observations made in the Sections 6.8 and 6.9, lead to the following recommendations as to the implementation of the present results into one-dimensional morphological models for the Rhine branches and the Meuse River in The Netherlands:
(1) **Influence of gradation**

Considering the effect of the gradation on in particular the hydraulic roughness, the sorting layer thickness and the sediment transport, it seems appropriate to consider the incorporation of the influence of the gradation on these aspects. It is proposed, however, first to do a number of exploring computations (using the insights into the effect obtained during the present study) to study the influence of this incorporation on the morphological changes.

(2) **Hydraulic roughness**

The Chézy coefficient of graded sediments is (according to the present experiments) larger than the same parameter for uniform sediments. Generally speaking, however, in one-dimensional morphological models the Chézy coefficient is a parameter for which a value is taken based on a comparison between model behaviour and prototype observations, so it may be assumed that this effect is taken into account implicitly. When simulations are made in which significant sorting takes place, the influence of the change in gradation may become substantial.

(3) **Thickness of sorting layer**

The effect of the gradation on the sorting layer thickness is significant. When no prototype measurements are available of the dune dimensions there are two ways of establishing the sorting-layer thickness:

(i) using existing predictors for the average dune height,
(ii) computing $k_s$ from "measurements" of $C$ and relating $H$ to $k_s$, using a graph like Figure 6.16.

It seems that via both methods the gradation is not sufficiently taking into account, so it is proposed (if appropriate, see (1)) to include the effect of the gradation more explicitly when selecting a value for the sorting layer thickness in one-dimensional morphological models.

(4) **Sediment transport**

Sediment transport in one-dimensional morphological models for graded sediments should be based on the computation of the fractional transport of mixtures. The present study does not provide new results which allow for a revision of the sediment transport predictors for fractional transport.
Furthermore the following remarks are made:

- The present study is limited to the conditions under which the experiments were carried out (see at the end of Section 6.7). It may be expected that e.g. during the formation of armour layers the influence of the gradation becomes still much more pronounced. See for the morphological phenomena related to armoured river beds e.g. Klaassen (1983).

- When a study using a one-dimensional model, deals with the cutting-of bends (or the reverse case: making a canalized river more natural again) the possibility of a decrease in sediment transport in the curved reach should be taken into account.

6.11 Implications for field measurements

In the present study it is shown that vertical sorting plays an important role in both sediment transport processes and the hydraulic roughness of rivers with graded bed material. Coarse sediments can be stored in the river at levels corresponding to the troughs of the bedforms that occur during floods. During lower flows these coarse materials are relatively less abundant in the upper layer of the river bed.

The consequence of the above is that taking surface samples of the river bed only may result in a biased estimate of the particle distribution of the bed material of a river. The best way of sampling the bed material of a river, therefore, is to collect samples not only of the surface but also of the lower levels of the sorting layer. These lower levels should include the levels that are reached by the troughs of the bedforms during floods. This is especially important because during floods the morphological processes are most active and also the hydraulic roughness is especially important during flood conditions. The above implies that a good sampling program should include the sounding of the bed during flood conditions, and based on the results of the soundings decide on the depth to which the sampling should be extended.

It is obvious that bed material samplers like the bucket sampler or the American US BM 54 typically cannot provide samples of the bed material that are representative for the sorting layer during floods. It is advisable to do borings to sufficient depth to get a good insight in the properties of the bed material in a river.
Finally attention is drawn to three-dimensional aspects. In the straight flume three-dimensional phenomena play only a minor rôle (although differences between the middle and the side profiles are still suggesting some influence of alternate bars, see Wang (1986)). In real rivers, however, three-dimensional phenomena are much more important. This implies that the results of the present study should be interpreted for field conditions too. It may well be that outer bends play a similar rôle in storing coarser bed material as the lower levels of the sorting layer do under predominantly two-dimensional conditions. This should be explored in a separate study.

6.12 Need for additional studies

The present report describes experiments in a straight flume into the hydraulic roughness and sediment transport of mixtures and the effect of gradation. From the discussions in the preceding Sections it is clear that many phenomena that were observed cannot or only partly be explained and that for many phenomena simply no explanation is present. This, however, is not only to the fact that the influence of the gradation of the sediment complicates the sediment transport phenomena, but also, and possibly even more because in general the understanding of sediment transport processes is still very limited.

The present status can be described by stating that some important parameters have been identified, often in the form of dimensionless parameters, but that the interrelationships between these parameters is only known in statistical terms only. These statistical relationships are often based on a limited set of data (and even then mostly flume data), and have no general applicability. The influence of complicating factors like the unsteadiness (in real life steady conditions are almost always absent!), gradation (uniform sediments are the exception and not the rule!) and three-dimensional effects (straight rivers are very exceptional!) is only known in a very approximate way.

Also the present study did not provide ready answers to the problems tackled. It may even be stated that the experimental results presented here have identified more unsolved problems than they have solved already existing ones. It is clear from the present investigation that gradation is an important phenomena and that the scatter that is normally associated with sediment transport processes may be due to the influence of the gradation
and its fluctuation in time due to (temporal?) storage of coarse and fine sediment in the river bed and elsewhere. It is also clear that much research is still needed before sediment transport processes in rivers are sufficiently understood and can be predicted with sufficient accuracy.

It is in this perspective that the present study, and in fact much of the experimental research that has been done in the sand flume over the past 15 years within the framework of the TOW Rivers, should be seen. In these studies the emphasis has been on improving the knowledge of the bedforms that occur at the interface between water and sediment, because it is felt that only an improved understanding of bedform mechanics may lead to an advance in the understanding of sediment transport processes.

Over the past fifteen years, therefore, detailed experimental data have been collected on sediment transport processes in general and on bedforms in particular. The present study has added information on one parameter that previously had not been explored during these studies, notably the gradation of the sediment. Experimental data from laboratory flumes alone are definitely not sufficient. In addition theoretical studies are needed to develop appropriate theories, and data from the field to verify the observations in the laboratory and to check theoretical models. The above implies that in order to reach a satisfactory level of understanding of sediment transport processes (allowing to benefit from the opportunities that rivers provide and to limit the risks they provide), still much research will be required.

Additionally studies, therefore, are required and these can be divided in studies aiming particularly at the influence of gradation and in more general studies that improve the understanding in sediment transport phenomena, and more particularly in the crucial role that bedforms play. In conformity with the above these studies should consist of a well-balanced mix of theoretical studies and experimental investigations in laboratories and in the field. Within the present framework it is impossible to give a detailed outline of all the studies that could be done, so the review given here is limited to studies that are a logic continuation of the studies carried out within the framework of TOW Rivers until now. Hereafter these additionally required studies are described in some details. A distinction is made in (1) studies on the effect of gradation, (2) studies on bedform mechanics in general, and (3) studies on the effect of gradation using the results of the studies under (2).
Re (1) Studies on the effect of gradation

For the study of the effect of gradation it seems that first of all an investigation in the field is needed to verify whether the vertical sorting phenomena that plays such a crucial role is also pronounced apparent in the field. This can be studied by making a number of borings in bedforms and to interpretate the results in connection with information of the dimensions of the bedforms in the considered river reaches. Also the implications of the observed phenomena for the sampling of the river bed should be studied (see Section 6.12). Initially these field measurements should concentrate on reaches where three-dimensional phenomena are minor, but in due time special attention should be paid on the influence of three-dimensional phenomena (e.g. the possible storage of coarser sediments in the outer bends during low flow conditions).

Secondly, it may be considered to do a similar series of tests in the sandflume but for different hydraulic conditions. These tests should include both tests with uniform sediment and with a mixture. The aim of these tests should be to verify the results obtained in the present studies, while improving on certain aspects that were not studied sufficiently accurate in the present tests, notably the size distribution of the transported sediment and to a lesser extent the composition of the bed. A similar sequence of discharges could be considered (so a hydrograph, see Figure 3.7*), because this has shown to be quite fruitful.

Thirdly, theoretical studies could be done in the effect of the gradation on bedform dimensions. Within the frame-work of TOW Rivers a mathematical model has been developed that could be used as the basis for these theoretical studies, but the model should be improved and extended before it can be applied. See under heading (3).

Forthly, it may be considered to introduce some of the phenomena observed in the present study into a mathematical model that includes vertical sorting (e.g. the model of Ribberink (1987) that is available at DELFT HYDRAULICS), to study the importance of the observed phenomena on the extent of celerity of morphological processes. This exploratory would also allow to weigh the importance of the aspect studied in the present study (notably gradation) against other uncertainties that are present in these morphological models.
Re (2) Studies on bedform mechanics in general

Within the frame-work of TOW Rivers a start has been made with a detailed study of bedform mechanics. A mathematical model was made in which all the existing knowledge on the detailed flow pattern over dunes and on local sediment transport was incorporated, and this model with the name DUGRO can be used for a detailed study of bedform mechanics (see e.g. Klaassen et al (1986) and Termes, 1989). It was intended to test the flow sub-model and the sediment sub-model separately, so detailed measurements were done in the sandflume to obtain verification data (see van Mierlo and de Ruiter, 1989). This model can be used for a study of the effect of gradation on bedform dimensions (in particular dune heights), but then it is needed that the model is improved and verified first. This can be done for uniform sediment, as sufficient data are available from the tests in the sandflume in the period 1974 onward (see e.g. Bakker (1986)).

An important limitation of the present DUGRO model is that it can be used for regular dunes only. In reality dunes are irregular, but introducing this in the DUGRO model implies that also the generation of dunes has to be included in the model.

The model in its present status (so without the possibility of changes in the dune length due to generation and "melting together") may be sufficient to use it for a study of transitional aspects, so the lagging behind of dunes with respect to the discharge variations. This would already mean an important improvement over the model of e.g. Fredsoe (1979, 1981) that considers dune crests only and that did not provide sufficiently reliable answers (see Wijbenga and Klaassen, 1983). For this study into the changes in dune height following a change in discharge sufficient material for verification is present (see Wijbenga and Van Nes, 1986a; 1986b; 1986c; 1986d).

Re (3) Studies on the effect of gradation using the results of the studies under (2)

With the DUGRO model (after extension) it is possible to study the effect of gradation on e.g. sediment transport, bedform dimensions and hydraulic roughness. The extension required refers to the vertical sorting process that occurs at the lee-side of dunes. Tentative expressions for this sorting process can be included in the DUGRO model, and the composition of the
deposited sediment at the lee-side and in the dune trough should be computed and stored in vertical layers for further use. The local sediment transport, and thus the bed level transport via the gradient of the local transport, should then be computed taking into account the local sediment size distribution.

For this, it is required to get insight in the importance of selective transport on the stoss-side of the dunes. The assumption that this is negligible (see Klaassen et al, 1987) is possibly not correct. It may be considered to do a number of special tests to verify this assumption.
7. Conclusions and recommendations

7.1 Conclusions

In the present report experiments are described with graded sediments in the dune phase in a straight flume under one-dimensional conditions. The sequence of the experiments (a number of tests with initially gradually larger discharges and later on again a gradual decrease of the discharge, so a "real" hydrograph) was such that the effect of sorting and the subsequent fining of the sorting layer could be studied.

The conditions during the tests were such that a comparison could be made with tests with uniform sediments of approximately the same average bed-material size. These tests were carried out in the same facility, although in an earlier period. The uniform bed material data helped to improve the understanding of the effect of gradation on sediment transport processes.

From the experiments with graded sediments the following conclusions can be drawn:

(1) During the tests the previous observations of e.g. Ribberink (1987a) were verified that in dunes vertical sorting takes place, and that as a consequence the coarsest sediments are more dominant in the lower layers of the dunes.

(2) During the "recession" of the discharge (so the tests T52 and T53), the layer below the throughs may have acted as a reservoir for the coarsest particles. As a consequence the sorting layer (the exchange layer of Ribberink (1987a)) during these tests would be finer than during the tests in the rising limb of the hydrograph (the tests T49 and T50). Although the accuracy of the data did not allow the identification of this process at a significant level, the results presented below strongly suggest this phenomenon.

(3) The implication of the observations during the present tests is that during floods in rivers the sorting layer in dunes has probably the coarsest composition.
During the recession of the "hydrograph" the hydraulic roughness, the sediment transport rates, and the bedform dimensions were different from the conditions during the rising limb. This is probably due to the fining mentioned under conclusion (2).

The smaller dune heights and dune lengths that were observed during the recession, are not in line with the predictors like Van Rijn (1984c), also not when it is assumed that the sorting layer did become finer.

Different from what was expected (see Klaassen et al (1987)), it was observed that no clear relation exists between the size of the transported sediment and the rate of sediment transport. This may imply that selective transport on the stoss side of the bedform is of importance in addition to vertical sorting (as assumed in Klaassen et al (1987)).

Due to the absence of a clear relationship, it was not possible to establish the relation between the hydraulic conditions and the gradation of the transported sediments.

For all discharges in the flume, the transported sediments were finer than the initial composition of the bed material, implying that equal mobility of all fractions was not present.

From the comparison between the tests with graded sediments and the tests with uniform sediments the following conclusions can be drawn:

There is a substantial difference between the results of the tests with graded sediments and of the tests with uniform sediments.

The Chézy coefficients of tests with graded sediments are larger than for the uniform sediments.

Different from what was suggested in the literature, this is not due to smaller dune heights (actually the dune heights for the graded sediments are larger than for the uniform case), but it is caused by the increased dune lengths in the case of the graded sediments.

To what extent the difference in skin roughness is important could not be ascertained in the present tests.
(13) The dune heights for the graded sediments are larger than for the uniform sediment, so also the thickness of the sorting layer is larger. The relative sorting-layer thickness is approximately the same for uniform and sediment and for mixtures, and the sorting layer thickness corresponds to 1.5 to 2 times the average dune height.

(14) The increased dune heights for the graded sediments is in particular due to deeper troughs. The dune crest levels were not different from the uniform sediment conditions.

(15) Also the sediment transport is larger for the tests with graded sediments, but probably this is in line with what is predicted by different prediction techniques for the transport of graded sediments.

Furthermore, some additional conclusions are obtained regarding some special aspects:

(16) From a comparison with a movable-bed model of the Waal River it was concluded that for the lowest discharge the Chézy coefficients were smaller and the sediment transport rate less than for the straight test. This is due to the three-dimensional effects in the movable bed model, that may hamper the armour layer formation. For the larger discharges the difference was small only suggesting that for those conditions the influence of three-dimensionality (the found in meandering rivers) on sediment transport and hydraulic roughness is negligible.

(17) There appears to be no major difference in physical behaviour during transitions when the uniform sediment and the graded sediments are compared.

7.2 Recommendations

A number of additional studies is recommended, on the one hand to study the effect of gradation in more detail and on the other hand to improve the understanding of sediment transport processes via increased understanding of bedform mechanics. The latter can especially be arrived at via a continuation of the research with the mathematical model DUGRO.
The studies recommended hereafter consist of a well balanced mix of field studies, investigations in laboratory flumes and theoretical investigations, notably:

(1) Special field measurements should be carried out to check the phenomena identified in this study and to determine how relevant these phenomena are for three-dimensional conditions.

(2) A number of exploring computations should be made with a one-dimensional morphological model in which sorting can be simulated, to investigate the sensitivity of the computed bed levels for certain cases to be selected, on the phenomena identified here. Based on the outcome of this exploratory study it should be decided to what extent these phenomena should be incorporated in these models.

(3) Similar series of tests (with uniform and graded sediments), but under different hydraulic conditions, should be carried out to check whether the conclusions arrived at for the present series of tests have a more general applicability.

(4) Special measurements should be directed at the variation of the bed-material size with the rate of transport, to check whether the assumptions in Klaassen et al. (1987) as to the limited role of selective transport on the stoss side of dunes are justified.

(5) The mathematical model DUGRO should be extended to include the effect of gradation and next simulations should be carried out with this mathematical model to see whether the observed behaviour during the flume tests can be reproduced. If so, the model should be used for field conditions too.

(6) The experiments have demonstrated the importance of the dune lengths and its variation in time. For the time being this phenomena is not sufficiently accounted for in the DUGRO model, because in the model the bedform lengths remain constant. It is suggested to do some additional (theoretical?) tests with the DUGRO model (e.g. with irregular dune patterns and the generation of new dunes conform Allen (1976)), to try to improve our knowledge.

For more details on the above recommendations, reference is made to Section 6.12.
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Appendix A

Commission for further analysis and reporting
rijkswaterstaat

dienst binnenwateren / riza
dossier: DBW/RIZA-overeenkomst 377 met het WL

Aan het Waterloopkundig Laboratorium
Postbus 152
8300 AD EMMELOORD

leystad, 10 maart 1988
ons kenmerk: BX/ 3343
verzonden: 11. Mrt 1988
bijlagen:

in behandeling bij: A.W.C. Hoogendoorn

Hierbij draag ik u de hierna vermelde onderzoekswerkzaamheden op tot een bedrag van fl. 75.000,= (inkl. BTW) voor het dienstjaar 1988, overeenkomstig de door u verstrekte kostenraming.

Van toepassing op deze opdracht is de raamovereenkomst nr.DW 25 tussen RWS en SWL, rekening houdend met de op blz. 2 van deze brief genoemde voorwaarden.

Op correspondentie en declaraties dient u te vermelden opdracht nr.DB 377 en in afwijking van het gestelde in art.3 lid 2 van overeenkomst nr.DW 25 mij éénmaal per maand een voortgangsrapportage te doen toekomen.

Projektbeschrijving:
Q 788-95 Gegradeerd materiaal; verslaggeving modelonderzoek en nota vervolgonderzoek

PROGRAMMERING BESTEDINGEN
bedragen in fl. incl. BTW

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(Almere - Stad)
157 van Amsterdam (Reisvlaardingen)
406000 (Almeyer - Buiton)
Voorwaarden

1. Resultaten van het onderzoek, verricht volgens deze opdracht of nadere deelopdrachten, worden zo spoedig mogelijk in rapportvorm voor algemeen gebruik vrijgegeven. De stuurgroep TOW, bepaalt welke rapporten hiertoe gereed zijn en stelt het tijdstip van vrijgegeven vast.

2. Rekenprogrammatuur in de vorm van research-programma's, welke programmatuur als onderdeel van het onderzoek als omschreven op de voorzijde is ontwikkeld, wordt zo spoedig mogelijk voor algemeen gebruik vrijgegeven. De stuurgroep TOW bepaalt het tijdstip van vrijgeven.

3. Het gestelde in artikel 5, leden 1, 2 en 3 eerste alinea en lid 4 van de raamovereenkomst DW 25 is niet van toepassing.

DE HOOFDINGENIEUR-DIREKTEUR,

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