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rivers

flow resistance and bedform dimensions for varying flow conditions

comparison of predicted initial changes in dune height, using Fredsøe's (1979) method, and measurements in a laboratory flume

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"Informaties" of the Delft Hydraulics Laboratory, which are published within the framework of the Applied Reserach Waterstaat (T.O.W.) Rivers, are no official publications of the Laboratory. They are intended as means of internal communication to inform persons belonging to the organization of the Delft Hydraulics Laboratory as well as to the Delft University of Technology and Rijkswaterstaat upon the progress of the research activities.

It should be stressed that in many cases the conclusions are of a preliminary nature only, the related part of the investigations not being finished.

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FLOW RESISTANCE AND BEDFORM DIMENSIONS FOR VARYING FLOW CONDITIONS;
COMPARISON OF PREDICTED INITIAL CHANGES IN DUNE HEIGHT, USING FREDSØE'S (1979) METHOD, AND MEASUREMENTS IN A LABORATORY FLUME.

1. Introduction

Within the framework of the T.O.W. (Toegepast Onderzoek Waterstaat = Applied Research Waterstaat) on Rivers, commissioned by the Dutch Water Control and Public Works Department, flume experiments are being carried out for varying flow conditions. The background of this investigation has been described in previous publications ("informatie" R657-XIX (Wijbenga, 1980) and Wijbenga & Klaassen (1981)).

In this "informatie" the predicted initial changes in dune height according to Fredsøe (1979) are compared with the initial changes in dune height measured during these flume tests. The results of these tests are described in "informatie" R657-XIX (Wijbenga, 1980) and "informatie R657-XXXIII (Wijbenga, 1981). In the comparison the results of two transport formulas have been considered. A discussion of the results is presented in chapter 5. The main conclusions are summarized in chapter 6. The present "informatie" has been prepared by Mr. J.H.A. Wijbenga.

2. Theory of Fredsøe (1979)

2.1 General

Until now only one theoretical approach to the modification of individual dunes for unsteady flow conditions in an alluvial stream has been presented (Fredsøe 1979 and 1980). In his first paper the initial change in dune height is presented for flow conditions with low Froude numbers at which mainly bedload occurs resulting in transitions from one spectrum of dunes to another spectrum with dunes of different magnitude. Hereafter such transition will be called dune-dune transitions. In his second paper the changes in bed form dimensions are given for high Froude numbers (transition from dunes to plane bed).

As far as the flume tests carried out at the Delft Hydraulics Laboratory, are concerned only dune-dune transitions have been considered. Therefore the description of Fredsøe's theory will be restricted to his 1979 paper of which only a summary will be given in the next section. About dune to plane-bed transitions as described in Fredsøe's 1980 paper will be reported in a forthcoming "informatie".

2.2 Theory

For dune-dune transition Fredsøe bases the initial change in dune height on
- the propagations of bed forms without change in form during equilibrium conditions
- similarity in the shearstress distribution on the top of the dunes as determined with the continuity equation and impuls equation for the flow
- continuity equation for sediment (bed load)
- an equation for the sedimenttransport.

Hereafter Fredsøe's theory will be given in more detail.

During equilibrium conditions (= constant discharge and constant sedimenttransport) Fredsøe assumes the bed forms to travel in the downstream direction with velocity c_b and without changing in form:

$$z_b = z_b\,(x - c_b\,t) \qquad (2.1)$$

in which:

c_b = celerity of bed form

t = time

x = coordinate in flow direction

z_b = bed level

The changes in the bed level are described with the total derivative:

$$\frac{d\, z_b}{dt} = \frac{\partial\, z_b}{\partial t} + c_b \frac{\partial\, z_b}{\partial x} \tag{2.2}$$

During equilibrium the left hand side of equation (2.2) at the top of the dunes equals zero.

The propagation of bed forms with a constant velocity and without change in form, equation (2.1) and the continuity equation for sediment (only bed load is considered):

$$\frac{\partial\, s_b}{\partial x} + \frac{\partial\, z_b}{\partial t} = 0 \tag{2.3}$$

are fulfilled if the sediment transport is described by

$$s_b = c_b\, z_b + \text{constant} \tag{2.4}$$

in which:

s_b = bed load per unit width including the volume of pores.

The constant in equation (2.4) equals zero if the bed elevation is put to zero in the troughs where the bed load vanishes. (see also Figure 1).

In the following the subscript 1 indicates the flow and transport conditions before the change in discharge, while the subscript 2 indicates the conditions after the change.

In determining the initial change in dune height Fredsøe has focussed his attention on the changes in bed level at the top of the dunes. The following assumptions have been made:

i After the change in discharge a change in sediment transport occurs as if equilibrium conditions existed between the instantaneous flow conditions and the sediment transport.

ii The dimensionless rate of sediment transport is related to the local value of the dimensionless shearstress due to the skin friction on the surface of the dunes.

iii For Froude numbers far from unity (Fr << 1) the bed shear stress distribution after the change in discharge is similar to the distribution in the equilibrium situation before the change in discharge.

The initial change in dune height is described with equation (2.2) by inserting the conditions for $\frac{\partial z_b}{\partial t}$, determined with the continuity equation, equation (2.3), and the conditions for the bed level celerity c_b after the change in flow conditions, equation (2.4) (assumption i):

$$\frac{d\, z_b}{dt} = \frac{dH}{dt} = - \frac{\partial\, s_{b2}}{\partial x} + \frac{s_{b2}}{H} \frac{\partial\, z_b}{\partial x} \tag{2.5}$$

in which:

H = bed level at the top of the dunes = dune height.

As only bed load is considered the dimensionless sediment transport is related to the dimensionless shearstress due to skin friction, (assumption ii):

$$\phi = \phi(\theta') \tag{2.6}$$

in which

ϕ = dimensionless sedimenttransport defined as $\phi = s_b/\sqrt{\Delta g D_{50}^3}$

θ' = dimensionless shearstress defined as $\theta' = h'i/(\Delta D_{50})$

Δ = relative density of bed material in water defined as $\Delta = (\rho_s - \rho)/\rho$

ρ = density of water

ρ_s = density of sediment

D_{50} = characteristic grain diameter

g = acceleration of gravity

h' = waterdepth due to skin friction

i = mean slope of energy line

Equation (2.5) is rewritten by using the definition for the dimensionless sedimenttransport ϕ and equation (2.6):

$$\frac{dH}{dt} = \sqrt{\Delta g D_{50}^3}\ \{-\frac{d\phi_2}{d\theta_2}\ \frac{\partial\theta_2}{\partial x} + \frac{\phi_2}{H}\ \frac{\partial\ z_b}{\partial x}\} \qquad (2.7)$$

Assumption iii yields:

$$\theta_2' = \delta\theta_1' \qquad (2.8)$$

and

$$\frac{\partial\theta_2'}{\partial x} = \delta\ \frac{\partial\theta_1'}{\partial x} \qquad (2.9)$$

Inserting equation (2.9) into equation (2.7) yields

$$\frac{dH}{dt} = \sqrt{\Delta g D_{50}^3}\ \{-\frac{1}{\phi_2}\ \frac{d\phi_2}{d\theta_2}\ \delta\ \frac{\partial\theta_1'}{\partial x} + \frac{1}{H}\ \frac{\partial z_b}{\partial x}\}\ \phi_2 \qquad (2.10)$$

Now the terms $\partial\theta'_1/\partial x$ and $\frac{1}{z_b}\ \partial z_b/\partial x$ are considered in more detail:

The partial derivative $\partial\phi_1/\partial x$ is defined as:

$$\frac{\partial\phi_1}{\partial x} = \frac{d\phi_1}{d\theta_1'} \cdot \frac{\partial\theta_1'}{\partial x} \qquad (2.11)$$

After inserting $\partial\phi_1/\partial x$ using the definition of ϕ and equation (2.3) for ϕ_1 and θ_1 but expressed as equation (2.5), $\partial\theta_1'/\partial x$ is written as:

$$\frac{\partial\theta_1'}{\partial x} = \phi_1\ \frac{1}{H}\ \frac{\partial z_b}{\partial x}\ /\ \frac{d\phi_1}{d\theta_1'} \qquad (2.12)$$

For almost triangular dunes the following expression is justified according to Fredsøe (1979)

$$\frac{1}{H}\ \frac{\partial z_b}{\partial x} \sim \frac{1}{L} \qquad (2.13)$$

in which:

L = dune length

After inserting equation (2.12) and (2.13) into equation (2.10) the initial change in dune height is found as:

$$\frac{dH}{dt} = \frac{\sqrt{\Delta g D_{50}^3}}{L} \left\{1 - \frac{\delta \left(\frac{1}{\phi}\frac{d\phi}{d\theta}\right)_2}{\left(\frac{1}{\phi}\frac{d\phi}{d\theta}\right)_1}\right\} \phi_2 \tag{2.14}$$

According to Fredsøe several bed load transport formula $\phi = \phi(\theta)$ can be used in equation (2.14), see section (2.3).

The dimensionless shear stress which has to be used in equation (2.14) corresponds with the dimensionless shear stress on the top of the dunes. With the usual friction relations (see section 4.2) the mean shear stress on the bed due to skin friction θ' is calculated. A correction for the increase in shear stress on the top of the dunes has to be applied. The correction factor is determined as follows: (Fredsøe,1981)

The shear stress is proportional to the square velocity:

$$\tau \sim u^2 \tag{2.15}$$

The velocity on the top of the dunes follows from the decrease in cross section from the mean bed level to the dune top:

$$u_{top} = \bar{u} \left(\frac{R_b}{R_b - \frac{H}{2}}\right) \tag{2.16}$$

Combining (2.15), (2.16) and the definition for the dimensionless shear stress yields the following correction factor:

$$\theta'_{top} = \theta'_{mean} / \left(1 - \frac{H}{2R_b}\right)^2 \tag{2.17}$$

2.3 Sensitivity for bed load formula applied

Fredsøe (1979) uses in his paper the Engelund & Fredsøe (1976) transportformula. According to Fredsøe: "Bed load transportformulas like those of Einstein (1950) or Meijer-Peter & Müller (1948) do not deviate much from Engelund & Fredsøe

(1976) and can be used in the analysis with approximately the same quantative results".

In the following the results for the initial change in dune height determined with the Meijer-Peter & Müller (1948) formula are being compared with those using the Engelund & Fredsøe (1976) formula. This is done to demonstrate that even small differences in the sediment transport may lead to significant deviations in the predicted dH/dt, due to the fact that the second derivation of the transport formula has to be used.

First equation (2.14) is linearized with

$$\frac{\theta'_2}{\theta'_1} = 1 + \frac{d\theta'}{\theta'_1} \qquad (2.18)$$

and

$$\frac{F_2}{F_1} = 1 + \frac{dF}{F_1} \qquad (2.19)$$

in which $F = \frac{1}{\phi}\frac{d\phi}{d\theta}$

The linearized relation reads as:

$$\frac{dH}{dt} = - \frac{\sqrt{\Delta g D_{50}^3}}{L}\, \phi \left\{\frac{1}{\theta} + \frac{1}{F}\frac{dF}{d\theta'}\right\} d\theta' \qquad (2.20)$$

The transport formula which have to be inserted in equation (2.20) are respectively:

1. Engelund & Fredsøe (1976)

$$\phi = 16.67\,(\theta-\theta c)(\sqrt{\theta} - 0.7\,\sqrt{\theta_c}) \qquad (2.21)$$

in which

θ_c = critical dimensionless shear stress

2. Meyer-Peter & Müller (1948)

$$\phi = 13.33\ (\mu\theta - 0.047)^{1.5} = 13.33\ (\theta' - 0.047)^{1.5} \qquad (2.22)$$

For the ripple factor μ has been accounted by using the dimensionless shear stress θ' due to skin friction.

In Figure 2 the dimensionless sedimenttransport is plotted versus the dimensionless shear stress for both transportformulas. For shear stresses less than .6 the differences are small.

As fas as differences may occur in the initial change in dune height, depending on the transportformula used, they appear in the term

$$\phi\ \left\{\frac{1}{\theta} + \frac{1}{F}\ \frac{dF}{d\theta}\right\}$$

In Figure 3 this term is plotted versus the dimensionless shear stress. The dimension less shear stress is in the order of 0.1 to 0.2, see Tables 3...6, so that a difference of 20% to 30% may occur in the quantative results for the initial change in dune height, depending on which of the considered transport formula will be used.

3. Flume experiments

3.1 General

Experiments have been carried out in a flume which has been built at the Delft Hydraulics Laboratory. A short description of the flume is presented in the next Section.

To study the changes in bedform dimensions for varying flow conditions flume tests have been carried out in a flume with a flume width of 1.50 m. The results of these tests are summarized in "informatie" R657-XIX (Wijbenga, 1980).

As it was expected that the results of these tests were influenced by three-dimensional phenomena, observed in the flume (Klaassen 1980, Van Rijn & Klaassen 1981) some of the tests have been repeated in the same flume but with a flume width of 0.50 m. The results of these tests are summarized in "informatie" R657-XXXIII (Wijbenga, 1981).

A description of the tests carried out is presented in section 3.3.

3.2 Experimental facility

The sand flume constructed at the Delft Hydraulics Laboratory has been built in reinforced concrete with a measuring section of a steel frame work with glass windows (see Figure 4). The main dimensions of the flume are:

overall length	97 m
length with glass windows	50 m
measuring length	30 m
flume width, adjustable from	0.3 m to 1.50 m
maximum water depth (without sediment)	1.0 m
water discharge variable between	0.02 m^3/s and 0.80 m^3/s
maximum sediment supply (as submerged weight)	0.800 kg/h

The following measuring devices (see also "informatie" R 657-XIX) have been installed:

measuring device	purpose
Romein weir	water supply
Rehbock weir	discharge control
hydrocyclones	sediment supply and control of sediment transport
pitot tubes upstream and downstream of measuring section	measuring of energy slope; control of energy slope by means of pressure difference box and feed-back system
measuring carriage with three bed level followers and one water level follower	recording of bed levels and water level
micro-computer + micro-processor	automatic acquisition and processing of data and changing boundary conditions

For a more detailed description of the sand flume reference is made to "informatie" R 657-XIX (Wijbenga, 1980) and (Wijbenga and Klaassen, 1981).

3.3 Tests performed

In his publication of 1979 Fredsøe compares the results of his theory with the measurements obtained by Gee (1973). As only dune to plane bed transitions in the upper flow regime (Fr > 0,5) have been considered no data of dune-dune transitions for low Froude numbers were available. Therefore a number of tests in this field of interest has been carried out at the Delft Hydraulics Laboratory. The varying flow conditions have been realized by a sudden change in the discharge (step function). Two types of stepfunction are considered (see Figure 5):

i Step functions with an increase in dicharge, the initial water depth in the tests being 0.10 m or 0.20 m. The dimensions of the bed forms have been measured.

ii Step functions with a decrease in dicharge, the final water depth being 0.10 m or 0.20 m. Again the bedform dimensions have been measured.

The two types of stepfunctions has been realized in two series of tests. The first one has been carried out in a flume with a flume width of 1.50. The flume width in the second one equalled 0.50 m.

The tests for a flume width of 1.50 m have been carried out as follows. First the discharge and sediment transport (independent variables) were kept constant until an equilibrium stage was reached characterized as sediment supply up-streams = measured sediment transport downstreams. Then the discharge and the sediment transport were suddenly changed in such a way that the mean energy slope in the new equilibrium stage has not changed with respect to the initial value. During the preceding equilibrium stage, the transition inbetween both equilibrium stages and the final equilibrium stage, measurements have been carried out. The results and a more detailed description of the tests are presented in "informatie" R 657-XIX. In these tests the dependent variables consisted of the waterdepth and the mean energy slope. A review of the test for a flume width of 1.50 is presented in Figure 6.

The tests for the flume with a flume width of 0,50 m were carried out in a slightly different way. The difference between the series of tests consisted of the choice in independent variables. During these flume tests the discharge and the mean energy slope were supposed as independent variables, the water depth and sediment transport being the dependent variables. The use of the mean energy slope as an independent variable had been realized by the installation of a slope control system as described in "informatie" R 657-XIX. The results and a more detailed description of the tests are presented in "informatie" R 657-XXXIII. A review of the tests carried out for a flume width of 0.5 m is given in Figure 7.

For all tests the bed slope equalled 1.6×10^{-3}. The bed material used had the following characteristics grain diameters:

$D_{10} = .70 \times 10^{-3}$ m
$D_{35} = .76 \times 10^{-3}$ m
$D_{50} = .78 \times 10^{-3}$ m
$D_{65} = .80 \times 10^{-3}$ m
$D_{90} = .84 \times 10^{-3}$ m
$D_{m} = .77 \times 10^{-3}$ m

4. Initial changes in dune height

4.1 General

For the flow conditions imposed during the two series of flume tests the initial change in dune height has been calculated with the theory of Fredsøe (1979). These calculations are commented in more detail in Section 4.2. In Section 4.3 the initial change in dune height is determined from the results of the flume tests. Finally in section 4.4 the results of Fredsøe's theory are compared with the results of the flume tests.

4.2 Predictions by Fredsøe (1979)

To calculate the initial change in dune height the equilibrium flow conditions as measured during the flume test (see "informatie" R 657-XIX and "informatie" R 657-XXXIII) have to be known. A summary of measured flow conditions is presented in the Tables 1 and 2. In determining the hydraulic radius the side wall correction procedure of Einstein (1934) has been applied.

In determining the initial change in dune height for the flow conditions, as measured during the flume tests, the following procedure has been followed.

First the bed form dimensions are plotted versus the measured hydraulic radius (see Figure 8). As far as possible a regression line is added in the Figure. Then the equilibrium flow conditions has been determined for these bed form dimensions and a hydraulic radius of 0.10 m, 0.15 m, 0.20 m, ..., 0.40 m using the following friction relations

$$f_b = f_b' + f_b'' \qquad (4.1)$$

in which:

f_b, f_b' and f_b'' = total friction factor, skin friction factor and friction factor due to bed form roughness respectively.

The total friction factor is defined as

$$f_b = \frac{2g}{C^2} = \frac{2}{g^2}\, g\, i\, R_b^3 \qquad (4.2)$$

Waar is dit voor nodig in dit kader

For the friction factor due to skin friction the Einstein (1950) relation is taken:

$$f_b' = \frac{2}{\{6+2.5 \ln (\frac{R_b'}{D_{90}})\}^2} \qquad (4.3)$$

in which:

R_b' = hydraulic radius due to skin friction, determined as

$$R_b' = \frac{f_b'}{f_b} R_b \qquad (4.4)$$

The friction factor due to the bed forms can be determined as a series of Carnot losses, see Engelund (1978):

$$f_b'' = 2.5 \exp (-2.5 \frac{H}{R_b}) \frac{H^2}{R_b L} \qquad (4.5)$$

Then the dimensionless shear stress on the top of the dunes is determined with equation (2.17). The results of the calculations are presented in Table 3. The mean energy slope and the characteristic grain diameters D_{50} and D_{90} equals 1.6×10^{-3}, 0.78×10^{-3} m and 0.84×10^{-3} m respectively, the discharge, hydraulic radius and bed form dimensions are as presented in the Table.

The next step in the determination of the initial change in dune height according to Fredsøe (1979) is the calculation of the flow conditions after the change in discharge with the bed form dimensions which have not yet changed. The changes in the discharge are chosen in such a way that the final hydraulic radius equals 0.10 m, 0.15 m, 0.20 m, ... , 0.40 m.

The results for increasing discharges with an initial hydraulic radius of 0.10 m and 0.20 m are presented in the Tables 4 and 5 (step functions of type i, see Section 3.3). The results for decreasing dicharges with a final hydraulic radius of 0.10 m and 0.20 m are shown in the Tables 6 and 7 (step functions of type ii).

The final step is the calculation of the initial change in dune height with equation (2.14) for both the increasing and decreasing step functions in the discharge. The calculations have been carried out for the Engelund & Fredsøe

(1976) formula as well as for the Meijer-Peter & Müller (1948) formula. The results are presented in the Tables 8 and 9. Furthermore the initial change in dune height as calculated with Fredsøe (1979) are plotted versus the ultimate change in dune height in the Figures 9 and 10.

4.3 Results of flume tests

The initial change in dune height immediately after the change in discharge is determined from "informatie" R 657-XIX, the Figures 25...31 and "informatie" R 657-XXXIII, the Figures 29...23, where the dune height is plotted versus the time. The results are summarized in the Tables 10 and 11. The measured initial change in dune height is plotted in the Figures 9 and 10.

It has to be stressed that the measured change in dune height corresponds with the initial change in mean dune height as measured in the three longitudinal profiles. No preprocessing of the data such as filtering has been applied.

4.4 Comparison

In the Figures 9 and 10 both the results of measured and predicted initial change in dune height are plotted versus the ultimate change in dune height. A comparison of the results in Figure 10 with an initial and final hydraulic radius of 0.20 m shows that

- the predicted and measured initial change in dune height is of the same order of magnitude for small values in the ultimate change in dune height
- the discrepancies between measurements and predicted values increase with increasing ultimate changes in dune height for both increasing and decreasing discharges
- the measured and predicted initial change in dune height for step functions with a decrease in discharge seems to deviate more from each other than the results for step functions with an increase in discharge.

For the results presented in Figure 9 (initial and final hydraulic radius of 0.10 m) more or less similar conclusions can be drawn.

In Figure 11 the measured initial change of all tests with increasing and decreasing step functions in the discharge are plotted versus the absolute value of the ultimate change in dune height. Apparently there is no significant difference in initial change in dune height for increasing and decreasing step functions in the discharge.

Furthermore in the Tables 10 and 11 a column is added in which the adaption time defined as $(H_\infty - H_o)/(dH/dt)$ is presented. Allen (1976[a], 1976[b], 1976[c] 1978) has proposed a change in dune height according to

$$\frac{dH}{dt} = \frac{1}{T_H} (H_\infty - H(t)) \tag{4.6}$$

in which T_H = adaption time for the dune height; it is considered constant

From the fact that the adaptation time as measured in the flume tests is not constant the application of equation (4.6) is not allowed.

5. Discussion

From the results presented in this "informatie" one may conclude that the initial change in dune height can be predicted with Fredsøe's (1979) theory of "the modification of individual dunes" for unsteady flow conditions which results in relatively small changes in dune height. In the case of step functions in the discharge the discrepancies increase with increasing changes in the ultimate change in dune height.

In nature the changes in the discharge are more gradual. In these circumstances the change of bed form already starts while the change in discharge is still progressing. At this very moment no insight is available about the time lag which may be expected between the instantaneous flow conditions and bed forms. If the time appears not to be too large, then the theory of Fredsøe might give reasonable results. Therefore the series of test with varying discharge has been extended with two series of test in which the behaviour of the bed forms has been determined during a succession of hydrographs. The difference between both series of tests consists of the time scale in the hydrographs. Upon the results of these tests will be reported in a forthcoming "informatie".

Regarding the difference between the results of the flume tests and the theoretical calculations the following remarks can be made

- i The dimensionless shear stress on the top of the dunes may not be predicted with sufficient accuracy
- ii To predict the change in bed level not only the sediment transport but also the change of the sediment transport in the flow direction is important. The latter is determined by the change in dimensionless shear stress and therefore not only the local value of the dimensionless shear stress is important but also its gradient in flow direction. A non similarity in shear stress distribution before and after the sudden change in discharge might be the case for large values of the ultimate change in dune height.
- iii The coefficients in the sediment transport formula are determined for steady flow conditions. Applying the same coefficients for non steady flow conditions may not be correct.
- iv The local bed slope at the top of the dunes ($\partial z_b/\partial x$) is approximated with the steepness of the dunes. Therefore in this way the predicted change in dune height may even be exaggerated.

v The change in dune height according to Fredsøe (1979) is defined as the change in bed level at the top of the dunes. The change in bed level at the trough is neglected. The dune height measured during the flume tests is determined as the difference of the bed level of dune top and dune trough. The predicted change in dune height is therefore underestimated.

vi Fredsøe (1979) describes the development of individual dunes during non steady flow conditions. As the bed form dimensions in flume experiments are of a stochastic natu: the development of individual dunes cannot be followed sufficient accurate to make a comparison between prediction and measurement. Therefore the mean value of the change in dune height of about 20 dunes has been compared with Fredsøe's predicted change in dune height. It is not quite clear whether this procedure introduces discrepancies for larger values of the ultimate change in dune height.

vii The dune dimensions as measured in the flume tests are determined in a rather straight forward way. A linear regression line through the measured bed levels is determined. Next the amount of zero crossings of the recorded bed level profiles and the regressionline has been determined. The mean bed form dimensions such as dune height and dune length are calculated as the mean value of all top-trough distances respectively the mean value of all distances between two upgoing zero crossings. As no filtering procedures are applied the zero crossings of small ripples might have influenced the mean bed form dimensions.

With respect to a verification of the items mentioned above the following suggestions can be made.

ad i and ii The dimensionless shear stress on the top of the dunes as predicted with the equations (4.1)...(4.5) and (2.7) can be compared with the dimensionless shear stress as obtained with the WABED model see "informatie" R 657-XXX (Van der Knaap, 1981)

ad iii The sensitivity of the initial change in dune height to (small) changes in the coefficients of the bed load formula can be determined with a number of calculations or a sensitivity analysis of equation (2.14) with respect to the parameters used.

ad iv...vi Some insight into these items may be obtained with a detailed study for a number of selected individual dunes. The following parameters have to be investigated in more detail:

- the change of the bed level at the top of the dunes
- the change of the bed level at the trough of the dunes
- the changes in bed form celerity of the individual dunes
- the bed slope at the top of the dunes
- local value of the flow conditions at the top of the dunes

ad vii The effect of filtering on the initial change in dune height can be determined by using an appropriate filter procedure.

6. Conclusions

From the results presented in this "informatie" the following conclusions can be drawn.

- For small changes in the ultimate change in dune height the initial change in dune height can be determined with reasonable accuracy by the theory of Fredsøe. For larger changes in dune height the predicted initial change in dune height should be considered critically.
- In the analysis of Fredsøe (1979) comparable transport formula can be used. Due to differences in the first and second order derivatives which appear in the formula for the initial change in dune height, the predicted value can be sensitive for the formula used.
- A number of Fredsøe's assumption should be verified in more detail (see Section 5, items i...vii).
- To verify the theory of Fredsøe for gradually varying flow conditions flume tests with an imposed hydrograph have to be carried out.

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Test number	unit discharge q (m^2/s)	energy slope i (10^{-3})	water depth h (m)	measured dune height H (m)	measured dune length L (m)	mean velocity $\bar{u}$ (m)	hydraulic radius R_b (m)
T00022	.177	1.64	.302	.077	1.20	.586	.276
23	.097	1.60	.200	.071	1.38	.485	.187
24	.177	1.56	.301	.087	1.45	.588	.274
25	.098	1.65	.200	.071	1.39	.490	.187
26	.267	1.53	.405	.104	1.59	.659	.361
27	.098	1.61	.201	.069	1.25	.488	.188
29	.177	1.68	.301	.086	1.41	.588	.276

Table 1 Summary of flow conditions during equilibrium conditions for flume width 1.50 m

Rijn	820108	19,98	$1,16.10^{-4}$	11,48	0,59	24,0	1,74	11,48
	0109	21,28	$1,14.10^{-4}$	11,68	0,65	25,55	1,82	11,68

Test number	unit discharge q (m^2/s)	energy slope i (10^{-3})	water depth h (m)	measured dune height H (m)	measured dune length L (m)	mean velocity $\bar{u}$ (m/s)	hydraulic radius R_b (m)
T00034	.098	1.66	.211	.055	1.16	.465	.174
35	.178	1.69	.328	.080	1.31	.543	.255
36	.098	1.67	.209	.054	1.16	.469	.172
37	.044	1.62	.120	.035	.88	.367	.105
38	.098	1.62	.209	.055	1.22	.469	.171
39	.268	1.70	.436	.092	1.36	.615	.325

Table 2 Summary of flow conditions during equilibrium conditions for flume width 0.50 m

Hoe bepaald
(Alle dune afmetingen ?

hydraulic radius R_b (m)	unit discharge $q = R_b\ u$ (m^2/s)	dune height H (m)	dune length L (m)	friction factor f (-)	friction factor f' (-)	friction factor f" (-)	dimensionless shear stress θ (-)	dimensionless shear stress θ' (-)	dimensionless shear stress θ'_{top} (-)
.100	.0376	.0335	.87	.0221	.0082	.0140	.124	.046	.066
.150	.0655	.0495	1.05	.0247	.0076	.0171	.186	.058	.083
.200	.0970	.0650	1.21	.0266	.0073	.0194	.249	.068	.097
.250	.133	.0785	1.35	.0278	.0070	.0208	.311	.078	.110
.300	.173	.0900	1.47	.0284	.0067	.0217	.373	.088	.122
.350	.216	.1000	1.57	.0288	.0065	.0223	.435	.098	.134
.400	.263	.1090	1.65	.0291	.0063	.0228	.498	.108	.145

h'   dθ   dθ'

Table 3 Equilibrium flow conditions

11,48   19,98   0,59   24,0   0,0345   0,224   0,116   0,122   5,92   0   9,08
11,68   21,28   0,65   25,55   0,0315   0,224   0,124   0,131   6,47

bij R_b=0,1 ?

hydraulic radius		unit discharge after the change	dune height	dune length	friction factor			dimensionless shear stress		
just before the change R_b (m)	after the change R_b (m)	$q = R_b u$ (m^2/s)	M (m)	L (m)	f (-)	f' (-)	f'' (-)	θ (-)	θ' (-)	θ'_{top} (-)
.100	.140	.0655	.0335	.87	.0200	.0074	.0127	.174	.064	.083
.100	.176	.0970	.0335	.87	.0182	.0068	.0114	.219	.082	.100
.100	.211	.133	.0335	.87	.0167	.0064	.0103	.263	.101	.119
.100	.245	.173	.0335	.87	.0155	.0061	.0093	.305	.121	.139
.100	.278	.216	.0335	.87	.0145	.0059	.0086	.346	.141	.159
.100	.311	.263	.0335	.87	.0136	.0057	.0079	.386	.161	.180

Table 4 Flow conditions just after the change in dicharge; initial hydraulic radius 0.10 m

hydraulic radius		unit discharge after the change	dune height	dune length	friction factor			dimensionless shear stress		
just before the change R_b (m)	after the change R_b (m)	$q = R_b u$ (m /s)	H (m)	L (m)	f (-)	f' (-)	f'' (-)	θ	θ'	θ'_{top}
.200	.242	.133	.0650	1.21	.0253	.0069	.0184	.301	.082	.109
.200	.284	.173	.0650	1.21	.0239	.0065	.0174	.353	.096	.123
.200	.323	.216	.0650	1.21	.0226	.0063	.0163	.401	.111	.138
.200	.362	.263	.0650	1.21	.0215	.0061	.0154	.450	.128	.155

Table 5 Flow conditions just after the change in discharge, initial hydraulic radius 0.20 m

hydraulic radius		unit discharge after the change	dune height	dune length	friction factor			dimensionless shear stress		
just before the change R_b (m)	after the change R_b (m)	$q = R_b u$ (m^2/s)	H (m)	L (m)	f (-)	f' (-)	f" (-)	θ (-)	θ' (-)	θ'_{top} (-)
.150	.105	.0376	.0495	1.05	.0254	.0084	.0171	.130	.043	.073
.200	.106	.0376	.0650	1.21	.0261	.0084	.0177	.131	.042	.088
.250	.104	.0376	.0785	1.35	.0250	.0083	.0166	.129	.043	.111
.300	.101	.0376	.0900	1.47	.0230	.0082	.0147	.126	.045	.146
.350	.098	.0376	.1000	1.57	.0207	.0081	.0126	.122	.047	.199
.400	.094	.0376	.1090	1.65	.0186	.0079	.0106	.117	.050	.282

Table 6 Flow conditions just after the change in discharge; final hydraulic radius 0.10 m

hydraulic radius		unit discharge after the change	dune height	dune length	friction factor			dimensionless shear stress		
just before the change R_b (m)	after the change R_b (m)	$q = R_b\ u$ (m^2/s)	H (m)	L (m)	f (-)	f' (-)	f" (-)	θ (-)	θ' (-)	θ'_{top} (-)
.250	.205	.0970	.0785	1.35	.0287	.0073	.0214	.255	.065	.100
.300	.208	.0970	.0900	1.47	.0298	.0074	.0224	.258	.064	.104
.350	.209	.0970	.1000	1.57	.0304	.0074	.0230	.260	.063	.109
.400	.210	.0970	.1090	1.65	.0308	.0074	.0234	.261	.063	.115

Table 7 Flow conditions just after the change in discharge; final hydraulic radius 0.20 m.

Reveal sec in [illegible] dt

Transition hydraulic radius from R_{b1} (m) → to R_{b2} (m)	Dimensionless shear stress		Dune length	Engelund & Fredsøe (1976)				Meyer-Peter & Müller (1948)			
	θ'_1 top (-)	θ'_2 top (-)	L (m)	Dimension-less. sed. transport ϕ_2 (-)	F_2 (-)	F_1 (-)	dH/dt (10^{-6}m/s)	Dimension-less. sed. transport ϕ_2 (-)	F_2 (-)	F_1 (-)	dH/dt (10^{-6}m/s)
.10 → .15	.066	.083	.87	.072	43.49	81.89	2.42	.092	41.67	78.95	3.09
.10 → .20	.066	.100	.87	.133	29.90	81.89	5.99	.163	28.30	78.95	7.49
.10 → .25	.066	.119	.87	.217	22.19	81.89	11.17	.258	20.83	78.95	13.60
.10 → .30	.066	.139	.87	.322	17.44	81.89	17.83	.372	16.30	78.95	21.18
.10 → .35	.066	.159	.87	.440	14.35	81.89	25.61	.500	13.39	78.95	29.77
.10 → .40	.066	.180	.87	.580	12.09	81.89	34.90	.647	11.28	78.95	39.77
.15 → .10	.083	.073	1.05	.043	59.76	43.49	- .758	.057	57.69	41.67	- 1.016
.20 → .10	.097	.088	1.21	.088	38.34	31.64	- .639	.110	36.59	30.00	- .853
.25 → .10	.110	.111	1.35	.180	24.89	25.28	.073	.217	23.44	23.81	.094
.30 → .10	.122	.146	1.47	.362	16.22	21.32	1.93	.415	15.15	20.00	2.31
.35 → .10	.134	.199	1.57	.718	10.58	18.42	5.90	.790	9.87	17.24	6.616
.40 → .10	.145	.282	1.65	1.448	6.82	16.38	14.60	1.518	6.83	15.31	15.25

Table 8 Basic data and resulting initial change in dune height; initial and final hydraulic radius of 0.10 m.

Transition hydraulic radius from R_{b1} (m)	→	to R_{b2} (m)	Dimensionless shear stress θ'_1 top (-)	θ'_2 top (-)	Dune length L (m)	Engelund & Fredsøe (1976) Dimensionless sed. transport ϕ_2 (-)	F_2 (-)	F_1 (-)	dH/dt (10^{-6}m/s)	Meyer-Peter & Müller (1948) Dimensionless sed. transport ϕ_2 (-)	F_2 (-)	F_1 (-)	dH/dt (10^{-6}m/s)
.20	→	.25	.097	.109	1.21	.170	25.67	31.64	1.09	.207	24.19	30.00	1.40
.20	→	.30	.097	.123	1.21	.237	21.04	31.64	2.68	.280	19.74	30.00	3.35
.20	→	.35	.097	.138	1.21	.315	17.63	31.64	4.74	.367	16.48	30.00	5.79
.20	→	.40	.097	.155	1.21	.415	14.88	31.64	7.47	.473	13.89	20.00	8.92
.25	→	.20	.110	.100	1.35	.133	29.9	25.28	- .652	.163	28.30	23.81	- .852
.30	→	.20	.122	.104	1.47	.150	27.86	21.32	-1.017	.182	26.32	20.00	-1.316
.35	→	.20	.134	.109	1.57	.170	25.67	18.42	-1.272	.207	24.19	17.24	-1.625
.40	→	.20	.145	.115	1.65	.198	23.46	16.38	-1.427	.237	22.06	15.31	-1.796

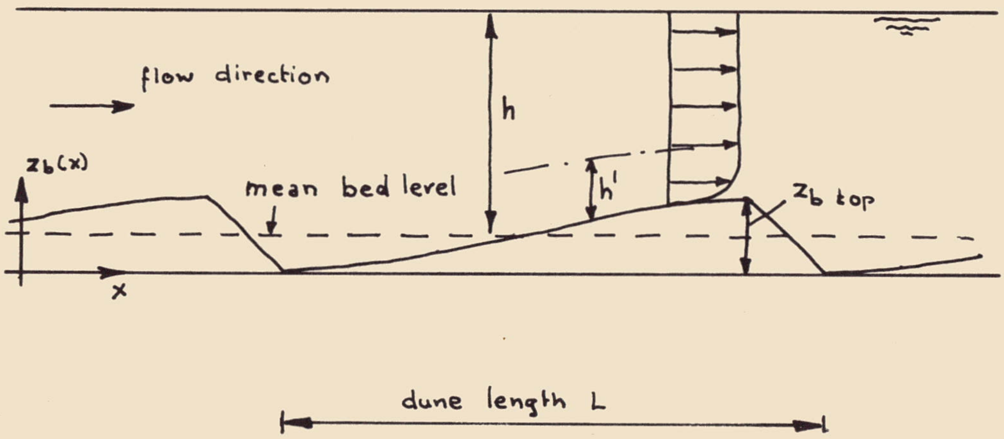
Table 9 Basic data and resulting initial change in dune height; initial and final hydraulic radius of 0.20 m.

Test number	Water depth transition		Equilibrium dune height		initial change in dune height $\frac{dH}{dt}$ $(10^{-6} m/s)$	Adaptation time $\frac{H_\infty - H_o}{\frac{dH}{dt}}$ (s)
	from h_0 (m)	to h_1 (m)	at t = o H_o (m)	at t = ∞ H_∞ (m)		
T00023	0.3	0.2	.077	.071	- 3.2	1875
T00024	0.2	0.3	.071	.087	3.2	5000
T00025	0.3	0.2	.087	.071	- 1.5	10665
T00026	0.2	0.4	.071	.104	15.3	2155
T00027	0.4	0.2	.104	.069	-26.7	1310
T00029	0.2	0.3	.069	.086	3.0	5665

Table 10 Initial change in dune height measured during flume tests in a flume with flume width 1.50 m

Test number	Water depth transition		Equilibrium dune height		initial change in dune height $\frac{dH}{dt}$ $(10^{-6} m/s)$	Adaptation time $\frac{H_\infty - H_o}{\frac{dH}{dt}}$ (s)
	from h_0 (m)	to h_1 (m)	at t = o H_o (m)	at t = ∞ H_∞ (m)		
T00035	.2	.3	.055	.080	15.8	1580
T00036	.3	.2	.080	.054	10.8	2401
T00037	.2	.1	.054	.035	6.7	2850
T00038	.1	.2	.035	.055	8.4	2395
T00039	.2	.4	.055	.092	21.7	1705

Table 11 Initial change in dune height measured during flume tests in a flume with flume width 0.50 m



DEFINITION SKETCH

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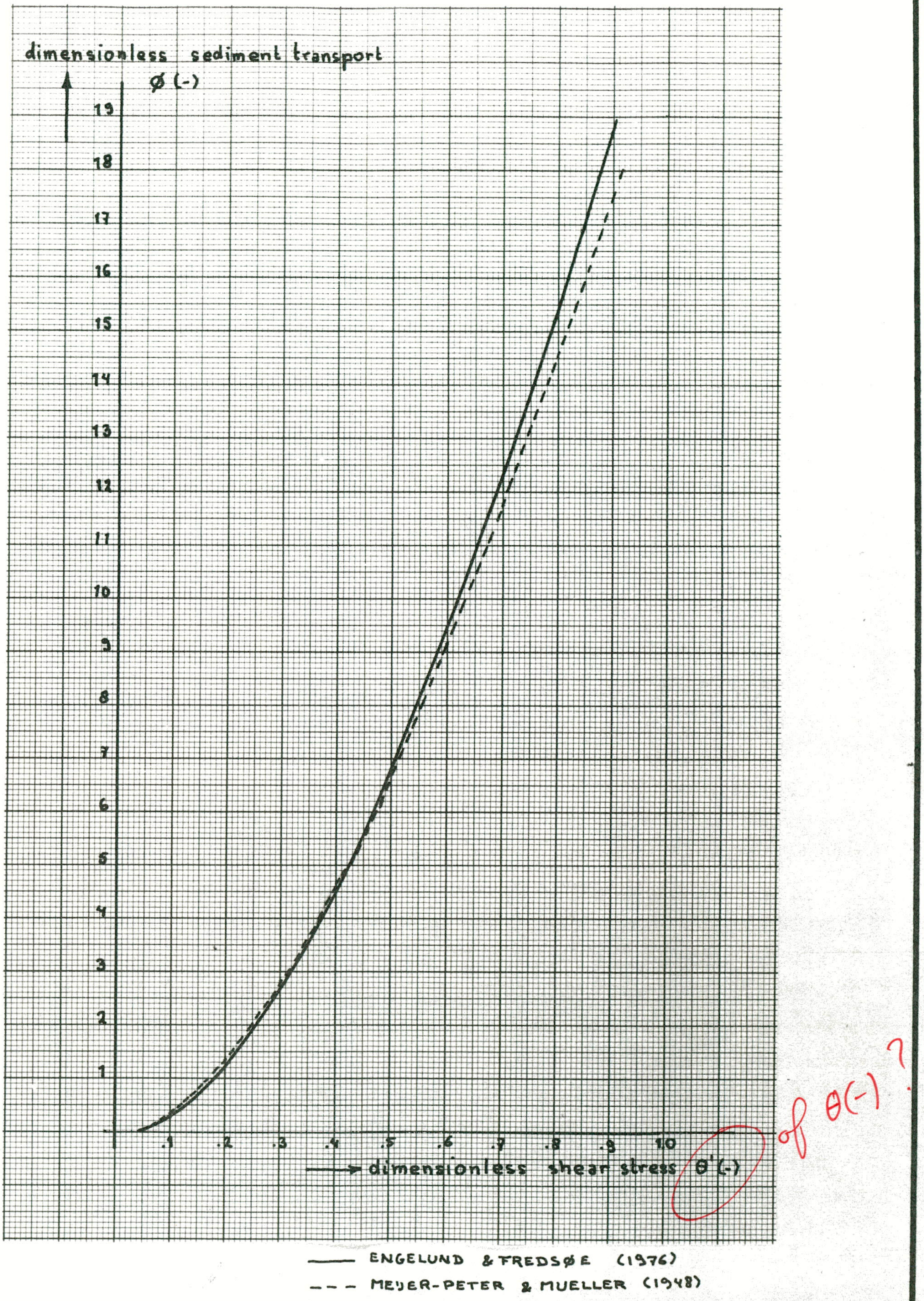
R657/R1364

FIG. 1

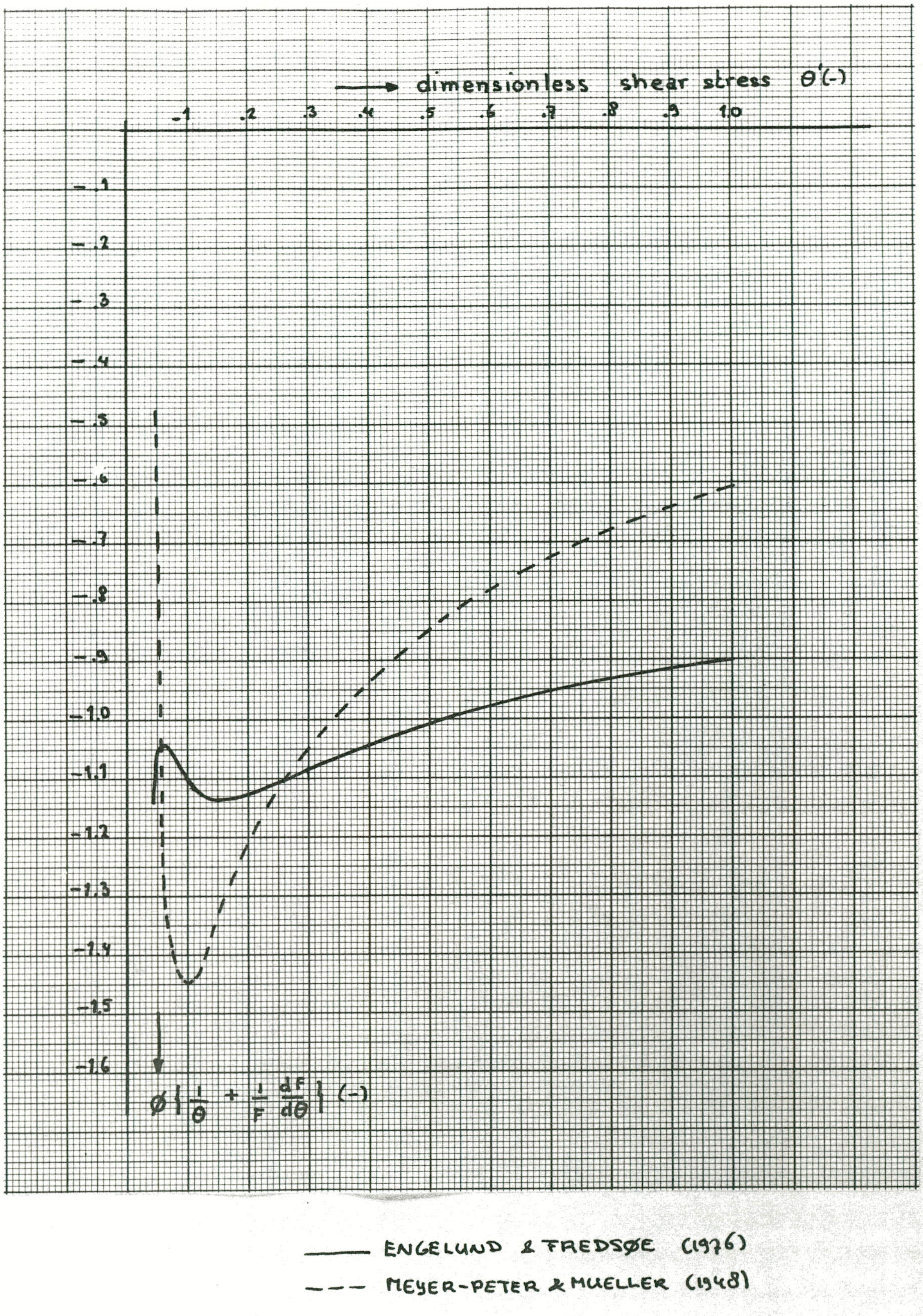


DIMENSIONLESS SEDIMENT TRANSPORT VERSUS DIMENSIONLESS SHEAR STRESS

WATERLOOPKUNDIG LABORATORIUM

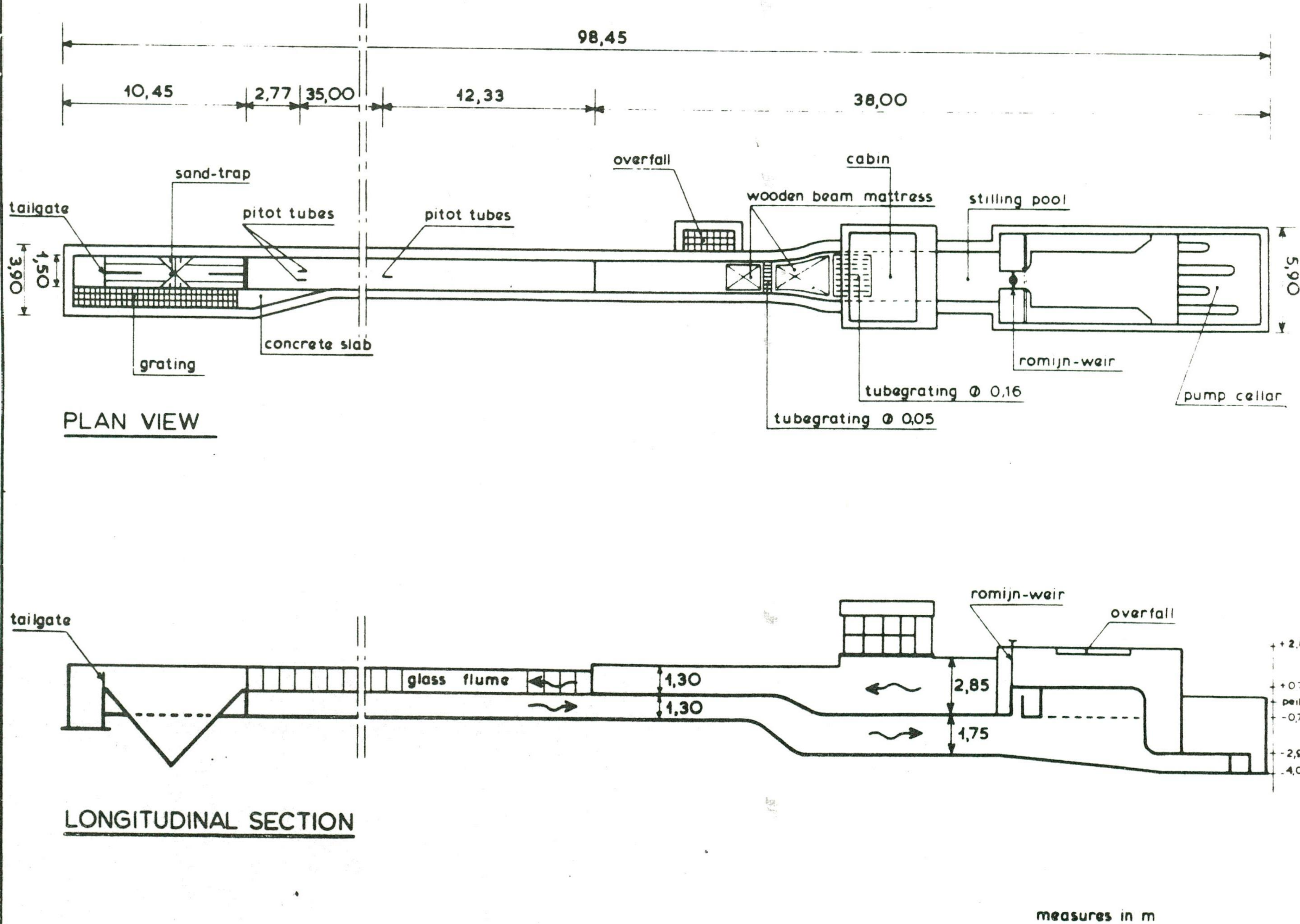
R657/M1384

FIG. 2.



SOURCE OF DIFFERENCE IN INITIAL CHANGE IN DUNE HEIGHT DETERMINED WITH ENGELUND & FREDSØE (1976) AND MEYER-PETER & MUELLER (1948) VERSUS DIMENSIONLESS SHEAR STRESS

WATERLOOPKUNDIG LABORATORIUM | R 657/M 1314 | FIG. 3



PLAN VIEW AND LONGITUDINAL SECTION OF SAND FLUME

SCALE 1 : 300

DELFT HYDRAULICS LABORATORY

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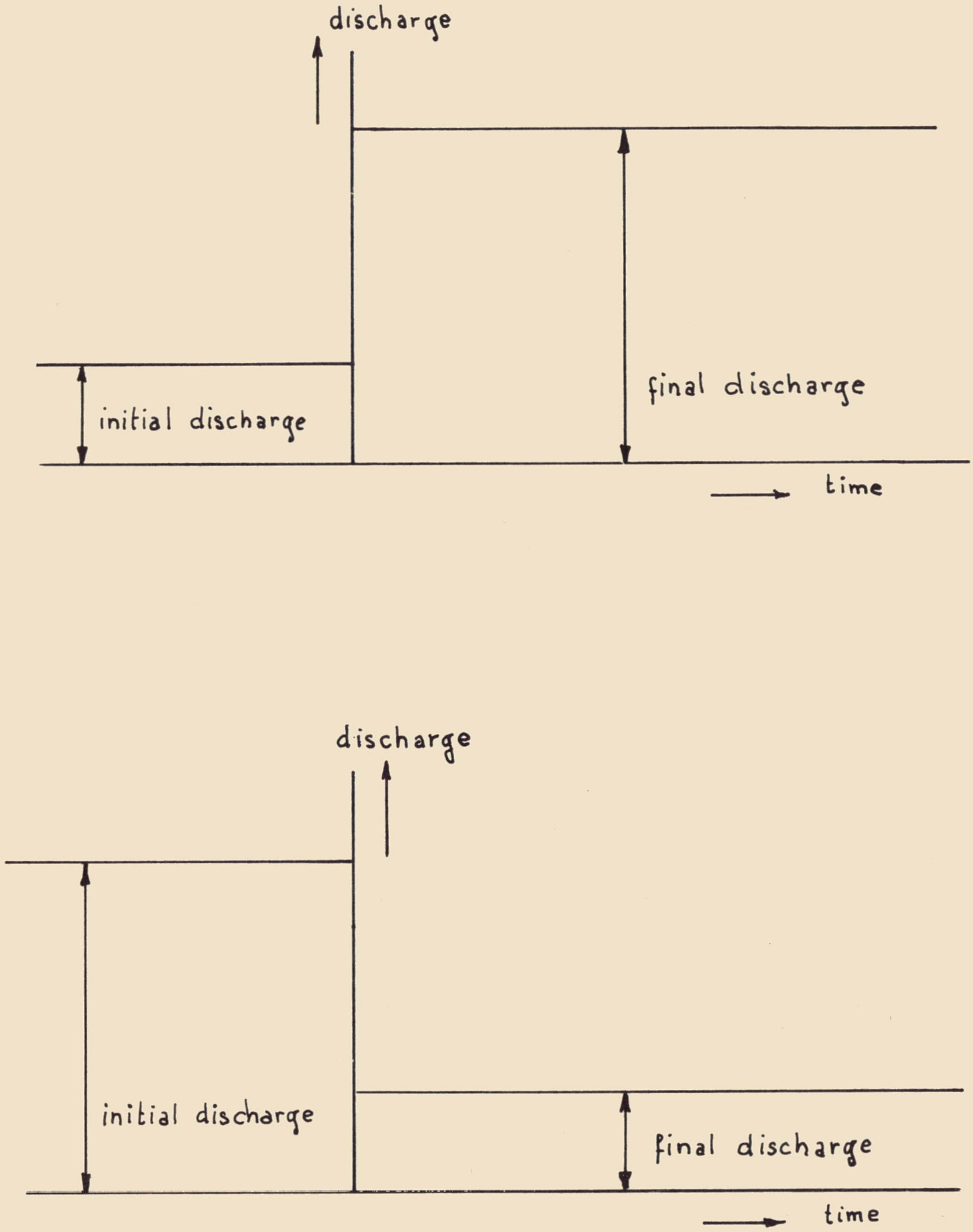
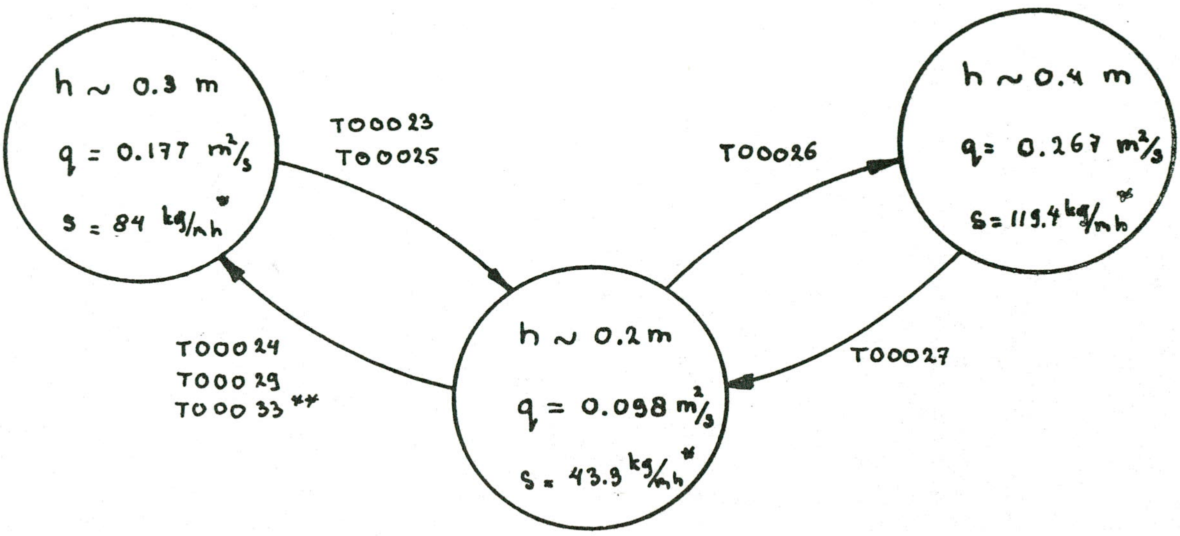
FIG. 4



TYPES OF STEPFUNCTIONS IN THE DISCHARGE

DELFT HYDRAULICS LABORATORY | R657 / R1364 | FIG. 5

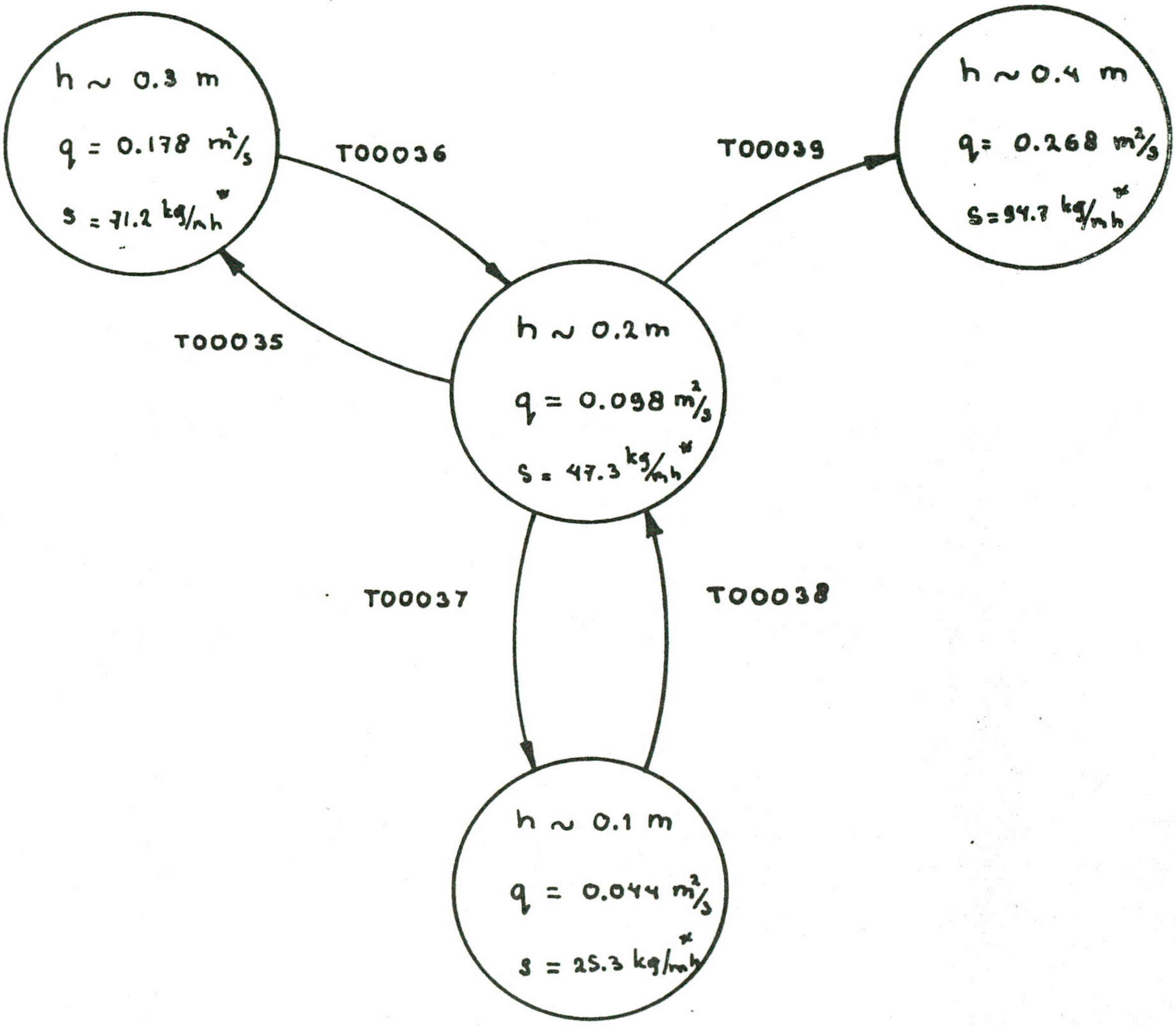


* S = SEDIMENT TRANSPORT PER UNIT WIDTH (SUBMERGED)

** THE FLUMEWIDTH DURING THIS TEST EQUALS 1.125 M.

REVIEW OF TESTS IN FLUME WITH FLUME WIDTH 1.50 m

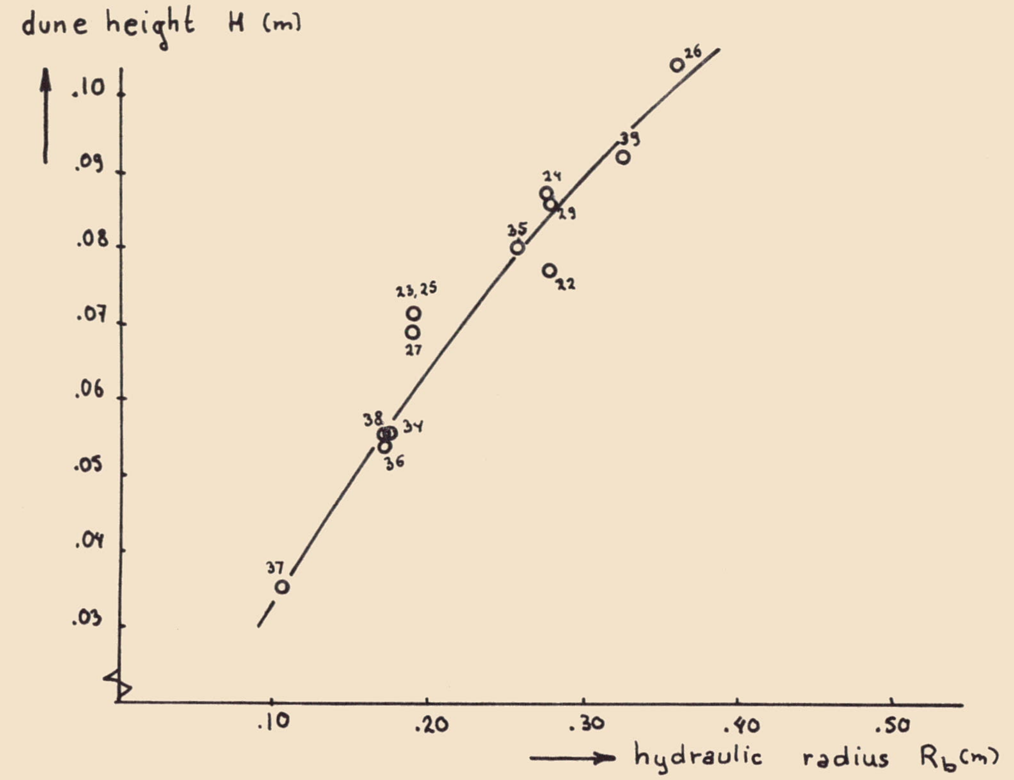
DELFT HYDRAULICS LABORATORY | R657/R1364 | FIG. 6

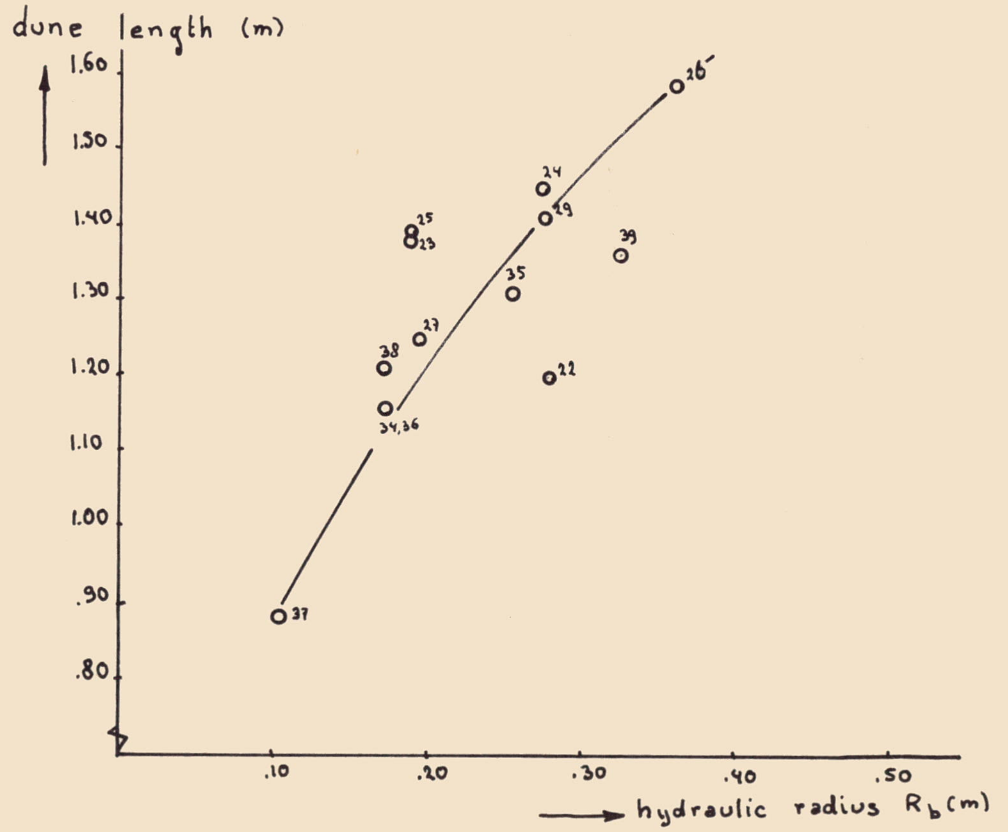


* S = SEDIMENT TRANSPORT PER UNIT WIDTH (SUBMERGED)

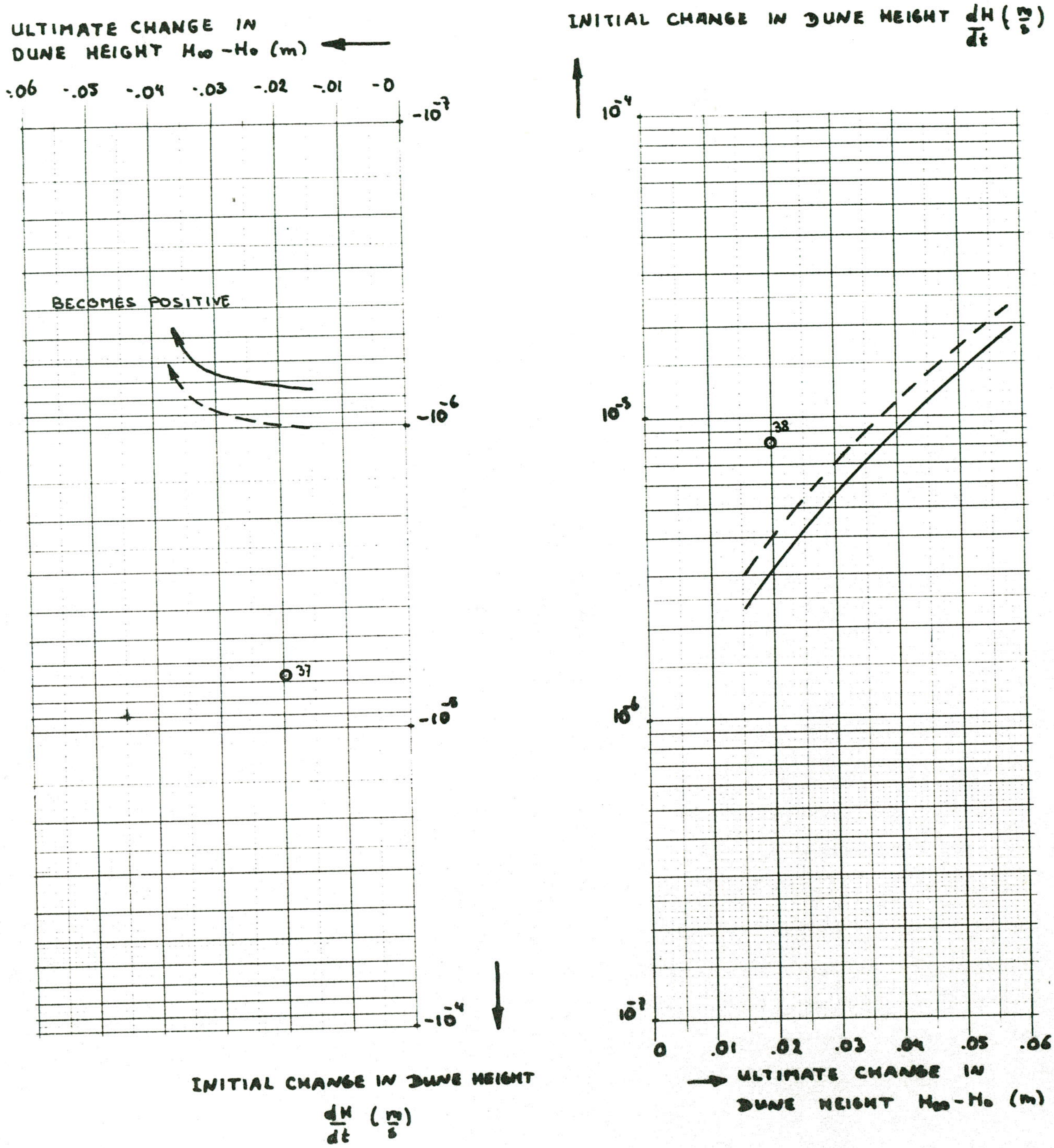
REVIEW OF TESTS IN FLUME WITH FLUME WIDTH 0.50 m

DELFT HYDRAULICS LABORATORY | R657/R1364 | FIG. 7





BEDFORM DIMENSIONS DURING EQUILIBRIUM FLOW CONDITIONS		
DELFT HYDRAULICS LABORATORY	R657/M1314	FIG. 8



FINAL HYDRAULIC RADIUS .10 M

INITIAL HYDRAULIC RADIUS .10 M

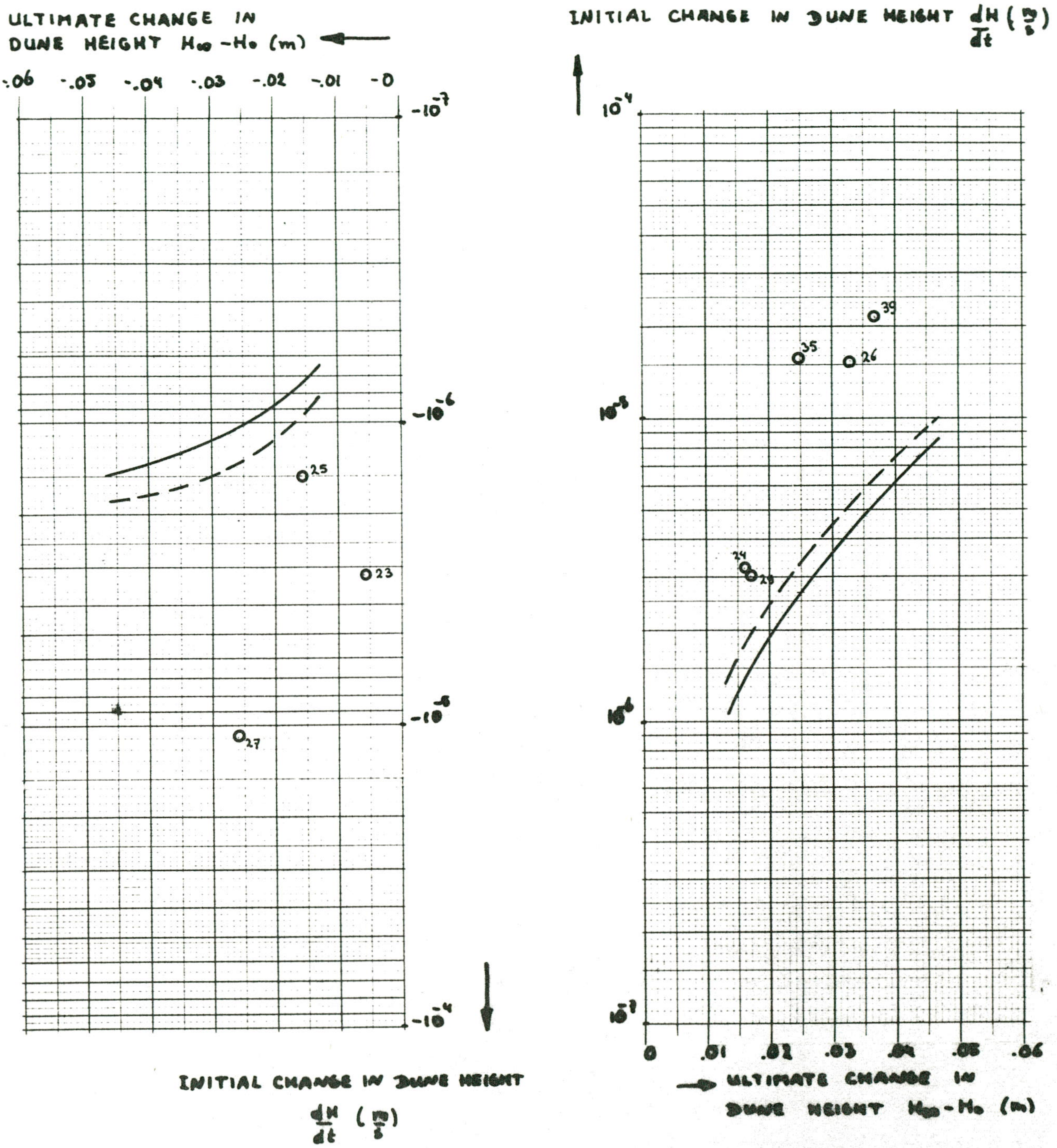
o	MEASURED	
———	PREDICTED WITH FREDSØE ; TRANSPORT FORMULA	ENGELUND & FREDSØE (1976)
– – –	" " " "	MEYER-PETER & MUELLER (1948)

INITIAL CHANGE IN DUNE HEIGHT VERSUS ULTIMATE CHANGE IN DUNE HEIGHT, INITIAL AND FINAL HYDRAULIC RADIUS OF 0.10 m.

DELFT HYDRAULICS LABORATORY

R657 / R1364

FIG. 9



FINAL HYDRAULIC RADIUS .20 M

INITIAL HYDRAULIC RADIUS .20 M

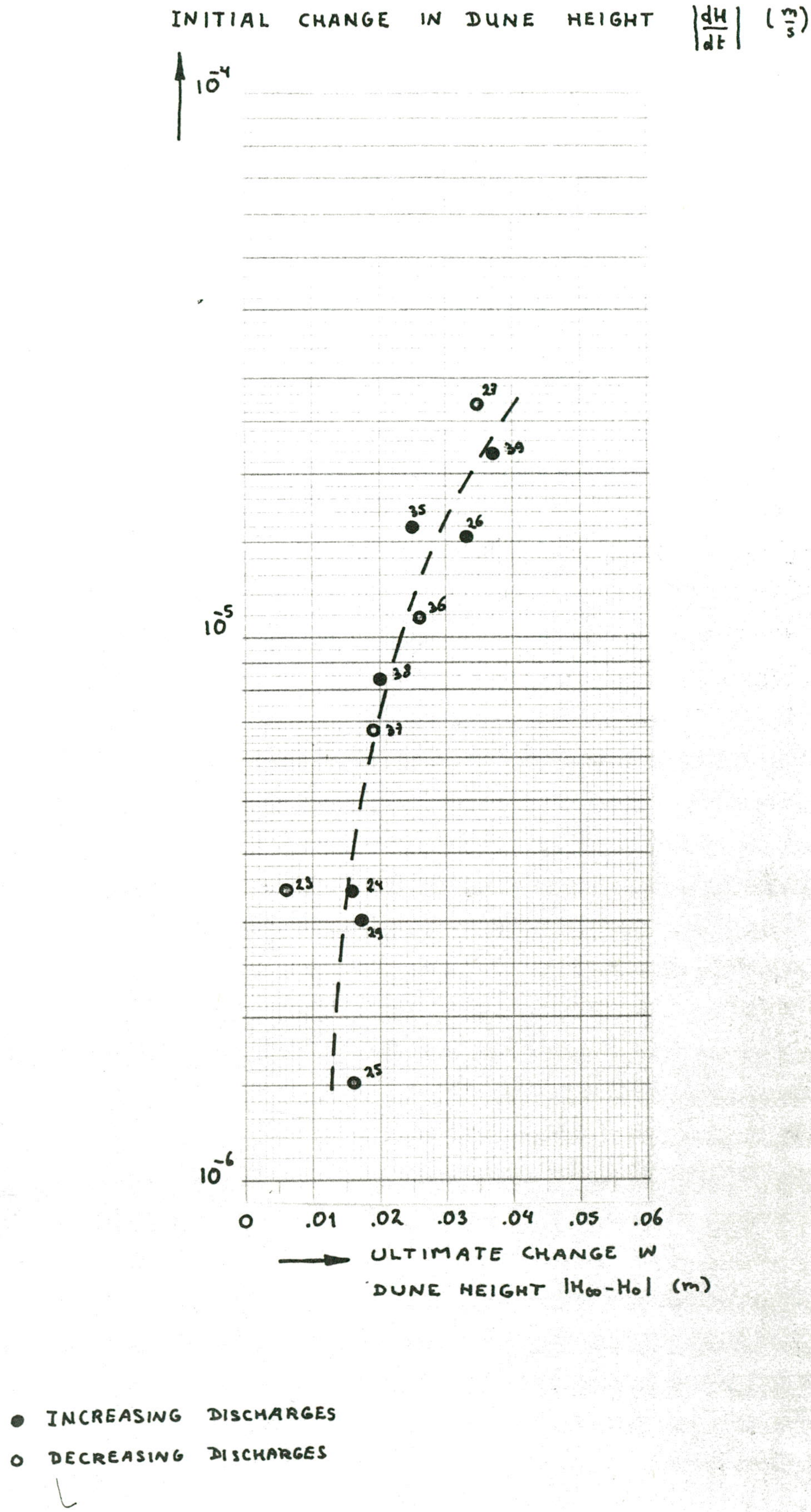
o MEASURED

——— PREDICTED WITH FREDSØE ; TRANSPORT FORMULA ENGELUND & FREDSØE (1976)

– – – " " " " MEYER-PETER & MUELLER (1948)

INITIAL CHANGE IN DUNE HEIGHT VERSUS ULTIMATE CHANGE IN DUNE HEIGHT, INITIAL AND FINAL HYDRAULIC RADIUS OF 0.20 m.

DELFT HYDRAULICS LABORATORY | R657 / R1364 | FIG. 10



INITIAL CHANGE IN DUNE HEIGHT $|dH/dt|$ VERSUS ULTIMATE CHANGE IN DUNE HEIGHT $|H_\infty - H_0|$ FOR ALL TESTS

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FIG. 11

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