waterloopkundig laboratorium
delft hydraulics laboratory

storm surge barrier Oosterschelde

computation of siltation in dredged trenches; semi – empirical model for the flow in dredged trenches

report on investigation

R 1267-III / M 1536

November 1980

storm surge barrier Oosterschelde

computation of siltation in dredged trenches; semi - empirical model for the flow in dredged trenches

report on investigation

R 1267-III / M 1536

November 1980

CONTENTS

CONTENTS (continuation)

APPENDIX

REFERENCES

TABLES

FIGURES

PHOTOGRAPHS

LIST OF SYMBOLS

a	ratio of boundary layer thickness and flow depth	(-)
B	bottom length of the trench	(L)
C	coefficient of Chézy	$(L^{\frac{1}{2}}T^{-1})$
D	particle diameter	(L)
d	trench depth	(L)
ΔE	energy loss in deceleration zone	(L)
Fr	Froude number	(-)
g	acceleration of gravity	(LT^{-2})
H	watersurface level above a datum	(L)
h	flow depth	(L)
i	watersurface slope	(-)
k	average height of roughness elements	(L)
k_s	equivalent roughness height of Nikuradse	(L)
L	length of the trench side	(L)
L_D	length of the deceleration zone	(L)
L_O	relaxation length of the outer layer in the relaxation zone	(L)
L_S	length of the separation zone	(L)
L_W	relaxation length of boundary layer in the relaxation zone	(L)
l	mixing length	(L)
m	ratio of flow velocity in the reversed flow layer and outer layer	(-)
n	exponent	(-)
p	static pressure	$(ML^{-1}T^{-2})$
Q	total discharge	(L^3T^{-1})
q	discharge per unit width	(L^2T^{-1})
R	hydraulic radius	(L)
Re	Reynolds number	(-)
T	time	(T)
TE	temperature	(^oC)
t	exponent	(-)
U	instantaneous longitudinal flow velocity	(LT^{-1})
u	mean longitudinal flow velocity	(LT^{-1})
u'	longitudinal flow velocity fluctuation	(LT^{-1})
$\bar{u}$	depth averaged flow velocity	(LT^{-1})
$\tilde{u}$	root-mean-square value of longitudinal flow velocity fluctuations	(LT^{-1})

LIST OF SYMBOLS (continuation)

u_r	maximum longitudinal flow velocity in reversed flow layer	(LT^{-1})
u_e	longitudinal flow velocity in the outer layer	(LT^{-1})
u_w	longitudinal flow velocity at z = 0.05 h above the bed	(LT^{-1})
u_{max}	maximum longitudinal flow velocity	(LT^{-1})
u_*	shear velocity	(LT^{-1})
W	instantaneous vertical flow velocity	(LT^{-1})
w	mean vertical flow velocity	(LT^{-1})
w'	vertical flow velocity fluctuation	(LT^{-1})
$\tilde{w}$	root-mean-square value of vertical flow velocity fluctuations	(LT^{-1})
V_1, V_2	instantaneous longitudinal flow velocity components under $\pm 45^o$	(LT^{-1})
x	longitudinal coordinate	(L)
y_o	zero-velocity level above under-side of the roughness elements	(L)
z	vertical coordinate	(L)
z_r	boundary level of reversed flow layer below water surface	(L)
γ	angle of side slope of trench	(-)
δ	thickness of upstream boundary layer	(L)
δ_r	thickness of reversed flow layer	(L)
δ_e	thickness of outer flow layer	(L)
δ_m	thickness of mixing layer	(L)
δ_w	thickness of boundary layer in the relaxation zone and the acceleration zone	(L)
ε_m	diffusion coefficient of momentum	(L^2T^{-1})
η	dimensionless vertical coordinate	(-)
Θ	time shift	(T)
κ	constant of Von Karman	(-)
Λ	integral time scale	(T)
ξ	energy loss coefficient	(-)
ρ	density of water	(ML^{-3})
τ	shear stress	$(ML^{-1}T^{-2})$
χ	empirical constant	(-)

Indices

A	upstream boundary of acceleration zone
B	downstream boundary of acceleration zone
b	bed

LIST OF SYMBOLS (continuation)

cr	critical
D	upstream boundary of deceleration zone
E	equilibrium value
o	upstream zone
R	downstream boundary of deceleration zone
S	upstream boundary of separation zone

STORM SURGE BARRIER OOSTERSCHELDE

Computation of siltation in dredged trenches

Semi-empirical model for the flow in dredged trenches

1. Introduction

The design of the storm surge barrier in the entrance of the Oosterschelde estuary consists of prefabricated (monolith) piers founded in a dredged trench.
An important objective is the estimation of the siltation of sediment particles in the trench for both the long and short term.
To estimate the siltation, a mathematical model based on the diffusion - convection equation for the suspended sediment particles was developed at the Delft Hydraulics Laboratory.
In the first version of the model the flow velocity was described by logarithmic velocity profiles, and the diffusion coefficient was described by a function based on equilibrium conditions. But as the vertical flow velocity was not taken into account, the model was only valid for gentle-sided trenches.

To extend the application of the model to steep-sided trenches, the Delft Hydraulics Laboratory was ordered by the Deltadienst of Rijkswaterstaat to improve the description of the flow field.
In the case of a steep-sided trench the flow velocity and turbulence field is very complex, particularly if flow separation occurs. A good method to obtain quantitative information is the application of a so-called "turbulence" model, but a major drawback of such a model is the large computer time, and hence the high costs, particularly for long-term computations.
Another method by which to compute the flow velocity field is the use of a semi-empirical model based on extensive laboratory measurements for varying trench geometries.
For this research the semi-empirical approach was followed, which means that the longitudinal flow velocity and the diffusion coefficient in each characteristic zone of the trench are described by semi-empirical relations.
The study was done in the Delft Hydraulics Laboratory by Mr. L.C. van Rijn, who also drew up this report.

2. Summary and conclusions

In this report a semi-empirical model for the flow in dredged trenches is described. Using this model the longitudinal and vertical flow velocities as well as the diffusion coefficient can be computed while in the case of steep-sided trenches flow separation and reversed flow velocities can also be described. In the longitudinal direction five zones are distinguished: an upstream zone, a deceleration zone, a relaxation zone, an acceleration zone, and a downstream zone (Figure 1). In each zone the vertical distribution of the longitudinal flow velocity is described by semi-empirical functions, while the empirical parameters were determined from extensive laboratory experiments for varying trench dimensions. The vertical flow velocity is determined from the continuity equation.

The general characteristics of the flow and turbulence field in a dredged trench are described in chapter 3, and the laboratory experiments used to determine the empirical parameters of the model are presented in chapter 4. Flow velocity measurements were made by means of a micro-propeller meter and a Laser Doppler velocity meter (Figures 3 and 4), with the last-mentioned also being used to determine the turbulence intensities and shear stresses. In some experiments also static pressure differences were determined, with the results being presented in Tables 1 ... 25 and Figures 5 ... 10. Evaluation of the turbulence measurements indicated that the shear stresses measured by means of the Laser Doppler velocity meter are still not very accurate, particularly for low (bed roughness related) Reynolds numbers (Figure 12).
The mathmatical formulation of the model and the determination of the empirical parameters, are presented in chapter 5.
The calibrated model was verified by means of laboratory tests and field data (chapter 6). As regards the field data, flow velocity measurements in two test pits in the Oosterschelde and Westerschelde estuaries were used. The measured and computed longitudinal flow velocities show good agreement (Figures 21 ... 28), but the computed vertical flow velocities are not in agreement with measured values, possibly due to three-dimensional effects in the experiments (Figure 11).
Finally, it can be concluded that the semi-empirical model used to predict the flow velocity field in a dredged trench, although based on sometimes rather crude assumptions, is quite useful for engineering purposes, while also the low computer costs are an important advantage.

3. General flow characteristics in a trench

A boundary layer, initially in equilibrium, will be perturbated by the presence of a dredged trench (perpendicular to the flow). In the case of a gentle-sided trench there will be no significant change in the turbulence structure, but with a steep-sided trench the boundary layer changes to a mixing or free shear layer with a significant change in the turbulence structure.
In a trench perpendicular to the flow three main zones can be distinguished (Figure 1):

- deceleration zone,
- relaxation zone, and
- acceleration zone.

Deceleration zone

Near the water surface an outer layer with an almost constant flow velocity can be observed. This layer can be considered as a continuation of the outer layer of the upstream boundary layer. The structure of the turbulence remains almost constant. Due to the absence of vertical velocity gradients, the flow can be considered as a potential flow in which the motion of the fluid particles is mainly governed by the Bernouilli Law. Of course, the outer layer is influenced by side effects of the flow deceleration and separation phenomena such as streamline curvature and the generation of an adverse pressure gradient (increasing pressure). In the case of flow separation, an inner layer with reversed flow will occur. The layer between the outer and inner layer is called the mixing or free shear layer, in which most of the kinetic energy of the mean flow velocity is transferred into pressure energy (pressure recovery) and turbulent energy.
The process which leads to separation is primarily determined by the development of an adverse pressure gradient (due to pressure recovery) and wall friction. The fluid particles near the wall, which are retarded by pressure and frictional forces, cannot penetrate too far in the region of increased pressure because of their relatively small kinetic energy. As a result the boundary flow will be separated and moved outwards from the wall. Near rough boundaries, where the frictional forces are relatively high, the process of separation will start earlier, resulting in a more upstream position of the separation point (s).

The fluid particles in the layer with reversed flow are strongly influenced by the adverse pressure gradient and are moved in a direction opposite to the main flow. The mean velocity of the fluid in the reversed flow layer is usually one order of magnitude smaller than that of the main flow.
The (separating) streamline below which reversed flow velocities occur, is by no means a stationary boundary. It exists only momentarily or as a time-mean condition. In this latter sense the separating streamline can be defined as the collection of locations where the time-mean longitudinal velocity is zero, or where the instantaneous velocities are directed forward or backward in 50% of the time. The phenomenon of flow separation is always associated with the formation of vortices and with relatively large energy losses. Due to the large vertical velocity gradients in the mixing layer, much higher levels of turbulent energy and shear stress exist than in an ordinary boundary layer flow. As large eddies contribute most to the shear stress production, the mixing layer is also a layer of relatively large-scale eddies.
Another important feature of the mixing layer is the large rate at which fluid is entrained from the reversed flow layer into the mixing layer.
The end of the deceleration zone is supposed to be located in the reattachment point (R) which can be defined in the same way as the separating streamline. Near the reattachment point a splitting process can be observed at which a part of the flow is deflected upstream into the layer with reversed flow to supply the entrainment of fluid to the mixing layer, while the other part of the flow moves in a downstream direction. Consequently, the velocities near the reattachment point will show large fluctuations in magnitude and may be positive or negative with respect to the main flow direction. The maximum shear stress located near the dividing streamline defined as the line above which the discharge remains constant, decreases rapidly to a value of zero at the reattachment point [4].

Relaxation zone

Downstream of the reattachment point the mixing layer will gradually disappear and a new equilibrium boundary layer will develop. To obtain equilibrium conditions, at which the turbulence-related statistical quantities do not change in a longitudinal direction, the flow velocities in the outer layer (near the water surface) must decrease, while the flow velocities in the inner layer (near the bed) must increase.

Experiments [4] show qualitatively that the inner layer near the wall responds much faster than the outer layer which is affected not only by local conditions but by a long course of events in its part (memory effects). Close to the wall the distribution of the mean flow velocity follows the logarithmic law. Based on experiments the relaxation length, defined as the length needed to develop a new equilibrium boundary layer, of the inner layer with a logarithmic velocity distribution is approximately 10 times the local flow depth [4]. Outside the inner layer the velocity profiles show a marked dip. Since the lifetimes of the eddies in the outer layer are longer than those of the small eddies in the inner layer, the relaxation length of the outer layer will also be longer. Experiments indicate a value of 40 to 50 times the local flow depth.
It is almost superfluous to state that the relaxation process is a strongly non-linear process, in which most of the relaxation phenomena occur in the early stages.
Bradshaw [4] gives the following qualitative features for the reattached boundary layer:

- an inner layer with a local energy equilibrium following the logarithmic law,
- a mixing layer in which the apparent mixing length scale increases relatively rapidly in a vertical direction, and
- an outer layer which retains the characteristics of the outer layer in the deceleration zone until the effects of the altered boundary condition at the wall propagate through it.

Acceleration zone

In this zone the flow is accelerated as a result of a negative pressure gradient (decreasing pressure), producing more uniform velocity profiles.
Pressure energy is transfered into kinetic energy for the mean flow, while the level of turbulent energy decreases over the entire layer.
Experimental results [5] indicate that the turbulence becomes much less isotropic in the layer close to the wall.

4. Flume experiments

4.1 Experimental set-up

To describe the flow in a trench, laboratory experiments have been carried out in a flume of the Delft Hydraulics Laboratory. The flume had a length of 17 m, a depth of 0.7 m, a width of 0.5 m and a maximum discharge of 0.25 m^3/s (Photo 1).

In the experiments the longitudinal and vertical flow velocities, the root-mean-square (r.m.s.) value of the turbulent flow velocity fluctuations, the turbulent shear stresses and the static pressure differences were measured at different locations in a trapezoidal trench (Photo 1).

The following parameters were varied:

- the upstream flow velocity (0.20 and 0.40 m/s)
- the upstream flow depth (0.10, 0.20 and 0.32 m)
- the width of the trench (1.8, 3.2 and 4.0 m)
- the side slopes (1:2, 1:3, 1:4, 1:6 and 1:8)
- the height of the roughness elements at the bed (0.006 and 0.011 m).

As bed roughness a layer of gravel was used. In all, two types of gravel were used, the size distributions being given in Figure 2. The average height (k) of the roughness elements on the bottom of the flume was determined by measuring at 50 (arbitrary) locations the height of the roughness elements with respect to the original flume bottom, which resulted in k = 0.006 m for the finer gravel and k = 0.011 m for the coarser gravel. The flow depth is defined as the distance from the water surface to the zero-velocity level, with the latter being assumed to be at 0.8 k above the under-side of the roughness elements [6] ; see also Figure a (page 7).

The dimensions of the trenches and the upstream hydraulic conditions are given in Table 1. Also additional parameters are reported. Side-wall effects have been taken into account according to the method of Vanoni - Brooks [11].

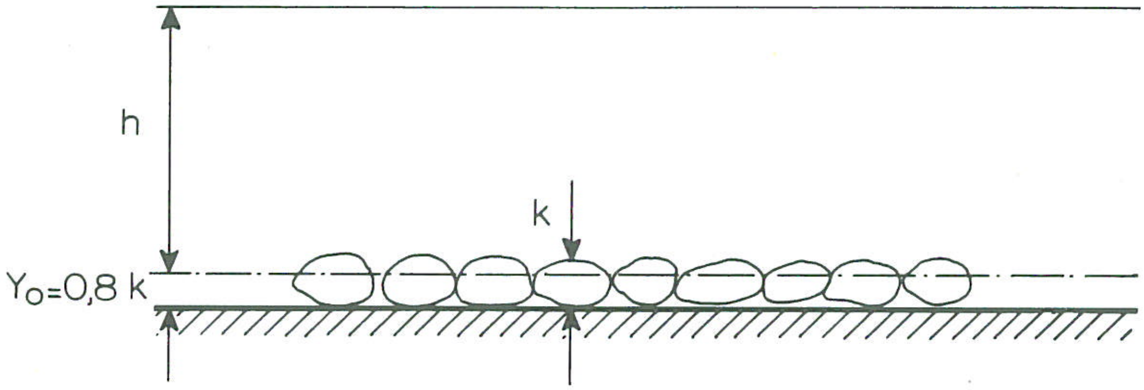


Figure a

4.2 Measuring equipment and accuracy

4.2.1 Discharge

The discharge of the flow was measured by means of an electro-magnetic discharge meter, the accuracy of which is 1% of the full scale, resulting in 0.0025 m^3/s.

4.2.2 Water surface slope

Upstream of the trench, the slope of the water surface was determined by measuring the fall of the water surface over a length of 5.0 m by means of pointer gauges in the centre line of the flume. During each test several measurements were made. The relative standard deviation was about 10%. The pointer gauges were also used to measure the flow depth.

4.2.3 Flow velocity

Flow velocities were measured by means of a Laser Doppler velocity meter (L.D.V.). For the largest flow depth, the vertical range of the L.D.V. was not sufficient to measure the flow velocities in the upper part of the flow, so for that part of the flow a micro-propeller meter was used. All measurements were made in the centre line of the flume. For each instrument the measuring time was 200 seconds. Simultaneous measurement of the longitudinal flow velocity in a fixed point with the micro-propeller meter and the L.D.V. showed values within 3% of each other.

Micro-propeller meter

The micro-propeller meter is a mechanical instrument (Photo 2). The number of revolutions of the propeller is a measure for the flow velocity.
The calibration depends on the friction in the bearings, the density and pollution of the water and the water temperature.

Laser Doppler Velocity meter [7]

The Laser Doppler method (Photos 1 and 3) is based on the difference between the frequency of the scattered light from very small particles (such as dust) passing the measuring volume and the frequency of the incident laser light. The value of this frequency shift or Doppler shift is proportional to the velocity of the particles in the measuring volume and the angle between the directions of the incident light and that of the scattered light. The only method to measure the relatively small frequency shifts at these high frequencies is the direct measurement of the Doppler shift, which is done by means of mixing on the surface of a photo detector of the scattered light from a certain direction with light from the same direction that has not undergone this shift (reference beam). Then, the output signal of the detector contains among others the Doppler frequency. Two reference beams and one incident beam are needed if both the longitudinal and vertical flow velocities must be determined (Figure 3). One strong (incident) beam and one weak (reference) beam are lying in a horizontal plane and the same strong beam with a second weak (reference) beam in a vertical plane. All beams are focussed by a lens (with a focal distance of 0.25 m) so that they will intersect at the same point.

To determine the absolute value and the direction of the flow velocity, the two beams of each of the two pairs must already have a frequency difference. This is done by giving each beam a different pre-shift frequency, using Bragg-cells (linear moving diffraction gratings). If the two beams of each pair have a frequency difference (pre-shift), there will be a frequency difference for zero velocity. For velocities in one direction this frequency difference will

increase, while for velocities in the other direction this frequency difference will decrease.
For the conversion of the Doppler Signals a two-channel frequency tracker with a range of 0.1 - 2 Mhz was used. Figure 4 shows the scheme of the signal converting equipment.
Due to the turbulent velocity fluctuations, the Doppler signal will show very rapid changes in frequency, and therefore the response time of the frequency tracker must be very small.
The frequency tracker improves the quality of the Doppler signal by generating a signal with a constant amplitude and a frequency (as much as possible) equal to the Doppler frequency. If the measuring volume contains no particles, the tracker generates a signal with the last observed frequency. Hence, a continuous output signal is obtained.
In the case of very turbulent flows with rapid frequency changes, the response time of the tracker may give rise to inaccuracies.

Important advantages of the L.D.V. are:
- no disturbance of the flow,
- small measuring volume,
- no calibration, and
- accurate determination of the instantaneous flow velocity.

To measure also at small distances above the bed, the longitudinal flow velocity (U) and the vertical flow velocity (W) must be measured indirectly by means of the components (V_1 and V_2) under $+45^o$ and -45^o, resulting in:

$$\begin{aligned} V_1 &= \tfrac{1}{2}\sqrt{2}\,U - \tfrac{1}{2}\sqrt{2}\,W \\ V_2 &= -\tfrac{1}{2}\sqrt{2}\,U - \tfrac{1}{2}\sqrt{2}\,W \end{aligned} \qquad (4.1)$$

By means of addition and subtraction the instantaneous value of the longitudinal (U) and the vertical (W) flow velocities can be obtained.
The time-averaged values (u and w) were determined by means of a (Solartron) time domain analyser. The root-mean -square values ($\tilde{u} = \sqrt{\overline{(u')^2}}$, $\tilde{w} = \sqrt{\overline{(w')^2}}$) of the turbulent velocity fluctuations (u' and w') were determined by means of a Disa r.m.s. meter with a frequency range of 0.1 Hz to 100 kHz. The measuring time was 120 seconds.

Accuracy of the Laser Doppler velocity meter

Errors in the measurement of the flow velocities may be caused by:

- inaccurate determination of the Doppler frequency by the electronic equipment, resulting in an error of the order of 0.001 m/s,
- inaccurate determination of the angle between the incident light beams, resulting in relative error of 0.5%, and
- misalignment of the three laser beams with respect to a horizontal datum so that the velocity components are not measured at $+45^{\circ}$ and -45° exactly.

Particularly, the latter may give rise to a relatively large error in the vertical flow velocity. For example, an error of only 0.5° in the orientation of the light beams introduces a mean vertical velocity (w) of about 1% of the mean longitudinal flow velocity (u). Consequently, an error of more than 20% will occur in the mean vertical flow velocity if this value is smaller than 5% of the mean longitudinal flow velocity.
Repeated measurements in a fixed point at 0.02 m above the underside of the roughness elements showed a relative standard deviation of 5% for the mean longitudinal flow velocity, and 20% for the mean vertical flow velocity.

4.2.4 Turbulent shear stress

The L.D.V. was also used to determine the spatial variation of the turbulent shear stress.
Basically, two methods can be applied to determine the turbulent shear stress: a one-phase method and a two-phase method (see Appendix B).
In these experiments the two-phase method was used. Assuming that the measured values of the instantaneous longitudinal and vertical flow velocities are accurate, the relative error in the turbulent shear stress can be estimated by (see Appendix B):

$$\frac{\sigma_\tau}{\tau} = \left(\frac{2\delta}{u_o T}\right)^{\frac{1}{2}}$$

which results in a relative error of about 10% for $\delta = h_o = 0.2$ m, $u_o = 0.4$ m/s and $T = 120$ s.

The relative systematic error can be estimated by (see Appendix B):

$$\frac{B(\tau)}{\tau} = \frac{\delta}{u_o T}$$

which results in a value of about 0.5%.

In practice these errors may be significantly higher because the measurement of the instantaneous vertical flow velocity is not always very accurate (see paragraph 4.2.3).

4.2.5 Static pressure differences

In the deceleration and relaxation zones of the trench the static pressure difference with respect to the upstream flow conditions was measured. In each profile 4 measurements at different heights above the bed were made, all in the centre line of the flume. The pressure differences were measured by a pressure difference meter graduated to read to 0.0001 m. of water column. The pressure difference meter was connected to two Pitot-tubes (Photo 3).
The measurement of the mean static pressure in a turbulent flow by means of Pitot-tubes is not a simple matter because the mean pressure in the static holes of the tube is affected by turbulent velocity fluctuations normal to the tube. Generally, the static pressure will be measured too low [9].

4.3 Experimental results

4.3.1 Upstream flow conditions

The flow conditions upstream of the trench are specified in Table 1.
For the average flow velocity the ratio of the discharge and the cross-sectional area is given. Generally, this value is somewhat smaller than the depth-averaged flow velocity in the centre line of the flume.
For the upstream flow conditions also the following additional parameters were determined (Table 1):

- hydraulic radius related to the bed according to Vanoni-Brooks [11],
- coefficient of Chézy related to the bed (C_b),

- shear velocity related to the bed ($u_{*,b}$), and
- equivalent roughness height of the gravel grains ($k_{s,b}$).

4.3.2 Flow conditions in the trench

For the various trench geometries the following variables were measured:

- longitudinal and vertical flow velocities,
- r.m.s. value of the longitudinal and vertical turbulent flow velocity fluctuations,
- shear stresses,
- static pressure differences.

The flow and turbulence measurements are presented in Tables 3 ... 18, and the static pressure differences in Tables 20 ... 25.

Test T1

The flow and turbulence conditions in Profiles 1 ... 8 were determined by means of the L.D.V., while in Profiles 9 ... 11 the longitudinal flow velocity was measured by the micro-propeller meter.
Photographs 4 ... 8 show a visualization of the mixing and reversed flow layer.

Tests T2, T3, T5, T6, T7, T8, T13

All measurements were made by means of the L.D.V.

Tests T4, T9, T14

The longitudinal flow velocity in the upper part of the flow was measured by means of the micro-propeller meter because the vertical range of the L.D.V. was not large enough.

Tests T10, T11, T15, T16

The micro-propeller meter was used to measure the longitudinal flow velocity and turbulence intensity. The longitudinal flow velocity in the zone with reversed flow was determined in two phases: during the first phase the mean forward flow velocity was determined, while during the second phase the mean backward flow velocity was measured. The resulting mean flow velocity was obtained by subtraction.

The most important features are:

- a pronounced separation zone for the steep-sided trenches,
- relatively small vertical (downward) flow velocities in the deceleration zone,
- relatively large vertical (upward) flow velocities in the layer with reversed flow,
- relatively large shear stresses near the dividing streamline,
- relatively small changes in the turbulence intensities in a longitudinal direction,
- slow decay of the maximum shear stress in a longitudinal direction,
- relatively large vertical (upward) flow velocities in the near-bed layer of the acceleration zone (downstream slope),
- nearly uniform longitudinal flow velocities at the downstream end of the trench,
- very low shear stresses in the near-bed layer of the acceleration zone, and
- increasing static pressure differences in the deceleration zone and decreasing values in the acceleration zone.

4.3.3 Three-dimensional effects

In the tests T1 ... T16 all measurements were made in the centre line of the flume. Determination of the discharge per unit width in the centre line showed that continuity was not preserved. Particularly, the experiments with a trench depth larger than the upstream flow depth showed deviations, of upto 25%, indicating serious three-dimensional effects.
To examine these effects, the lateral distribution of the longitudinal mean flow velocity in the test with the vertical-sided trench (T1) was also measured, and the results presented in Figure 11. At the upstream boundary the lateral distribution of the flow velocity is nearly uniform, only close to the side-wall are the flow velocities significantly lower (profile A). In cross-section 2 the highest flow velocities in the separation zone can be observed in the centre line of the flume, while towards the side-walls the reversed flow velocities decrease due to frictional forces. Close to the side-walls the separation zone is hardly present. In the middle part of profile B the flow velocities are significantly higher than in the centre line of the flume, which can also be observed in cross-section 3.

4.3.4 Evaluation of the turbulence measurements

To evaluate the accuracy of the turbulence measurements, the turbulence intensities measured in equilibrium conditions (upstream of the trench) were compared with measurements reported in literature. The vertical distribution of the measured shear stresses was compared with the theoretical linear distribution based on the measured water surface gradient. The results are presented in Figure 12. The turbulence intensities are scaled with the shear velocity related to the bed.

The agreement with measurements of Blinco [3] and Grass [8] is reasonably good except for the measurements near the bed. The measurements of Blinco were done by means of a hot wire anemometer, while Grass made use of bubble and photo techniques.

The shear stresses are scaled with the bed shear stress based on the water surface gradient. The agreement with the theoretical linear distribution seems to depend on the Reynolds number related to the shear velocity ($u_{*,b}$) and equivalent roughness height ($k_{s,b}$), which is a measure for the state of the turbulence near the wall. For high Reynolds numbers (T5 ... T14) the agreement is much better than for low Reynolds numbers.

From these results it can be concluded that the shear stresses were not determined very accurately, particularly for low (roughness related) Reynolds numbers. The cause of this is not yet understood.

5. Mathematical description of the flow in a trench

5.1 Definitions

To describe the flow in dredged trenches, a semi-empirical model has been developed, with the empirical parameters being evaluated from flume experiments. The model is only valid for a simple trapezoidal geometry.
In the longitudinal direction five zones are defined (Figure 1):

Upstream zone

As long as the local slope (γ) of the bed is not steeper than 1:20, or

$$\cot \gamma > 20 \qquad (5.1)$$

an equilibrium flow with a logarithmic velocity profile is supposed to be valid.

Deceleration zone

The deceleration zone starts at the downstream end (D) of the upstream zone (Figure 1). The downstream boundary of the deceleration zone is defined in the deepest point of the trench. In the case of flow separation a layer with reversed flow will occur. The separation point (s) is defined as the point where the local slope of the bed exceeds a critical value ($\cot \gamma > \cot \gamma_{cr}$). In that case the downstream boundary of the deceleration zone is assumed to be in the reattachment point (R) which is defined as the intersection point of the bed profile and a line with an angle equal to γ_{cr} through the separation point (Figure 13).

From the flume experiments the critical slope (γ_{cr}) was found to depend on the flow depth (in the separation point) (h_s) and the trench depth (d). The results can be represented by (Figure 14):

$$\cot \gamma_{cr} = -1.38 \left(\frac{h_s}{d}\right)^2 + 1.07 \left(\frac{h_s}{d}\right) + 7.81, \text{ for } 0.5 < \frac{h_s}{d} < 1.6 \qquad (5.2)$$

Outside the experimental range the following relations were assumed:

$$\cot\gamma_{cr} = 8 \quad \text{for} \quad \frac{h_s}{d} \leqslant 0.5$$

$$\cot\gamma_{cr} = 6 \quad \text{for} \quad \frac{h_s}{d} \geqslant 1.6 \qquad (5.3)$$

Relaxation zone

The relaxation zone follows after the deceleration zone. The downstream boundary of the relaxation zone is assumed to be in the point (A) where

$$\cot\gamma < 20 \qquad (5.4)$$

Acceleration zone

The acceleration zone follows after the relaxation zone. The downstream boundary is assumed to be in the point (B) where

$$\cot\gamma > 20 \qquad (5.5)$$

Downstream zone

The acceleration zone is followed by the downstream zone, where the flow is supposed to be an equilibrium flow with a logarithmic velocity distribution.

5.2 Longitudinal flow velocity

5.2.1 Upstream zone

In the vertical direction two layers are distinguished:

- a boundary layer (δ) with a logarithmic velocity profile and
- an outer layer (δ_e) with a uniform flow velocity.

Boundary layer

The thickness (δ) of the boundary layer is defined as (Figure 13):

$$\delta = a\,(h - y_o) \qquad (5.6)$$

in which:

h	=	flow depth	(m)
y_o	=	zero velocity level above the bed	(m)
a	=	ratio of boundary layer thickness and the flow depth	

From experimental results the a-value was found to vary from 0.7 - 0.9, with the average value being approximately 0.8.

The flow velocity is represented by:

$$\frac{u_z}{u_*} = \frac{u_e}{u_*} + \frac{1}{\kappa} \ln \left(\frac{h - z}{\delta}\right) \qquad (5.7)$$

in which:

u_z	=	flow velocity at a distance z from the water surface	(m/s)
u_e	=	flow velocity in the outer layer	(m/s)
u_*	=	$\frac{\bar{u}\,(g)^{0.5}}{C}$ = shear velocity	(m/s)
g	=	acceleration of gravity	(m/s^2)
$\bar{u}$	=	depth-averaged flow velocity	(m/s)
C	=	$18 \log \left(\frac{12R_b}{k_s}\right)$ = coefficient of Chézy	($m^{\frac{1}{2}}/s$)
R_b	=	hydraulic radius related to the bed	(m)
k_s	=	equivalent roughness of Nikuradse	(m)
κ	=	constant of Von Karman	(-)
h	=	flow depth	(m)

Outer layer

The thickness (δ_e) of the outer layer is:

$$\delta_e = h - \delta \qquad (5.8)$$

The (constant) flow velocity (u_e) is determined by means of the continuity equation:

$$q = \int_{o}^{h-y_o} u_z dz = u_e (h - \delta) + \int_{h-\delta}^{h-y_o} \{u_e + \frac{u_*}{\kappa} \ln (\frac{h - z}{\delta})\} dz \qquad (5.9)$$

resulting in ($y_o << \delta, h$):

$$q = u_e h - \frac{u_* \delta}{\kappa} , \text{ or} \qquad (5.10)$$

$$u_e = \frac{q}{h} + \frac{u_* \delta}{\kappa h} = \bar{u} + a \frac{u_*}{\kappa} \qquad (5.11)$$

in which:

q = discharge per unit width (m^2/s)

5.2.2 Deceleration zone with flow separation

Zone preceding flow separation

In the vertical direction two layers are distinguished (Figure 13):
- a boundary layer and
- an outer layer.

Outer layer

The thickness (δ_e) of the outer layer is constant and defined as:

$$\delta_e = h_D - \delta_D = h_D(1-a) \qquad (5.12)$$

in which:

h_D = flow depth at the upstream boundary (D) of the deceleration zone (m)

δ_D = a h_D = thickness of the boundary layer at the upstream boundary (D) of the deceleration zone (m)

The flow in the outer layer is described by:

$$u_e \frac{\delta u_e}{\delta x} + \frac{1}{\rho} \frac{\delta p}{\delta x} = 0 \qquad (5.13)$$

in which:

u_e = flow velocity in the outer layer (m/s)
ρ = density of water (kg/m^3)
p = static pressure (N/m^2)

In the deceleration zone kinetic energy of the mean flow is transferred to turbulent kinetic energy and pressure energy. As a result of pressure recovery, the water surface level will increase.
From equation (5.13) the following expression can be derived (Figure 15):

$$u^2_{e,x} = u^2_{e,D} - 2g\, \Delta H_x \qquad (5.14)$$

in which:

$u_{e,x}$ = flow velocity in the outer layer at distance x from the upstream boundary (D) (m/s)
$u_{e,D}$ = flow velocity in the outer layer at the upstream boundary (D) (m/s)
ΔH_x = $H_x - H_D$ = increase of water surface level at distance x (m)

The increase of the water surface level (ΔH_x), which was not measured, in equation (5.14) is supposed to be linear:

$$\Delta H_x = \left(\frac{x - x_D}{L_D}\right) \Delta H \qquad (5.15)$$

in which:

L_D = length of the deceleration zone (m)
ΔH = $H_R - H_D$ = total increase of the water surface level (m)
H_R = water surface level above a datum at the downstream boundary (m)
H_D = water surface level above a datum at the upstream boundary (m)

From the energy balance the following expression for the total increase (ΔH) of the water surface level can be derived (see Appendix A):

$$\Delta H = \frac{(1 - \xi)}{2g} q^2 \left(\frac{1}{{h_D}^2} - \frac{1}{{h_R}^2}\right) \qquad (5.16)$$

in which:

ξ = energy loss coefficient (-)

q = discharge per unit width (m^2/s)

h_d = flow depth at the upstream boundary (m)

h_r = flow depth at the downstream boundary (m)

Substitution of (5.15) and (5.16) into equation (5.14) results in:

$$u_{e,x}^2 = u_{e,d}^2 - (1 - \xi)\, q^2 \frac{(x - x_D)}{L_D} \left(\frac{1}{h_D^{\,2}} - \frac{1}{h_R^{\,2}}\right) \tag{5.17}$$

Using equation (5.17) and measured flow velocities, the energy loss coefficient ξ was determined as (see also Table 2):

$$\xi = 1 - \frac{u_{e,D}^2 - u_{e,R}^2}{\bar{u}_D^{\,2} - \bar{u}_R^{\,2}} \tag{5.18}$$

in which:

$u_{e,D}$ = flow velocity in the outer layer at the upstream boundary of the deceleration zone (m/s)

$u_{e,R}$ = flow velocity in the outer layer at the downstream boundary of the deceleration zone (m/s)

$\bar{u}_D$ = depth-averaged flow velocity at the upstream boundary of the deceleration zone (m/s)

$\bar{u}_R$ = depth-averaged flow velocity at the downstream boundary of the deceleration zone (m/s)

The experiments indicate that the energy loss coefficient (ξ) depends on the steepness of the side slope of the trench. For a slope of 1:8 (T16) the ξ-value was about 0.1, while a slope of 1:2 (T3 ... T9) resulted in values of about 0.4. The experiments in which serious three-dimensional effects appeared (T2, T5 and T12) were not used.

For reasons of simplicity an average ξ-value of 0.35 is used in the model.

Boundary layer

The thickness (δ) of the boundary layer is:

$$\delta = h - \delta_e \tag{5.19}$$

in which:

h	=	flow depth	(m)
δ_e	=	thickness of the outer layer according to equation (5.12)	(m)

The flow velocity is represented by [1]:

$$\frac{u_e - u_z}{u_e} = (1 - \eta^t)^2 \tag{5.20}$$

in which:

u_e	=	flow velocity in the outer layer	(m/s)
u_z	=	flow velocity at distance z from the water surface	(m/s)

$$\eta = \frac{\delta - (z - \delta_e)}{\delta} \qquad (-)$$

The t-exponent in equation (5.20) follows from:

$$q = \int_o^h u_z \, dz = \text{constant} \tag{5.21}$$

resulting in:

$$q = u_e (\delta_e + \delta) - u_e \delta \left(\frac{2t^2}{2t^2 + 3t + 1}\right) = \text{constant} \tag{5.22}$$

Zone with flow separation

In the vertical direction three layers are distinguished (Figure 13):

- a reversed flow layer

- a mixing layer and
- an outer layer

Reversed flow layer

The upper boundary of this layer is defined as the line of the maximum reversed flow velocity and is represented by a power function (Figure 13):

$$z_r = h_S + (h_R - h_S) \left[1 - \left\{ \frac{L_S - (x - x_S)}{L_S} \right\}^n \right] \tag{5.23}$$

in which:

z_r = distance of the line of maximum reversed flow velocity below the water surface (m)
h_S = flow depth at the separation point (m)
h_R = flow depth at the reattachment point (m)
L_S = $x_R - x_S$ = length of the separation zone (m)

The thickness (δ_r) of the reversed flow layer is:

$$\delta_r = (h - h_S) - (h_R - h_S) \left[1 - \left\{ \frac{L_s - (x - x_S)}{L_S} \right\}^n \right] \tag{5.24}$$

From the flume experiments the n-exponent was determined to be 2.5 (Figure 16).

The flow velocity in the layer with reversed flow is represented by:

$$\frac{u_z}{u_r} = \left(\frac{h - z}{h - z_r} \right)^{1/7} \tag{5.25}$$

in which:

u_r = m u_e = maximum flow velocity in the reversed flow layer (m/s)
m = ratio of the maximum flow velocity in the reversed flow layer and the outer layer
h = local flow depth (m/s)

The ratio (m) of the flow velocity in the reversed flow layer and the outer layer is supposed to be a (parabolic) function of longitudinal distance:

$$m = 4\,\hat{m}\left[\left\{\frac{L_S - (x - x_S)}{L_S}\right\}\right]\left[1 - \left\{\frac{L_S - (x - x_S)}{L_S}\right\}\right] \tag{5.26}$$

The flume experiments indicate that the maximum value ($\hat{m}$) depends on the steepness of the side slope (Figure 17). The experimental results are represented by:

$$\hat{m} = -0.2 \quad , \text{ for } \cot\hat{\gamma} \leq 2$$

$$\hat{m} = -0.0017\,(\cot\hat{\gamma})^2 + 0.05\,(\cot\gamma) - 0.29, \text{ for } 2 < \cot\hat{\gamma} < 8 \tag{5.27}$$

$$\hat{m} = 0 \quad , \text{ for } \cot\hat{\gamma} \geq 8$$

in which:
$\hat{\gamma}$ = maximum value of the local bed gradients

Outer layer

The thickness of the outer layer (δ_e) is described by equation (5.12), and the velocity (u_e) by equation (5.17).

Mixing layer

The thickness of the mixing layer is:

$$\delta_m = z_r - \delta_e = (h_S - \delta_e) + (h_R - h_S)\left[1 - \left\{\frac{L_S - (x - x_S)}{L_S}\right\}^n\right] \tag{5.28}$$

The flow velocity is represented by:

$$\frac{u_e - u_z}{u_e - u_r} = (1 - \eta^t)^2 \tag{5.29}$$

in which:

u_e = flow velocity in the outer layer (m/s)

u_r = flow velocity in the reversed flow layer (m/s)

$$\eta = \frac{\delta_m - (z - \delta_e)}{\delta_m} \qquad (-)$$

The t-exponent in equation (5.29) follows from:

$$q = \int_0^h u_z \, dz = \text{constant} \qquad (5.30)$$

resulting in:

$$q = u_e (\delta_e + \delta_m) - (u_e - u_r) \delta_m \left(\frac{2t^2}{2t^2 + 3t + 1}\right) + \frac{7}{8} u_r \delta_r = \text{constant} \qquad (5.31)$$

5.2.3 Deceleration zone without flow separation

When no flow separation occurs (paragraph 5.1) in the deceleration zone two layers are distinguished in vertical direction:

- a boundary layer and
- an outer layer.

Boundary layer

The thickness of this layer (δ) is described by equation (5.19), and the flow velocity (u_z) by equation (5.20).

Outer layer

The thickness of this layer (δ_e) is described by equation (5.12). The flow velocity (u_e) is described by:

$$\frac{u_{e,x} - u^B_{e,x}}{u^{log}_{e,x} - u^B_{e,x}} = \frac{\text{cotan}\ \hat{\gamma} - \text{cotan}\ \gamma_{cr}}{20 - \text{cotan}\ \gamma_{cr}} \qquad (5.32)$$

in which:

$u_{e,x}$ = flow velocity in the outer layer (m/s)

$u^B_{e,x}$ = flow velocity in the outer layer after the Bernoulli equation (5.17) (m/s)

$u^{log}_{e,x} = \frac{u_*}{\kappa} \ln \{\frac{30\,(h - \delta_e)}{k_s}\}$ = flow velocity in the outer layer according to the logarithmic velocity distribution (m/s)

$\hat{\gamma}$ = maximum value of local bed gradients

Equation (5.32) ensures that for a side slope of 1:20 the flow velocity in the outer layer is represented by the value for equilibrium flow. For a slope equal to γ_{cR} the Bernoulli equation (5.17) is applied, while for intermediate values a linear interpolation is made.

In case the side slope of the deceleration zone is flatter than 1:20, the flow velocity is described by a logarithmic function:

$$u_z = \frac{u_*}{\kappa} \ln \{\frac{30\,(h - z)}{k_s}\} \qquad (5.33)$$

5.2.4 Relaxation zone

In the vertical direction three layers are distinguished:
- a boundary layer,
- a mixing layer, and
- an outer layer.

Boundary layer

The thickness (δ_w) of the boundary layer is assumed to be:

$$\delta_w = 0.05\ h \qquad (5.34)$$

The flow velocity is represented by:

$$u_z = \frac{u_*}{\kappa} \ln \left\{ \frac{30\ (h - z)}{k_s} \right\} \qquad (5.35)$$

The shear velocity in equation (5.35) is described by a relaxation function based on experiment T1, which was done to study the relaxation of perturbated flow velocity profiles into equilibrium profiles (Figures 5 and 18):

$$\frac{u_{*,x} - u_{*,R}}{u_{*,E} - u_{*,R}} = \left(\frac{x - x_R}{L_w}\right)^{0.5} \qquad (5.36)$$

in which:

$u_{*,R}$ = $\dfrac{k\ u_{(z=0.95\ h_R)}}{\ln \left\{ \dfrac{30\ (0.05\ h_R)}{k_s} \right\}}$ = shear velocity at the downstream boundary (R) of the deceleration zone (m/s)

$u_{(z=0.95\ h_R)}$ = flow velocity at $z = 0.95\ h_R$ below the water surface at the downstream boundary of the deceleration zone according to equation (5.20) or (5.29) (m/s)

$u_{*,E}$ = $\dfrac{g^{\frac{1}{2}}\ \bar{u}}{C}$ = equilibrium shear velocity in the relaxation zone (m/s)

$\bar{u}$ = depth-averaged flow velocity in the relaxation zone (m/s)

L_w = $10\ h_R$ = relaxation length of the boundary layer (m)

The equilibrium shear velocity ($u_{*,E}$) is determined from the flow conditions (h, $\bar{u}$ and C) at the downstream boundary of the deceleration zone, which is either the reattachment point (flow separation) or the deepest point of the trench (no flow separation). The relaxation length of the boundary layer is supposed to be equal to 10 times the flow depth in point R (chapter 3).

Outer layer

The thickness of the outer layer (δ_e) is described by equation (5.12). The flow velocity is described by a relaxation function derived from experiment T1 (Figures 5 and 18):

$$\frac{u_{e,R} - u_{e,x}}{u_{e,R} - u_{e,E}} = \tanh \; 7.2 \left(\frac{x - x_R}{L_0}\right) \qquad (5.37)$$

in which:

$u_{e,x}$ = flow velocity in the outer layer (m/s)

$u_{e,E}$ = equilibrium flow velocity in the outer layer according to equation (5.11) (m/s)

$u_{e,R}$ = flow velocity in the outer layer at the downstream boundary (R) of the deceleration zone (m/s)

L_0 = 40 h_R = relaxation length of the outer layer (m)

The equilibrium flow velocity in the outer layer is determined from the flow conditions (h, $\bar{u}$ and C) at the downstream boundary of the deceleration zone. The relaxation length of the outer layer is supposed to be equal to 40 times the flow depth in point R (Chapter 3).

Mixing layer

The thickness of the mixing layer is:

$$\delta_m = 0.95\, h - \delta_e \qquad (5.38)$$

The flow velocity is described by:

$$\frac{u_e - u_z}{u_e - u_w} = (1 - \eta^t)^2 \qquad (5.39)$$

in which:

u_w = flow velocity at z = 0.95 h below the water surface according to equation (5.35) (m/s)

$\eta = \dfrac{\delta_m - (z - \delta_e)}{\delta_m}$ (-)

The t-exponent in equation (5.39) follows from:

$$q = \int_0^{h - y_o} u_z \, dz = \text{constant} \qquad (5.40)$$

resulting in ($y_o << h$):

$$q = u_e (\delta_e + \delta_m) - (u_e - u_w) \delta_m \left(\frac{2t^2}{2t^2 + 3t + 1}\right) + \frac{u_* \delta_w}{\kappa} \{\ln \left(\frac{\delta_w}{y_o}\right) - 1\} \tag{5.41}$$

In a narrow trench with steep side slopes (flow separation), the reattachment point may be located at the downstream slope of the trench. In that case the separation zone is directly followed by the acceleration zone.

5.2.5 Acceleration zone

In the vertical direction three layers are distinguished:

- a boundary layer,
- an intermediate layer, and
- an outer layer.

Boundary layer

The thickness of the boundary layer is supposed to be:

$$\delta_w = 0.05\ h \tag{5.42}$$

The flow velocity is described by:

$$u_z = \frac{u_*}{\kappa} \ln \left\{\frac{30\ (h - z)}{k_s}\right\} \tag{5.43}$$

The shear velocity in equation (5.43) is described by an exponential function, the exponent being determined from measured flow velocities at the downstream side slope, resulting in (Figure 19):

$$\frac{u_{*,x} - u_{*,A}}{u_{*,B} - u_{*,A}} = \left(\frac{x - x_A}{x_B - x_A}\right)^{1.5} \tag{5.44}$$

in which:

$u_{*,A}$ = shear velocity at the upstream boundary of the acceleration zone according to equation (5.36) (m/s)

$u_{*,B}$ = $\dfrac{g^{\frac{1}{2}}\,\bar{u}_B}{C_B}$ = shear velocity at the downstream boundary of the acceleration zone (equilibrium value) (m/s)

Outer layer

The thickness of the outer layer (δ_e) is described by equation (5.12).

The flow velocity (u_e) is described by an exponential function, with the exponent being determined from measured flow velocities at the downstream side slope (Figure 19):

$$\frac{u_{e,x} - u_{e,A}}{u_{e,B} - u_{e,A}} \quad \left(\frac{x - x_A}{x_B - x_A}\right)^2 \tag{5.45}$$

in which:

$u_{e,A}$ = flow velocity at the upstream boundary at the acceleration zone according to equation (5.37) (m/s)

$u_{e,B}$ = flow velocity at the downstream boundary of the acceleration zone according to equation (5.11) (m/s)

Intermediate layer

The thickness of this layer is described by equation (5.38).

The flow velocity is represented by equation (5.39).

5.2.6 Downstream zone

In the vertical direction two layers are distinguished:

- a boundary layer and
- an outer layer with a constant flow velocity.

Outer layer

The thickness of the outer layer is described by equation (5.12). For reasons of simplicity the flow velocity is represented by equation (5.11).

Boundary layer

Also for simplification the flow velocity is represented by equation (5.7), but it must be realized that this equation cannot represent the nearly uniform flow velocity profiles which were measured directly downstream of the trench.

5.3 Vertical flow velocity

The vertical flow velocity is determined from the equation of continuity:

$$\frac{\delta u}{\delta x} + \frac{\delta w}{\delta z} = 0 \qquad (5.46)$$

in which:

u = longitudinal flow velocity (m/s)

w = vertical flow velocity (m/s)

Boundary conditions

The water surface slope is supposed to be negligibly small, resulting in:

$$w = 0 \quad \text{at} \quad z = 0 \qquad (5.47)$$

By means of integration it can be shown that

$$w = 0 \quad \text{at} \quad z = h - y_o \quad (u = 0) \qquad (5.48)$$

It must be stressed that at the boundaries of the (longitudinal) zones, discontinuities in the longitudinal flow velocity can occur, which may lead to unrealistic vertical flow velocities.

5.4 Diffusion coefficient in the separation zone

In equilibrium flow the diffusion coefficient for momentum (ε_m) is defined as:

$$\varepsilon_m = \frac{\tau}{\rho \frac{\delta u}{\delta z}} = \frac{\overline{u'w'}}{\frac{\delta u}{\delta z}} \tag{5.49}$$

in which:

τ	=	turbulent shear stress	(N/m^2)
ρ	=	density of water	(kg/m^3)
u'	=	longitudinal velocity fluctuation	(m/s)
w'	=	vertical velocity fluctuation	(m/s)

In the classical theories for mixing layers the diffusion coefficient is supposed to be constant in the vertical direction and is represented [10]:

$$\varepsilon_m = \chi\, \delta_m\, (u_e - u_b) \tag{5.50}$$

in which

χ	=	empirical factor	(-)
δ_m	=	thickness of the mixing layer	(m)
u_e	=	flow velocity at the upper boundary	(m/s)
u_b	=	flow velocity at the lower boundary	(m/s)

For free turbulent flows equation (5.50) has been used succesfully [10]. Some χ-values are:

Jet flow along a boundary: $\chi \approx 0.015$

Free circular jet : $\chi \approx 0.011$ à 0.016

If it is supposed that equation (5.49) is also valid for non-uniform conditions, the χ-value can be determined as:

$$\chi = \frac{\overline{u'w'}}{\delta_m (u_e - u_b) \frac{\delta u}{\delta z}} \tag{5.51}$$

The flow velocity and shear stress measurements in the trenches were used to determine the χ-value. Only experiments with a (bed roughness-related) Reynolds' number (upstream conditions) larger than 100 were used, because the measured shear stresses in the other experiments were considered to be too inaccurate. The flow velocity gradient was estimated by:

$$\frac{\Delta u}{\Delta z} = \frac{1}{2} \left(\frac{u_{i+1} - u_i}{z_{i+1} - z_i} + \frac{u_i - u_{i-1}}{z_i - z_{i-1}}\right) \tag{5.52}$$

Figure 20 shows the χ-values as a function of longitudinal distance. As can be observed, all χ-values in vertical direction are within 50% of the average vertical value.
In contrast to the classical theories for mixing layers, the χ-value is not constant in the longitudinal direction. Probably equation (5.49), which relates the diffusion coefficient to local flow conditions only, is not valid for non-uniform conditions where memory-effects are of essential importance.
The application of the linear relationship, as given in Figure 20, results for $x/d < 1$ à 2 in diffusion coefficients which are smaller than the upstream diffusion coefficient, which seems unrealistic considering the relatively high turbulence level in the deceleration zone of the trench. Therefore, an average χ-value of 0.0085 is applied in the model. It must be remarked that equation (5.50) is only used in the zone with reversed flow.

On the basis of an example it will be demonstrated that equation (5.50) with $\chi = 0.0085$ yields a larger diffusion coefficient than applying an expression for equilibrium flow.
For $\bar{u} = 1$ m/s, $h = 15$ m, $\delta_m = 10$ m, $u_r - u_e = 1.5$ m/s and $C = 50\ m^{\frac{1}{2}}/s$, the diffusion coefficient, according to equation (5.50) is about 0.13 m^2/s. Assuming equilibrium flow in the trench, the average diffusion coefficient can be represented by $\bar{\varepsilon}_m \approx 0.07\ u_* h$, which results in $\bar{\varepsilon}_m \approx 0.07\ m^2/s$.

6. Verification

To verify the semi-empirical model for the flow in dredged trenches, flume experiments and field data were used for the comparison of measured and computed flow velocities.

6.1 Flume experiments

Experiments with a trench depth larger than the upstream flow depth were not used for verification because serious three-dimensional effects occurred.

T1

Figure 21 shows measured and computed flow velocities in the centre line of the flume.
The length of the separation zone is quite well simulated, just as the maximum reversed flow velocities. In the mixing layer of the deceleration zone, rather large deviations between computed and measured longitudinal flow velocities can be observed (profiles 3 ... 6), which are mainly caused by three-dimensional effects. The discharge per unit width in profile 3 ... 6 is smaller than at the upstream boundary.

In the relaxation zone the agreement between measured and computed flow velocities for profiles 7 and 8 is remarkably good, while profile 9 indicates that the relaxation of the computed flow velocity in the outer layer proceeds somewhat too slowly.
The agreement between measured and computed vertical flow velocities is, on the average, not so good. Only in profile 2, do the deviations remain relatively small. (Note that the vertical flow velocities are represented on a 10 times larger scale).
In the relaxation zone the measured vertical flow profiles show a boundary layer with upward (positive) flow velocities and an outer layer with downward (negative) flow velocities, which is probably caused by three-dimensional effects. In a purely two-dimensional flow the vertical flow velocities in the relaxation zone can only be directed downwards because fluid must be supplied to the boundary layer with increasing longitudinal flow velocities.

T6, T8, T9, T13

The results are shown in Figures 22 ... 25.

For all these tests the following considerations exist:

- relatively good agreement between measured and computed longitudinal flow velocities in all zones, with the exception of the mixing layer where three-dimensional effects occur, and
- relatively good agreement between measured and computed vertical flow velocities in the separation and acceleration zones, while large deviations can be observed in the relaxation zone, probably due to three-dimensional effects.

T16

The results are shown in Figure 26.

In all zones of the trench the agreement between measured and computed longitudinal flow velocities is remarkably good. Vertical flow velocities were not measured.

6.2 Field conditions

Oosterschelde, Roompot, 29th November, 1979 (flood)

In the Roompot, one of the three main channels in the entrance of the Oosterschelde Estuary, a test pit was dredged to estimate the siltation level. The geometry of the test pit is shown in Figure 27. The depth of the trench was about 4.0 m with respect to the bed level in profile 1. The upstream flow depth was 15.0 m, while the depth-averaged flow velocity was 1.35 m/s. The upstream side of the test pit had a slope of 1 : 4, and the downstream side a slope of 1 : 15.

Flow measurements were made at the upstream boundary (profile 1) and in the middle part of the test pit (profile 4). For a good agreement of measured and computed longitudinal flow velocities at the upstream boundary, an equivalent roughness (k_s) of 1.0m was necessary, although this value is relatively large compared with the measured dune heights of 0.30 - 0.40 m.

The agreement between measured and computed flow velocities in profile 4 is reasonably good, although small deviations occur in the outer and boundary layers.

Westerschelde, Vaarwater boven Bath, May 1965 (flood)

Figure 28 shows a test pit in the Westerschelde, a wide tidal estuary. The test pit had a depth of about 9.0 m with respect to the upstream bed level (profile 1); the upstream flow depth was about 10.0 m; the depth-averaged flow velocity was about 1.0 m/s; and the sides of the trench had a slope of about 1 : 6.
Flow measurements were made at the upstream boundary (profile 1) and in the middle of the trench (profile 5). For a good agreement of the measured and computed flow velocity profile at the upstream boundary, an equivalent roughness of 3.0 m was necessary, which seems an unrealistic large value. The computed flow velocities in profile 5 show good agreement with measured values, with the exception of a layer close to the bed.

Summarizing, it can be stated that the semi-empirical model used to predict the longitudinal and vertical distributions of the flow velocities, although based on sometimes rather crude functions, is quite useful for engineering purposes, while also the relatively low computer costs are an important advantage.

REFERENCES

1 ANTONIA, R.A. and ATTA, C.W. van
Statistical Characteristics of Reynolds Stresses in a Turbulent Boundary Layer
AIAA Journal, 15, 1977

2 ABRAMOVICH, G.N.
The Theory of Turbulent Jets
Massachusetts Institute of Technology Press, 1963

3 BLINCO, P.H. and PARTHENIADES, E.
Turbulence Characteristics in Free Surface Flows over Smooth and Rough Boundaries
Journal of Hydraulic Research, Vol. 9, No. 1, 1971

4 BRADSHAW, P. and WONG, F.Y.
The Reattachment and Relaxations of a Turbulent Shear Layer
Journal of Fluid Mechanics, Vol. 52, 1972

5 COLEMAN, H.W., MOFFAT, R.J. and KAYS, W.M.
The Accelerated Fully Rough Turbulent Boundary Layer
Journal of Fluid Mechanics, Vol. 82, 1977

6 DELFT HYDRAULICS LABORATORY
Flow Resistance in Open Channels with an Alluvial Bed
Interim Report R 1267-3, 1980 (in Dutch)

7 GODEFROY, H.W.H.E.
Application of the Laser Doppler Velocity Measurement Method in Open and Closed Conduits
Imeko Conference on Flow Measurements of Fluids, Groningen, Holland, 1978

8 GRASS, A.J.
Structural Features of Turbulent Flows over Smooth and Rough Boundaries
Journal of Fluid Mechanics, Vol. 50, 1971

REFERENCES (continuation)

9 HINZE, J.O.
Turbulence (second edition)
Mc.Graw-Hill, 1975

10 SCHLICHTING, H.
Boundary Layer Theory
Mc.Graw-Hill, 1968

11 VANONI, V.A. and BROOKS, N.H.,
Laboratory Study of the Roughness and Suspended Load of Alluvial Streams,
Sedimentation Laboratory, No. E-68, California Institute of Technology,
Pasadena, California, December 1957

	discharge	flow depth	flow velocity	water surface slope	roughness height	side length	bottom length	trench depth	temperature	Froude number	Reynolds number	hydraulic radius	hydraulic radius of the bed	Chézy coefficient	Chézy-coefficient of the bed	shear velocity	shear velocity of the bed	roughness height of the bed	Reynolds number of the bed
	Q (m^3/s)	h_o (m)	$\bar{u}_o$ (m/s)	i_o	k (m)	L (m)	B (m)	d (m)	TE (°C)	$FR = \frac{\bar{u}_o}{(g\ h_o)^{\frac{1}{2}}}$	$Re = \frac{u_o\ h_o}{\nu}$	R (m)	R_b (m)	C ($m^{\frac{1}{2}}/s$)	C_b ($m^{\frac{1}{2}}/s$)	u_* (m/s)	$u_{*,b}$ (m/s)	$k_{s,b}$ (m)	$\frac{u_{*,b}\ k}{\nu}$
T1	0.042	0.207	0.405	$5.4\ 10^{-4}$	0.006	0	6.30	0.2	15	0.28	$7.3\ 10^4$	0.113	0.154	38.3	43.4	0.033	0.030	0.0080	158
T2	0.0105	0.101	0.205	$2.9\ 10^{-4}$	0.006	0.40	3.20	0.2	15	0.20	$1.8\ 10^4$	0.072	0.082	37.0	41.8	0.017	0.015	0.0050	79
T3	0.0210	0.20	0.21	$1.6\ 10^{-4}$	0.006	0.40	3.20	0.2	15	0.15	$3.7\ 10^4$	0.11	0.14	37.1	44.4	0.018	0.015	0.0060	79
T4	0.0325	0.324	0.20	$1.0\ 10^{-4}$	0.006	0.40	3.20	0.2	15	0.11	$5.7\ 10^4$	0.141	0.195	35.1	46.2	0.018	0.014	0.0065	74
T5	0.023	0.105	0.435	$1.15\ 10^{-3}$	0.006	0.40	3.20	0.2	15	0.43	$4.0\ 10^4$	0.074	0.088	39.6	43.0	0.034	0.032	0.0045	168
T6	0.041	0.206	0.40	$5.8\ 10^{-4}$	0.006	0.40	3.20	0.2	15	0.28	$7.2\ 10^4$	0.112	0.152	36.6	43.6	0.034	0.029	0.0075	153
T7	0.042	0.204	0.40	$8\ 10^{-4}$	0.011	0.40	3.20	0.2	15	0.28	$7.1\ 10^4$	0.112	0.175	31.3	34.7	0.040	0.037	0.0250	357
T8	0.0405	0.204	0.395	$5.4\ 10^{-4}$	0.006	0.40	1.0	0.2	15	0.28	$7.1\ 10^4$	0.112	0.152	37.6	43.8	0.033	0.029	0.0070	153
T9	0.061	0.32	0.38	$3.4\ 10^{-4}$	0.006	0.40	3.20	0.2	15	0.21	$10.7\ 10^4$	0.143	0.196	36.4	48.4	0.033	0.026	0.0050	137
T10	0.0125	0.206	0.21	$1.4\ 10^{-4}$	0.006	0.60	2.0	0.2	15	0.15	$3.8\ 10^4$	0.113	0.14	39	47.4	0.017	0.014	0.0040	74
T11	0.033	0.316	0.21	$1.2\ 10^{-4}$	0.006	0.60	2.0	0.2	15	0.12	$6.0\ 10^4$	0.14	0.199	34.9	44.0	0.019	0.015	0.0085	79
T12	0.215	0.098	0.435	$1.1\ 10^{-3}$	0.006	0.80	2.40	0.2	15	0.44	$3.7\ 10^4$	0.07	0.081	41.9	45.8	0.032	0.030	0.0030	158
T13	0.405	0.206	0.395	$5.4\ 10^{-4}$	0.006	0.80	2.40	0.2	15	0.28	$7.1\ 10^4$	0.113	0.152	37.6	43.8	0.033	0.029	0.0070	153
T14	0.635	0.317	0.40	$3.5\ 10^{-4}$	0.006	0.80	2.40	0.2	15	0.23	$11.1\ 10^4$	0.14	0.193	38.0	48.7	0.033	0.026	0.0045	137
T15	0.0395	0.20	0.395	$7.8\ 10^{-4}$	0.011	1.20	1.60	0.2	15	0.28	$6.9\ 10^4$	0.111	0.159	31.6	36.5	0.039	0.035	0.0180	338
T16	0.039	0.20	0.39	$7.4\ 10^{-4}$	0.011	1.60	1.80	0.2	15	0.28	$6.8\ 10^4$	0.111	0.156	32.1	37.6	0.038	0.034	0.0150	328

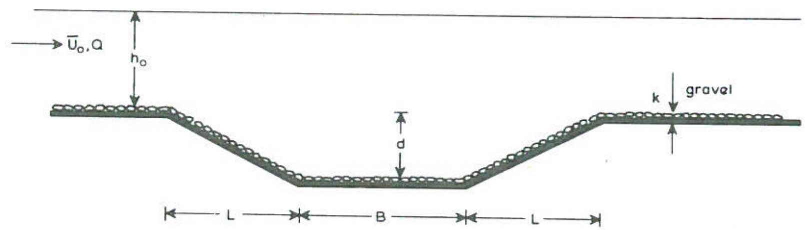


Table 1 Dimensions of the trench and (upstream) hydraulic conditions

	length of separation zone L_s (m)	critical slope γ_{cr}	energy loss coefficient ξ	ratio of reversed and outer flow velocity $\hat{m}$	ratio of upstream boundary layer thickness and flow depth a
T1	1.55	7.8	0.40	0.19	0.82
T2	1.60	8.0	0.15	0.23	0.84
T3	1.50	7.5	0.40	0.19	0.90
T4	1.30	6.5	0.40	0.19	0.71
T5	1.60	8.0	0.40	0.20	0.81
T6	1.50	7.5	0.45	0.20	0.87
T7	1.55	7.8	0.40	0.22	0.78
T8	1.45	7.3	-	0.17	0.88
T9	1.20	6.0	0.50	0.20	0.70
T10	1.50	7.5	0.45	0.13	0.83
T11	1.25	6.3	0.40	0.13	0.73
T12	1.60	8.0	0.25	0.14	0.82
T13	1.50	7.5	0.45	0.14	0.87
T14	1.20	6.0	0.35	0.11	0.69
T15	1.50	7.5	0.20	0.05	0.80
T16	-	-	0.10	-	0.75

Table 2 Summary of empirical parameters

Q	=	discharge	= 0.042 m^3/s
h_o	=	upstream flow depth	= 0.207 m
$\bar{u}_o$	=	upstream flow velocity	= 0.405 m/s
i_o	=	upstream surface slope	= 5.4 10^{-4}
k	=	average roughness height	= 0.006 m
z	=	height above under side of the roughness elements (10^{-2} m)	
$\bar{u}$	=	longitudinal flow velocity (10^{-2} m/s)	
$\bar{w}$	=	vertical flow velocity (10^{-2} m/s)	
$\tilde{u}$	=	longitudinal turbulence intensity (10^{-2} m/s)	
$\tilde{w}$	=	vertical turbulence intensity (10^{-2} m/s)	
$\overline{u'w'}$	=	shear stress correlation (10^{-4} m^2/s^2)	

profile 1, x=-0.20 m					
flow depth = 0.207 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.4	23.07	0.13	4.80	2.80	6.44
2.0	25.93	-0.07	1.67	2.87	6.09
3.0	30.07	-0.07	4.33	2.83	5.20
5.0	33.47	-0.33	4.07	2.73	5.07
7.5	38.00	-0.13	4.03	2.63	5.91
10.0	40.67	-0.33	3.60	2.50	4.44
13.3	43.93	-0.40	3.00	2.23	1.96
16.3	47.80	-0.87	2.10	1.57	1.42
18.0	48.40	-0.93	1.57	1.27	0.58

profile 2, x=0.2 m					
flow depth = 0.407 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.5	-3.73	0.53	1.83	0.93	-0.13
3.0	-4.87	0.80	1.73	1.13	-0.13
5.0	-5.07	1.24	2.20	1.40	0.09
9.0	-5.80	2.00	2.13	1.53	0.40
14.0	-5.73	2.60	2.30	2.33	0.80
19.0	3.60	0.93	4.93	3.63	16.13
26.0	32.67	0.33	4.47	3.23	8.36
33.0	42.53	-0.80	3.47	2.37	3.02
38.5	47.87	-0.73	1.67	1.33	0.18

profile 3, x=0.6 m					
flow depth = 0.407 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	-7.80	0.33	2.60	1.40	-0.40
2.5	-9.93	1.00	3.23	1.77	0
4.5	-8.80	1.20	2.97	2.43	1.96
8.5	-8.13	1.80	3.13	2.63	10.22
13.5	-1.27	0.73	4.63	3.80	14.09
18.5	10.53	-0.33	5.50	4.77	23.95
25.5	25.87	0.40	5.77	4.90	21.91
32.5	41.80	-0.40	3.53	2.70	4.53
38.5	47.33	-0.80	2.60	1.70	2.67

profile 4, x=1.0 m					
flow depth = 0.407 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.0	-6.00	0.73	3.13	1.47	-0.31
2.5	-6.93	1.27	3.67	2.47	0.71
4.5	-6.73	1.33	3.73	3.27	4.36
8.5	-4.93	1.27	4.67	3.93	14.71
13.5	-1.20	1.60	4.80	4.73	21.29
18.5	10.80	-1.00	5.90	5.30	33.11
25.5	23.93	-0.40	5.33	4.87	21.73
32.5	37.73	-1.07	4.43	3.70	4.04
38.5	44.73	-1.33	2.57	1.63	1.73

profile 5, x=1.2 m					
flow depth = 0.407 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	-4.67	0.80	3.07	1.50	0.44
2.5	-1.87	0.93	3.00	1.97	-0.40
4.5	-2.87	1.60	3.53	3.20	-
8.5	-1.80	1.53	3.77	3.47	8.67
13.5	3.60	0.73	5.33	4.87	19.29
18.5	12.20	-0.13	5.67	5.10	31.16
25.5	26.13	-0.80	5.67	4.70	21.47
32.5	36.80	-1.07	5.10	4.20	5.24
38.5	42.35	-0.93	3.03	1.97	1.38

profile 6, x=1.55 m					
flow depth = 0.407 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	1.40	0.53	3.33	1.67	1.20
2.5	0.60	0.67	3.37	2.43	2.49
4.5	0.07	1.60	4.07	3.43	3.96
8.5	0.40	2.13	3.90	3.80	6.36
13.5	5.20	1.40	5.03	4.53	16.04
18.5	10.00	0.80	5.60	5.20	28.53
25.5	22.93	-0.93	6.10	5.13	27.02
32.5	35.33	-1.20	5.03	4.00	13.78
38.5	40.00	-1.00	3.37	2.23	2.89

profile 7, x=2.0 m					
flow depth = 0.407 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	6.40	0.60	3.60	2.33	2.98
2.5	4.20	1.33	3.47	2.63	5.16
4.5	6.93	1.47	3.83	3.33	5.42
8.5	8.53	1.20	4.40	3.80	11.78
13.5	10.60	1.40	5.27	4.57	-
18.5	14.60	0.53	5.27	4.90	13.64
25.5	24.20	-0.73	5.70	4.90	26.13
32.5	34.80	-2.20	5.73	4.33	20.36
38.0	36.93	-1.53	4.13	2.97	9.11

profile 8, x=3.0 m					
flow depth = 0.411 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.1	7.47	-0.33	2.93	1.50	1.38
2.5	10.60	0.40	3.17	2.27	2.18
4.5	9.27	-1.07	3.93	3.23	2.89
8.5	12.13	0.93	3.90	3.27	4.80
13.5	15.47	-0.67	4.37	4.13	12.89
18.5	21.73	-1.60	3.77	4.23	18.09
25.5	24.40	-0.80	5.33	4.43	14.98
32.5	29.07	-1.73	4.97	4.17	13.33
38.5	26.67	-1.20	5.13	3.47	0.13

profile 9, x=4.0 m					
flow depth = 0.405 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	14.8				
4.0	16.1				
6.0	16.3				
10.0	19.2				
15.0	19.8				
20.0	21.2				
27.0	23.4				
34.0	23.0				
38.0	22.2				

profile 10, x=5.0 m					
flow depth = 0.405 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	16.7				
3.5	17.5				
5.5	18.2				
9.5	20.3				
14.5	20.8				
19.5	21.1				
26.5	21.7				
33.5	21.7				
37.5	20.9				

profile 11, x=6.3 m					
flow depth = 0.405 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	16.3				
3.5	18.8				
5.5	19.5				
9.5	20.1				
14.5	20.8				
19.5	21.9				
26.5	21.5				
33.5	21.0				
37.5	20.4				

profile					
flow depth =					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$

Table 3 T1

Q = discharge = 0.011 m^3/s

h_o = upstream flow depth = 0.101 m

$\bar{u}_o$ = upstream flow velocity = 0.205 m/s

i_o = upstream surface slope = 2.9 10^{-4}

k = average roughness height = 0.006 m

z = height above under side of the roughness elements (10^{-2} m)

$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)

$\bar{w}$ = vertical flow velocity (10^{-2} m/s)

$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)

$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)

$\overline{u'w'}$ = shear stress correlation (10^{-4} m^2/s^2)

profile 1, x=-0.2 m						profile 2, x=0.2 m						profile 3, x=0.4 m					
flow depth = 0.101 m						flow depth = 0.206 m						flow depth = 0.305 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.4	12.33	0.40	2.67	1.53	1.29	2.3	-3.07	1.93	0.40	0.47	0	1.8	-3.80	1.00	1.03	0.47	-0.04
1.7	13.6	0.33	2.60	1.50	1.11	3.0	-3.60	2.13	0.63	0.63	0	3.0	-3.33	1.00	0.87	0.53	-0.04
2.2	16.0	0.40	2.80	1.67	1.78	4.0	-3.53	2.07	0.47	0.70	-0.04	4.5	-3.13	1.07	1.03	0.80	0.09
3.2	19.33	0.27	2.57	1.60	1.38	6.0	-2.80	1.73	0.83	0.97	-0.09	7.5	-3.33	1.53	1.10	1.03	0.13
4.7	21.67	0.27	2.20	1.43	0.76	9.0	1.73	0.80	2.37	1.90	2.53	11.5	-2.80	1.87	1.60	1.50	0.31
6.2	22.33	0.47	1.77	1.27	0.53	11.0	11.2	0.13	4.00	2.67	7.33	15.5	-0.80	1.20	2.33	2.13	2.62
8.2	24.13	0.27	1.47	1.20	0.13	14.3	18.4	0.40	2.77	2.13	2.40	20.5	7.20	0.53	3.53	2.87	6.58
9.0	24.67	0.07	1.30	1.03	0.27	16.6	21.0	0.33	1.60	1.20	0.22	25.5	18.4	0.13	3.57	2.40	4.53
						19.0	22.0	0.07	1.53	1.07	0.09	29.5	22.8	0.20	1.53	1.13	0.13

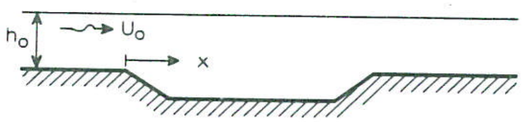
profile 4, x=0.71 m						profile 5, x=1.0 m						profile 6, x=1.55 m					
flow depth = 0.304 m						flow depth = 0.303 m						flow depth = 0.303 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.5	-4.67	0.73	1.40	0.80	0.09	1.3	-3.33	0.67	1.70	0.97	0.09	1.4	-0.53	0.47	1.07	1.00	0.07
2.5	-5.20	0.60	1.53	1.27	-0.09	2.5	-3.20	0.47	1.80	1.53	0.80	2.5	-0.80	0.07	1.77	1.23	-0.76
4.0	-4.53	0.93	1.63	1.30	0.36	4.0	-1.73	0.20	1.70	1.37	0.53	4.0	1.47	0.33	2.00	1.90	2.49
7.0	-3.20	0.53	1.47	1.33	0.93	7.3	-2.27	0.27	1.93	1.87	1.64	7.0	0.47	1.00	1.73	1.67	2.62
11.0	-3.87	1.60	1.83	1.77	2.18	11.0	-1.27	0.73	2.43	2.43	3.02	11.0	0.47	0.47	2.03	2.10	2.22
15.0	1.73	0.00	3.00	2.43	5.42	15.0	2.20	0.40	3.40	2.53	5.60	15.0	2.80	1.33	2.60	2.43	7.96
20.0	9.40	0.27	3.90	3.10	9.07	20.0	7.87	-0.20	4.00	3.00	12.04	20.0	6.93	0.67	3.43	3.17	8.93
25.0	14.13	0.47	3.73	2.70	4.62	25.0	13.60	0.33	3.70	2.73	5.96	25.0	7.87	0.20	3.53	2.83	4.13
29.5	20.27	0.20	2.67	1.73	1.29	29.5	18.27	-0.00	3.63	2.27	1.64	29.5	14.27	0.33	3.37	1.83	2.09

profile 7, x=1.75 m						profile 8, x=2.5 m						profile 9, x=3.6 m					
flow depth = 0.304 m						flow depth = 0.304 m						flow depth = 0.305 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.0	1.27	0.40	1.33	0.43	0.04	1.4	3.87	0.40	1.30	0.43	0.09	2.5	2.87	0.67	1.17	0.47	-0.09
2.0	2.40	0.20	1.63	1.20	0.09	2.5	4.67	-0.07	1.30	0.97	0.00	3.5	4.07	1.13	0.97	0.50	-0.09
3.5	3.60	0.13	1.93	1.47	0.93	4.0	6.40	0.27	1.50	1.23	0.18	5.0	5.00	1.07	0.73	0.47	-0.04
6.5	3.40	0.00	2.10	1.93	1.91	7.0	6.40	0.47	1.73	1.47	0.49	8.0	6.07	1.60	1.07	0.83	-0.04
10.5	5.27	0.47	2.60	2.27	5.73	11.0	6.40	0.40	1.60	1.50	1.33	12.0	7.20	1.47	1.10	1.00	0.13
14.5	4.73	1.00	2.50	2.47	4.04	15.0	7.87	0.00	2.00	2.00	1.51	16.0	7.80	1.20	1.07	1.13	0.04
19.5	7.73	0.53	3.27	2.63	7.24	20.0	7.87	0.20	1.80	1.57	0.84	21.0	7.87	1.07	0.90	1.07	-0.04
24.5	9.07	0.60	3.10	2.70	5.96	25.0	8.80	0.00	1.80	1.57	1.24	26.0	7.87	0.80	0.97	0.90	-0.04
29.5	11.93	0.20	3.17	1.80	1.33	29.5	9.13	0.27	2.07	1.33	0.04	30.0	8.47	0.33	1.37	0.97	-0.04

profile 10, x=3.8 m						profile 11, x=4.0 m						profile 12, x=4.4 m					
flow depth = 0.204 m						flow depth = 0.102 m						flow depth = 0.105 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.2	8.20	4.00	1.00	0.80	-0.13	1.2	21.07	6.00	1.50	1.13	0.00	1.2	11.0	1.27	2.70	1.30	0.76
3.0	9.07	4.53	1.13	0.83	-0.13	1.5	21.27	5.80	1.53	0.90	-0.36	1.5	14.6	0.53	2.77	1.53	1.33
4.0	9.13	3.93	0.77	0.73	-0.09	2.0	21.00	5.13	1.23	0.97	-0.09	2.0	16.8	0.33	2.63	1.46	1.16
6.0	9.60	3.67	0.77	0.93	-0.04	3.0	20.67	4.47	1.20	1.03	0.00	3.0	20.13	0.27	2.13	1.23	0.49
8.5	10.40	3.33	0.83	1.03	-0.04	4.5	20.33	3.40	1.13	11.7	-0.09	4.5	20.0	0.20	1.33	1.03	0.27
11.0	10.73	2.87	0.77	0.97	0.00	6.0	19.87	2.07	1.20	1.03	-0.09	6.0	22.33	0.13	0.90	1.00	-0.09
14.3	10.60	2.00	0.80	1.03	0.00	8.0	19.80	1.33	1.60	1.63	-0.00	8.0	22.47	0.07	0.63	0.83	-0.09
17.6	11.33	1.20	1.07	1.00	-0.09	9.2	19.60	0.73	0.73	0.83	-0.09	9.0	22.53	0.00	0.53	0.73	-0.09
19.0	11.20	0.60	0.93	0.73	-0.09												

Table 4 T2

Q	=	discharge	= 0.021 m^3/s
h_o	=	upstream flow depth	= 0.20 m
u_o	=	upstream flow velocity	= 0.21 m/s
i_o	=	upstream surface slope	= $1.6 \cdot 10^{-4}$
k	=	average roughness height	= 0.006 m
z	=	height above under side of the roughness elements (10^{-2} m)	
$\bar{u}$	=	longitudinal flow velocity (10^{-2} m/s)	
$\bar{w}$	=	vertical flow velocity (10^{-2} m/s)	
$\tilde{u}$	=	longitudinal turbulence intensity (10^{-2} m/s)	
$\tilde{w}$	=	vertical turbulence intensity (10^{-2} m/s)	
$\overline{u'w'}$	=	shear stress correlation (10^{-4} m^2/s^2)	



profile 1, x=-0.2 m						profile 2, x=0.2 m						profile 3, x=0.4 m					
flow depth = 0.200 m						flow depth = 0.204 m						flow depth = 0.400 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.5	10.67	0.20	2.27	1.23	0.67	2.7	-2.87	1.87	0.63	0.67	0.04	2.2	-3.33	1.00	1.13	0.37	-0.04
2.2	14.53	0.33	2.63	1.50	1.20	3.7	-2.33	1.60	0.40	0.77	0.04	3.5	-3.20	1.27	0.90	0.60	-0.18
3.2	16.27	0.53	2.47	1.47	1.42	5.5	-2.67	1.73	0.73	0.83	0.00	5.5	-2.87	1.27	1.13	0.87	-1.11
5.2	18.13	0.40	2.13	1.37	1.64	8.5	1.00	0.80	1.73	1.53	1.20	9.5	-3.53	1.67	1.37	1.50	0.62
7.7	20.53	0.20	1.97	1.37	0.58	12.2	8.53	0.47	3.47	2.23	4.36	14.5	2.53	2.67	2.77	2.40	1.38
10.2	22.80	0.00	1.63	1.23	0.36	16.2	16.80	0.33	2.47	1.73	1.69	19.5	9.20	0.40	3.73	2.60	7.64
13.5	23.80	0.07	1.53	1.10	0.44	21.2	20.67	0.40	1.87	1.33	0.49	25.5	19.27	0.07	2.93	1.90	5.20
16.8	20.93	-0.07	0.80	0.63	-0.09	26.2	23.87	0.13	1.37	1.03	0.22	31.5	23.00	-0.33	1.57	1.20	0.80
18.5	25.60	-0.07	0.87	0.57	-0.09	28.5	24.93	-0.20	0.87	0.60	-0.09	39.0	24.40	-0.20	0.83	0.27	-0.04

profile 4, x=0.71 m						profile 5, x=1.0 m						profile 6, x=1.55 m					
flow depth = 0.400 m						flow depth = 0.400 m						flow depth = 0.400 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.7	-3.73	0.53	1.50	0.90	-0.18	1.2	-2.93	0.47	2.03	1.00	0.04	1.3	0.47	0.47	1.37	0.97	0.27
3.0	-4.20	0.47	1.40	1.10	0.22	2.5	-3.67	0.53	1.20	1.00	-0.80	2.5	-0.20	0.53	1.70	1.23	-0.18
5.0	-3.87	1.07	1.43	1.13	0.98	4.5	-3.27	0.13	1.77	1.37	-0.71	4.5	0.53	0.80	1.70	1.63	0.18
9.0	-3.60	0.80	1.77	1.40	0.53	8.5	-1.60	0.87	2.00	1.73	1.64	8.5	2.07	0.53	2.00	1.90	1.73
14.0	-0.67	0.40	2.83	2.30	2.36	13.5	-0.33	1.53	2.23	2.10	3.87	13.5	3.73	0.87	2.70	2.70	5.51
19.0	5.40	0.33	3.17	2.60	7.07	18.5	6.00	0.20	3.60	3.00	5.33	18.5	5.60	0.80	3.37	2.87	6.22
25.0	13.00	0.00	3.40	2.57	5.87	24.5	11.67	-0.07	3.50	2.97	5.78	24.5	10.27	-0.13	3.33	2.73	8.27
31.0	19.60	0.13	2.17	1.50	1.56	30.5	19.40	-0.47	2.93	2.23	2.98	30.5	15.27	-0.13	3.00	2.27	5.02
38.5	23.33	-0.33	1.13	0.70	3.91	38.0	20.47	-0.20	1.20	0.63	0.09	38.2	20.40	-0.27	1.43	1.07	0.22

profile 7, x=1.75 m						profile 8, x=2.5 m						profile 9, x=3.6 m					
flow depth = 0.400 m						flow depth = 0.400 m						flow depth = 0.400 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.5	1.27	0.53	1.43	0.83	0.36	1.0	3.60	0.33	1.43	0.57	0.00	2.2	3.87	1.20	1.40	0.83	-0.04
3.0	2.27	0.47	1.63	1.27	0.40	2.5	5.33	0.67	1.43	0.97	0.09	3.5	4.80	1.53	1.30	0.87	0.13
5.0	3.80	0.13	2.30	1.83	2.13	4.5	6.33	0.67	1.53	1.17	0.62	5.5	6.40	1.87	1.47	1.20	0.40
9.0	2.93	0.87	2.30	1.90	3.20	8.5	7.20	-0.20	1.77	1.83	1.69	9.5	8.07	1.93	1.27	1.30	0.80
14.0	5.80	1.00	2.90	2.43	2.67	13.5	7.47	0.87	2.10	2.00	2.00	14.5	11.20	1.27	2.00	1.57	2.18
19.0	5.73	1.00	2.97	2.83	7.42	18.5	8.93	0.40	2.50	2.30	3.82	19.5	11.80	1.20	2.10	1.63	1.47
25.0	10.47	0.07	3.50	2.97	5.64	24.5	12.07	-0.20	2.77	2.40	4.67	25.5	13.00	0.87	1.77	1.80	1.78
31.0	15.00	-0.13	3.20	2.30	5.11	30.5	14.67	0.00	3.33	2.17	4.89	31.5	13.20	0.33	2.20	1.77	-0.09
38.5	20.47	-0.40	1.40	1.03	0.09	38.5	15.47	-0.27	2.63	1.57	-0.04	38.5	13.33	0.20	1.83	1.27	0.04

profile 10, x=3.8 m						profile 11, x=4.0 m						profile 12, x=4.4 m					
flow depth = 0.303 m						flow depth = 0.199 m						flow depth = 0.202 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	9.60	4.87	1.40	1.23	-0.40	1.2	21.13	6.33	2.07	1.20	-0.18	1.2	10.40	0.27	2.67	1.70	1.47
3.0	10.27	4.60	1.43	1.23	0.04	2.0	22.13	5.80	1.77	1.33	-0.36	2.0	15.40	0.53	2.77	1.60	1.87
4.5	11.27	4.53	1.50	1.40	0.58	3.0	22.33	4.80	1.50	1.53	0.27	3.0	18.27	0.33	2.40	1.50	1.42
7.5	12.40	4.00	1.73	1.63	0.67	5.0	21.13	3.47	1.53	1.60	0.58	5.0	20.80	0.00	1.73	1.33	1.02
11.5	13.00	3.80	2.03	1.60	1.69	7.5	20.40	2.67	1.43	1.77	0.71	7.5	22.27	-0.33	1.37	1.40	0.71
15.5	15.00	2.40	1.80	1.77	2.18	10.0	20.20	1.87	1.40	1.80	0.53	10.0	22.07	-0.33	1.40	1.53	0.67
20.5	15.93	1.47	1.77	1.70	1.64	13.3	20.20	1.07	1.53	1.73	0.40	13.3	22.00	-0.20	1.30	1.50	-0.04
25.5	15.67	0.73	1.67	1.40	0.13	16.6	19.53	0.27	1.37	1.50	-0.27	16.6	21.80	-0.80	1.37	1.50	0.04
28.5	15.13	0.27	1.60	1.23	-0.18	18.5	19.53	0.20	1.40	1.27	-0.13	18.5	21.60	-0.33	1.30	1.20	0.04

Table 5 T3

Q = discharge = 0.033 m³/s
h_o = upstream flow depth = 0.324 m
$\bar{u}_o$ = upstream flow velocity = 0.20 m/s
i_o = upstream surface slope = 1.0 10^{-4}
k = average roughness height = 0.006 m
z = height above under side of the roughness elements (10^{-2} m)
$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)
$\bar{w}$ = vertical flow velocity (10^{-2} m/s)
$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)
$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)
$\overline{u'w'}$ = shear stress correlation (10^{-4} m²/s²)

profile 1, x=-0.2 m						profile 2, x=0.2 m						profile 3, x=0.4 m					
flow depth = 0.324 m						flow depth = 0.425 m						flow depth = 0.527 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.4	9.60	0.40	2.00	1.13	0.44	2.5	-2.20	1.40	2.37	2.13	0.09	2.5	-2.53	0.93	0.83	0.37	-0.09
2.5	12.27	0.40	1.97	1.20	0.49	4.0	-2.40	1.67	0.30	0.47	-0.04	4.2	-3.46	1.33	0.63	0.57	-0.04
4.0	14.33	0.53	2.03	1.23	0.67	6.0	-2.13	1.40	0.47	0.73	0.04	6.7	-0.40	-1.20	0.50	0.43	-0.09
7.0	16.27	0.80	1.73	1.23	0.53	10.0	3.33	0.73	2.10	1.83	2.58	12.0	0.40	-0.80	0.40	0.67	-0.18
11.0	17.37	1.00	1.53	1.20	0.22	15.0	13.00	0.60	2.53	1.47	1.91	18.5	3.20	2.00	1.13	1.17	-1.16
15.0	21.30	0.60	1.17	1.07	0.00	20.0	17.07	0.67	1.70	1.23	0.40	25.0	8.00	6.50	1.30	1.37	-1.51
20.5	22.10					27.0	20.27	0.53	1.37	1.10	0.00	34.0	9.93	8.70	0.53	0.73	-0.09
26.0	23.00					34.0	21.50					43.0	20.30				
29.5	23.50					39.4	21.70					49.5	21.50				

profile 4, x=0.71 m						profile 5, x=1.0 m						profile 6, x=1.55 m					
flow depth = 0.527 m						flow depth = 0.527 m						flow depth = 0.527 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	-1.13	-2.40	0.40	0.77	-0.13	1.7	-2.60	0.53	1.27	0.77	-0.09	1.3	-0.20	0.33	1.47	0.70	-0.09
3.0	-2.93	-2.13	0.53	0.80	-0.27	3.5	-3.40	0.93	1.23	1.10	0.36	3.0	1.13	0.93	1.47	1.30	-0.13
5.5	-2.67	-1.93	0.60	0.87	-0.22	6.0	-2.73	1.13	1.83	1.47	1.78	5.5	1.27	1.20	1.93	1.63	1.60
11.0	0.67	-0.93	0.97	1.03	-0.53	11.0	0.47	0.33	2.03	1.90	1.47	11.0	3.47	0.27	2.23	2.13	2.62
17.5	2.80	1.53	1.37	1.43	-1.47	17.5	4.20	0.33	2.97	2.50	5.07	17.5	7.47	-0.40	2.87	2.53	6.49
24.0	6.27	5.00	1.33	1.40	-1.16	25.0	10.27	-0.47	3.43	2.47	3.42	24.0	10.07	-0.07	3.30	2.40	5.73
33.0	9.53	8.30	0.70	0.93	-0.31	34.0	16.40	-0.07	1.90	1.40	0.31	33.0	15.13	-0.20	1.83	1.60	0.80
42.0	18.80					43.0	19.00					42.0	18.60				
49.5	20.90					49.5	19.50					49.5	18.30				

profile 7, x=1.75 m						profile 8, x=2.5 m						profile 9, x=3.6 m					
flow depth = 0.520 m						flow depth = 0.520 m						flow depth = 0.523 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	2.93	0.60	1.57	0.87	0.31	1.4	4.67	0.27	1.40	0.63	0.04	2.5	3.93	1.07	1.33	0.93	0.09
3.0	3.60	0.47	1.70	1.33	0.22	3.0	7.07	0.60	1.47	1.10	0.18	4.0	5.33	1.60	1.47	0.97	0.22
5.5	4.67	0.87	1.90	2.03	1.87	5.5	8.00	0.40	1.53	1.33	0.84	6.5	6.93	2.07	1.37	1.03	0.36
10.5	6.60	0.20	2.03	2.13	3.11	10.5	8.40	0.20	2.03	1.77	1.07	12.0	9.47	1.93	1.43	1.33	0.62
17.0	8.27	0.00	2.67	2.37	2.80	17.0	10.33	0.20	2.23	2.00	1.91	18.5	11.53	1.47	1.73	1.57	1.16
23.5	10.80	-0.47	2.77	2.27	4.40	23.5	11.20	0.47	2.17	2.00	2.09	25.0	13.47	1.33	2.00	1.63	1.51
32.5	15.20	-0.53	1.93	1.67	1.38	32.5	13.40	0.27	1.93	1.73	1.56	34.0	16.40	0.67	1.50	1.40	1.42
41.5	17.90					41.5	16.90					43.0	17.40				
49.5	17.40					49.5	16.90					49.4	16.20				

profile 10, x=3.8 m						profile 11, x=4.0 m						profile 12, x=4.4 m					
flow depth = 0.412 m						flow depth = 0.321 m						flow depth = 0.319 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.2	10.00	4.87	1.43	1.07	-0.18	1.2	18.47	6.20	1.67	1.10	-0.36	1.4	10.53	0.47	2.50	1.40	1.07
3.5	9.80	4.67	1.43	1.10	-0.04	2.2	19.07	5.87	1.53	1.27	-0.09	2.5	15.33	0.40	2.73	1.60	1.33
5.5	10.87	4.47	1.43	1.37	0.40	3.7	19.73	4.87	1.37	1.50	0.40	4.0	17.73	0.27	2.43	1.40	1.16
10.0	12.47	3.87	1.77	1.50	0.80	7.0	19.93	3.27	1.50	1.53	0.93	7.0	19.67	-0.20	1.63	1.40	0.93
15.0	14.40	3.33	1.60	1.73	0.84	11.0	19.73	2.47	1.53	1.67	1.02	11.0	20.20	0.20	1.50	1.53	0.67
20.0	16.40	2.33	1.63	1.73	1.24	15.0	19.47	1.93	1.57	1.73	1.24	15.0	21.27	-0.33	1.37	1.40	0.80
27.0	17.93	1.47	1.43	1.40	0.93	20.5	20.60					20.5	22.40				
34.0	19.40					26.0	20.30					26.0	22.10				
39.4	16.30					29.4	20.30					29.4	21.40				

Table 6 T4

Q	=	discharge	= 0.021 m³/s
h_o	=	upstream flow depth	= 0.105 m
$\bar{u}_o$	=	upstream flow velocity	= 0.435 m/s
i_o	=	upstream surface slope	= 1.15 10^{-3}
k	=	average roughness height	= 0.006 m
z	=	height above under side of the roughness elements (10^{-2} m)	
$\bar{u}$	=	longitudinal flow velocity (10^{-2} m/s)	
$\bar{w}$	=	vertical flow velocity (10^{-2} m/s)	
$\tilde{u}$	=	longitudinal turbulence intensity (10^{-2} m/s)	
$\tilde{w}$	=	vertical turbulence intensity (10^{-2} m/s)	
$\overline{u'w'}$	=	shear stress correlation (10^{-4} m²/s²)	

profile 1, x=-0.2 m					
flow depth = 0.106 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.0	27.87	0.47	5.23	2.37	7.73
1.3	31.53	0.33	5.37	3.30	10.00
1.8	35.53	0.07	5.30	3.30	10.31
3.0	41.00	-0.13	5.10	3.13	9.51
4.5	44.47	-0.07	4.53	2.90	7.07
6.0	46.80	-0.20	3.97	2.60	4.31
7.2	48.07	-0.33	3.37	2.30	3.56
8.5	48.67	-0.33	3.13	2.30	1.47

profile 2, x=0.2 m					
flow depth = 0.207 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.75	-11.93	-3.27	1.40	1.30	1.60
3.75	-12.40	-2.87	1.40	1.47	1.91
5.75	-5.67	2.73	2.37	2.27	1.51
8.75	3.33	1.80	5.13	4.17	17.51
12.0	25.47	-0.27	6.23	4.93	27.11
15.75	42.73	-0.27	4.70	3.17	7.24
19.50	48.53	-0.33	3.13	2.27	1.29

profile 3, x=0.4 m					
flow depth = 0.299 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.3	-6.27	2.00	2.87	1.53	0.13
3.5	-7.17	2.13	2.53	1.53	0.22
5.0	-8.80	2.87	2.60	1.67	0.31
8.0	-7.67	2.73	2.80	2.10	1.82
12.0	-6.87	2.67	3.27	3.33	3.20
16.0	-2.80	2.13	4.77	4.33	8.67
21.0	20.13	-0.13	6.43	5.70	36.31
26.0	44.00	-0.67	5.60	4.13	8.31
28.5	48.13	-0.27	3.67	2.30	1.42

profile 4, x=0.71 m					
flow depth = 0.299 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.4	-9.47	0.67	3.13	1.83	-0.76
2.5	-11.60	1.13	3.80	2.57	-0.76
4.0	-9.20	1.20	3.87	2.93	-0.49
7.5	-9.27	2.00	3.90	3.47	10.80
11.0	-5.60	1.13	4.70	4.30	11.07
15.0	2.0	1.13	5.77	5.13	14.36
20.0	21.33	-0.67	6.43	5.63	42.58
25.0	37.53	-0.93	6.10	4.93	25.73
28.5	46.80	-0.93	4.93	3.20	4.49

profile 5, x=1.0 m					
flow depth = 0.299 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.5	-7.33	0.80	3.27	1.60	0.27
2.5	-8.80	0.87	3.93	2.43	0.80
4.0	-8.40	1.40	4.17	3.13	6.04
8.0	-4.27	-0.07	4.77	4.03	13.60
11.0	-3.00	1.33	5.17	4.87	20.62
15.0	6.00	-0.27	6.07	5.30	33.24
20.0	16.33	-1.50	6.50	6.00	28.98
26.0	37.33	-0.67	6.43	4.87	20.36
28.5	41.60	-0.40	5.70	3.77	11.07

profile 6, x=1.55 m					
flow depth = 0.299 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	-1.60	0.40	3.90	1.73	0.04
2.5	-1.47	1.40	3.90	2.60	1.96
4.0	-0.93	0.67	4.10	3.17	2.93
7.0	1.07	1.47	4.57	3.70	11.11
11.0	6.27	0.40	5.43	4.63	15.60
15.0	7.73	0.80	5.67	4.97	21.02
20.0	15.47	1.00	5.83	5.63	20.71
25.0	23.67	0.33	6.23	5.23	22.98
28.5	31.60	-0.07	5.80	4.23	7.29

profile 7, x=1.75 m					
flow depth = 0.299 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.2	5.93	0.73	4.23	2.77	2.89
3.5	2.93	1.33	4.00	3.20	4.84
5.0	4.80	0.20	4.17	3.93	5.64
8.0	6.13	0.80	4.90	4.33	7.07
12.0	7.60	1.53	5.10	4.53	11.07
16.0	11.07	0.47	5.47	4.97	22.36
21.0	14.73	0.67	5.63	5.17	26.00
26.0	20.00	0.53	5.80	4.77	19.38
28.5	24.13	0.07	5.97	4.07	7.60

profile 8, x=2.5 m					
flow depth = 0.299 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.4	8.40	0.33	3.13	1.33	0.84
2.5	9.33	0.67	3.20	1.97	1.11
4.0	12.93	0.73	3.37	2.53	2.00
7.0	12.27	1.20	4.03	3.07	6.13
11.0	13.87	0.13	3.57	3.33	4.31
15.0	13.93	0.93	3.50	3.40	3.80
20.0	13.80	0.33	3.30	3.23	3.87
25.0	17.33	-0.07	4.80	3.53	4.44
29.0	16.93	0.47	4.37	2.50	1.87

profile 9, x=3.6 m					
flow depth = 0.299 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.4	6.13	1.27	2.17	1.20	0.40
3.5	8.80	1.87	2.23	1.20	0.58
5.0	10.53	2.40	2.37	1.37	0.93
8.0	12.80	2.67	2.37	1.83	1.11
12.0	13.80	2.73	2.27	1.90	0.62
16.0	14.73	2.00	2.00	1.93	0.89
21.0	15.47	1.87	2.20	2.13	0.76
26.0	16.20	0.87	2.30	2.07	0.62
28.5	16.80	0.20	2.67	1.50	0.04

profile 10, x=3.8 m					
flow depth = 0.198 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	17.60	8.00	1.97	1.43	0.04
3.2	18.20	7.80	2.07	1.63	-0.13
4.2	18.27	7.87	1.87	1.70	0.40
6.2	19.47	7.13	1.80	1.80	0.71
8.7	20.60	6.13	1.83	2.00	1.56
11.2	21.07	5.13	1.73	2.03	0.58
14.5	22.33	-	1.50	2.03	0.71
17.8	22.47	1.53	1.73	1.70	0.13
18.5	22.53	0.67	1.83	1.57	0.09

profile 11, x=4.0 m					
flow depth = 0.09 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.1	48.13	4.53	1.83	1.40	0.04
1.5	48.87	9.80	1.70	1.67	-0.04
2.0	28.20	8.80	1.40	1.97	0.27
3.0	47.13	6.33	1.40	2.13	0.27
4.2	46.07	4.47	1.37	2.43	0.62
5.4	45.13	2.33	1.23	2.27	0.71
7.0	44.07	0.00	1.23	1.93	0.18
7.8	38.87	-6.27	1.13	1.20	0.40

profile 12, x=4.4 m					
flow depth = 0.09 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.1	26.20	1.93	5.73	3.17	5.87
1.5	34.67	0.53	5.70	3.57	9.73
2.0	41.27	0.20	5.50	3.53	9.51
3.0	47.33	-0.13	4.80	2.73	6.40
4.2	50.33	-0.13	2.87	2.27	1.69
5.4	50.93	-0.20	1.87	2.10	1.02
7.0	50.8	-0.60	1.43	1.93	-0.31
7.6	51.47	-0.40	1.50	1.73	-0.13

Table 7 T5

Q = discharge = 0.042 m^3/s
h_o = upstream flow depth = 0.206 m
u_o = upstream flow velocity = 0.40 m/s
i_o = upstream surface slope = 5.8 10^{-4}
k = average roughness height = 0.006 m
z = height above under side of the roughness elements (10^{-2} m)
$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)
$\bar{w}$ = vertical flow velocity (10^{-2} m/s)
$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)
$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)
$\overline{u'w'}$ = shear stress correlation (10^{-4} m^2/s^2)

profile 1, x=-0.2 m					
flow depth = 0.206 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.5	22.00	-0.07	4.60	2.67	6.49
2.0	23.27	0.53	4.50	2.67	5.69
3.0	29.33	0.20	4.60	2.73	7.20
5.0	33.87	-0.20	4.23	2.77	6.09
7.5	37.47	-0.07	3.87	2.63	5.33
10.0	41.13	-0.27	3.70	2.57	5.69
13.0	45.20	-0.60	3.33	2.27	3.64
16.0	46.80	-0.67	2.33	2.10	1.47
18.5	48.33	-0.73	1.60	1.20	0.31

profile 2, x=0.2 m					
flow depth = 0.299 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.75	-5.47	2.93	1.90	1.43	0.67
2.75	-5.80	3.07	1.67	1.40	0.67
4.25	-4.20	2.13	1.30	1.30	0.27
7.25	-1.13	2.27	3.40	3.00	7.64
11.25	18.13	0.07	5.93	4.20	20.89
15.25	32.13	0.40	4.70	3.23	7.07
20.25	40.40	-0.33	3.87	2.57	5.20
25.25	44.93	-0.47	2.70	1.97	2.67
28.25	47.73	-0.67	2.23	1.20	0.18

profile 3, x=0.4 m					
flow depth = 0.403 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.25	-5.60	2.00	2.27	1.33	0.27
3.75	-7.07	2.40	2.57	1.67	1.47
5.75	-7.33	2.40	2.67	1.70	1.60
9.75	-6.73	3.07	2.63	2.23	1.96
14.75	-3.60	2.73	4.10	3.33	9.33
19.75	9.87	1.00	5.37	4.63	21.78
26.25	30.13	0.73	5.30	3.83	16.22
32.75	40.33	0.53	3.63	2.57	3.96
37.25	46.67	-0.40	2.60	1.67	1.33

profile 4, x=0.71 m					
flow depth = 0.403 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.5	-8.67	0.93	3.03	1.67	0.36
2.5	-9.20	0.80	3.27	2.27	0.58
4.5	-8.53	1.40	3.60	3.07	1.87
8.5	-5.47	0.40	4.27	3.53	11.56
13.5	0.53	0.93	5.10	3.57	12.89
18.5	9.60	-0.53	5.87	5.00	23.11
25.0	25.47	0.13	5.93	4.77	21.78
31.5	43.33	-1.07	3.73	2.77	8.89
37.5	46.00	-0.93	2.87	1.97	0.98

profile 5, x=1.0 m					
flow depth = 0.403 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	-6.33	1.27	3.87	2.63	2.36
4.0	-7.00	1.60	4.10	3.47	5.47
6.0	-5.13	1.27	3.50	3.10	3.07
10.0	-2.07	1.00	5.17	4.40	15.11
15.0	4.53	0.20	5.57	5.03	28.44
20.0	12.80	0.33	6.23	5.37	36.36
26.0	27.33	-0.67	6.13	5.03	25.24
32.0	40.13	-1.13	5.13	3.43	12.67
38.0	43.60	-0.47	3.30	2.00	1.16

profile 6, x=1.3 m					
flow depth = 0.403 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	0.47	1.07	4.13	2.80	1.69
4.0	1.53	1.27	4.37	3.43	1.07
6.0	3.67	2.47	4.40	3.83	10.76
10.0	5.67	1.40	5.17	4.63	13.69
15.0	8.67	1.40	5.23	4.77	9.60
20.0	15.80	0.33	5.93	5.43	24.62
26.0	25.00	-0.67	6.10	5.00	28.80
32.0	33.93	-1.00	5.37	4.43	18.93
38.0	41.33	-0.93	3.73	2.17	1.69

profile 7, x=1.75 m					
flow depth = 0.403 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	4.07	0.67	3.93	2.70	1.87
4.0	5.47	1.33	4.23	3.33	5.96
6.0	4.27	1.60	4.20	3.63	3.47
10.0	7.20	2.27	5.07	4.60	16.53
15.0	9.33	1.73	5.10	4.90	14.84
20.0	16.27	0.00	5.83	5.27	25.02
26.0	23.27	-0.27	5.97	5.10	25.07
32.0	31.13	-1.00	5.43	4.43	15.56
38.5	38.80	-1.00	4.50	3.00	3.96

profile 8, x=2.5 m					
flow depth = 0.403 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	10.20	0.20	3.77	2.33	4.36
4.0	10.27	0.67	4.13	2.80	2.09
6.0	11.07	0.80	4.17	3.40	4.04
10.0	15.07	0.60	4.13	3.80	9.60
15.0	16.60	0.33	5.00	4.40	11.47
20.0	19.07	0.00	5.30	4.53	21.38
26.0	28.53	-1.87	5.63	4.53	24.98
32.0	30.13	-1.33	5.17	4.17	10.98
38.5	30.60	-1.13	5.10	3.50	3.20

profile 9, x=3.6 m					
flow depth = 0.404 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.8	6.33	1.27	3.23	1.83	0.98
3.5	10.60	2.13	3.63	1.87	2.62
5.5	13.40	2.40	4.07	2.47	5.11
9.5	16.53	2.73	3.93	3.33	7.07
14.5	19.33	2.93	4.07	3.40	8.04
19.5	23.20	1.80	4.40	3.80	11.20
25.5	24.87	1.80	4.00	3.73	8.00
31.5	27.73	-0.00	4.13	3.77	3.11
38.5	25.53	-0.07	4.30	2.87	-0.22

profile 10, x=3.8 m					
flow depth = 0.300 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	20.47	8.87	3.67	2.40	-2.58
3.0	21.47	9.20	3.27	2.77	1.29
4.5	22.07	8.87	3.37	3.10	3.11
7.5	25.73	8.00	3.67	3.50	7.16
11.5	28.13	6.07	3.93	3.47	9.07
15.5	28.93	5.07	4.03	4.00	8.84
20.5	31.33	2.40	3.67	3.63	3.07
25.5	31.13	0.73	3.60	3.50	0.36
28.0	30.60	-0.33	3.87	2.67	0.09

profile 11, x=4.0 m					
flow depth = 0.195 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	39.13	9.63	5.70	3.30	2.76
2.0	45.60	9.80	3.50	2.57	-0.89
3.0	45.87	8.47	3.47	3.17	1.73
5.0	42.93	6.87	3.43	3.80	5.47
7.5	42.87	4.13	3.17	3.77	6.00
10.0	41.93	2.80	3.20	3.87	5.07
13.3	41.87	1.47	3.07	3.60	2.76
16.6	40.53	0.13	2.97	3.20	-0.49
18.5	40.00	-0.67	3.33	2.67	-0.53

profile 12, x=4.4 m					
flow depth = 0.195 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	25.20	-0.53	5.53	3.77	12.18
2.0	34.40	-0.53	5.53	3.47	10.93
3.0	39.60	-0.67	5.20	3.17	9.20
5.0	43.07	-0.53	3.73	2.77	3.64
7.5	43.67	-0.60	3.33	3.20	3.02
10.0	43.93	-1.07	2.83	3.27	1.56
13.3	44.20	-1.40	2.83	3.33	0.71
16.6	44.33	-0.80	2.93	2.83	-0.58
18.0	43.93	-0.73	2.80	2.27	-0.44

Table 8 T6

Q = discharge = 0.042 m^3/s
h_o = upstream flow depth = 0.204 m
$\bar{u}_o$ = upstream flow velocity = 0.40 m/s
i_o = upstream surface slope = 8.10^{-4}
k = average roughness height = 0.011 m
z = height above under side of the roughness elements (10^{-2} m)
$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)
$\bar{w}$ = vertical flow velocity (10^{-2} m/s)
$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)
$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)
$\overline{u'w'}$ = shear stress correlation (10^{-4} m^2/s^2)

profile 1, x=-0.2 m						profile 2, x=0.2 m						profile 3, x=0.4 m					
flow depth = 0.204 m						flow depth = 0.296 m						flow depth = 0.400 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	24.60	-1.00	4.93	3.07	14.93	2.5	-6.40	3.27	2.27	1.47	1.07	2.5	-5.53	1.20	2.33	1.40	0.44
3.2	29.50	-1.13	5.20	3.27	14.40	3.5	-7.47	3.80	2.27	1.63	1.51	4.0	-6.40	1.87	2.73	1.57	0.67
4.2	30.30	-0.53	5.07	3.33	15.47	5.0	-6.73	3.07	1.50	1.50	0.67	6.0	-6.80	1.80	2.67	1.80	1.60
6.2	35.10	-0.27	4.93	3.40	13.24	8.0	-0.80	1.80	4.00	3.53	-	10.0	-6.40	2.60	2.97	2.77	4.00
8.5	39.50	-0.40	4.53	3.27	12.31	12.0	19.33	-0.13	6.10	5.10	29.65	15.0	-2.13	1.47	4.60	4.13	15.10
11.0	42.90	-0.53	4.07	2.80	12.36	16.0	33.73	0.47	5.40	3.87	11.33	20.0	15.60	-0.93	5.97	5.47	58.49
14.0	47.40	-1.07	3.60	2.47	5.87	21.0	43.73	-0.13	4.40	3.03	6.93	26.0	33.47	-0.27	5.43	4.17	24.00
17.0	50.80	-1.20	2.20	1.67	4.13	26.0	51.47	-0.53	3.20	2.37	4.36	32.0	45.40	-0.80	4.10	3.57	9.96
18.5	50.50	-1.07	2.13	1.40	1.87	28.5	53.20	-0.60	3.60	1.77	2.04	38.5	50.53	-1.10	2.40	2.00	-0.67

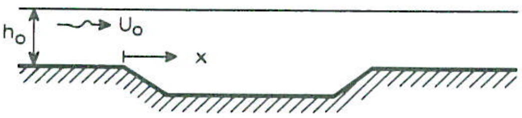
profile 4, x=0.71 m						profile 5, x=0.88 m						profile 6, x=1.0 m					
flow depth = 0.400 m						flow depth = 0.400 m						flow depth = 0.400 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
3.0	-10.27	1.07	3.50	2.60	1.02	2.5	-8.80	1.00	3.67	2.43	1.29	2.5	-7.27	0.67	3.80	2.23	-0.22
4.0	-9.60	1.27	3.27	2.43	1.24	4.0	-8.60	0.60	3.77	2.60	2.18	4.0	-7.80	0.80	3.60	2.87	2.13
6.0	-10.67	1.67	3.43	2.83	3.47	6.0	-7.73	1.73	4.03	3.47	5.69	6.0	-7.07	1.40	3.33	3.10	6.93
10.0	-8.40	-0.53	3.93	4.13	4.76	10.0	-5.87	1.27	4.83	4.23	15.42	10.0	-4.20	0.27	4.73	4.10	17.42
15.0	-1.07	0.40	5.37	4.77	15.29	15.0	0.87	1.20	5.60	5.10	36.93	15.0	14.20	-0.20	5.97	5.27	28.62
20.0	10.67	-0.07	5.87	5.13	29.11	20.0	13.00	-0.73	6.47	5.93	43.51	20.0	13.80	-0.47	6.43	5.57	38.71
26.0	26.53	-0.13	5.97	5.03	28.36	26.0	32.87	1.13	6.03	5.67	58.93	26.0	29.67	-1.00	6.40	5.57	32.80
32.0	43.27	-0.73	4.87	3.60	8.89	32.0	43.47	-1.87	5.47	5.47	19.29	32.0	38.93	-1.00	5.07	4.00	19.64
38.5	49.13	-0.60	3.20	1.97	2.13	38.5	48.53	-1.33	3.27	1.80	1.64	38.5	47.13	-1.27	3.40	2.27	1.96

profile 7, x=1.55 m						profile 8, x=1.75 m						profile 9, x=2.5 m					
flow depth = 0.400 m						flow depth = 0.400 m						flow depth = 0.400 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	-0.73	1.53	3.40	2.87	7.47	3.0	1.53	0.67	4.00	2.90	4.13	2.5	7.93	-0.07	3.67	2.40	3.24
4.0	0.40	0.80	4.33	3.80	6.40	4.0	3.20	0.87	4.33	3.07	3.91	4.0	9.27	-0.07	3.43	2.40	3.60
6.0	2.27	1.60	4.33	3.73	9.56	6.0	4.40	0.87	4.17	3.73	5.24	6.5	11.73	-0.20	4.37	3.63	8.31
10.0	1.40	2.27	4.93	4.73	13.24	10.0	6.27	1.67	4.70	4.17	10.76	10.0	14.60	-0.20	4.63	3.97	13.07
15.0	8.27	0.67	5.67	5.13	27.78	15.0	8.27	1.87	5.50	5.03	18.31	15.0	16.13	-0.33	5.17	4.33	18.98
20.0	15.47	0.20	6.10	5.40	30.80	20.0	13.60	-0.07	6.00	5.50	29.47	20.0	21.27	-1.07	5.37	4.80	20.13
26.0	23.53	-1.40	6.20	5.37	32.67	26.0	21.20	-0.13	5.83	5.37	35.82	26.0	25.07	1.93	5.67	4.83	25.42
32.0	35.07	-1.73	5.67	4.63	26.98	32.0	32.93	-1.87	5.93	4.53	20.31	32.0	30.67	-2.35	5.57	4.73	12.76
38.5	42.13	-1.60	4.13	2.53	4.80	38.0	40.93	-2.47	4.23	2.80	-2.13	38.0	27.20	-1.47	5.43	3.67	-3.51

profile 10, x=3.6 m						profile 11, x=3.8 m						profile 12, x=4.0 m					
flow depth = 0.400 m						flow depth = 0.304 m						flow depth = 0.194 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	6.80	1.53	4.00	2.30	1.33	2.5	15.60	5.07	5.07	2.60	-0.67	2.5	41.73	10.07	3.97	2.67	0.22
4.0	10.47	1.87	3.67	2.57	4.71	3.5	19.07	6.93	4.47	2.53	-2.27	3.2	42.00	9.40	3.53	3.00	0.62
6.0	15.20	2.40	3.97	2.63	3.38	5.0	22.33	7.60	3.83	3.07	1.87	4.2	41.80	8.20	3.40	3.20	2.58
10.0	17.27	2.73	4.10	3.23	6.89	8.0	24.27	7.47	3.73	3.23	2.71	6.2	42.07	6.53	3.43	3.90	5.73
15.0	20.80	2.33	4.40	3.50	9.60	12.0	26.33	6.53	4.13	3.70	8.80	8.7	41.80	4.20	3.17	3.70	6.76
20.0	20.93	2.00	4.37	3.80	8.62	16.0	27.80	5.73	4.07	3.97	8.00	11.2	42.27	2.13	3.57	3.87	4.71
26.0	25.87	1.00	4.37	3.83	7.51	21.0	30.53	2.87	3.73	3.70	5.60	14,5	40.00	1.67	2.93	3.57	2.00
32.0	27.67	-0.27	4.27	3.77	2.76	26.0	31.00	0.93	4.03	3.50	0.80	17.8	39.73	-0.47	3.20	2.90	-0.36
38.5	25.60	-0.40	4.17	2.77	-0.18	30.0	30.53	-0.53	3.83	2.63	-0.40	19.0	38.21	-0.87	3.17	2.50	-1.20

Table 9 T7

Q	=	discharge	= 0.042 m^3/s
h_o	=	upstream flow depth	= 0.204 m
$\bar{u}_o$	=	upstream flow velocity	= 0.395 m/s
i_o	=	upstream surface slope	= 5.4 10^{-4}
k	=	average roughness height	= 0.006 m
z	=	height above under side of the roughness elements (10^{-2} m)	
$\bar{u}$	=	longitudinal flow velocity (10^{-2} m/s)	
$\bar{w}$	=	vertical flow velocity (10^{-2} m/s)	
$\tilde{u}$	=	longitudinal turbulence intensity (10^{-2} m/s)	
$\tilde{w}$	=	vertical turbulence intensity (10^{-2} m/s)	
$\overline{u'w'}$	=	shear stress correlation (10^{-4} m^2/s^2)	



profile 1, x=-0.2 m						profile 2, x=0 m						profile 3, x=0.2 m					
flow depth = 0.204 m						flow depth = 0.204 m						flow depth = 0.205 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	20.73	-0.13	4.80	2.93	6.44	1.0	18.67	-1.00	4.40	2.80	7.73	1.8	-5.07	3.20	1.77	1.30	1.20
2.0	23.20	0.60	4.73	2.80	8.00	1.7	25.47	-0.93	4.77	2.70	5.96	2.8	-6.95	4.53	1.90	1.57	1.87
3.0	28.73	0.07	4.63	2.97	7.56	3.0	29.47	-0.67	4.50	2.77	5.16	4.3	-6.00	3.20	1.80	1.93	0.62
5.0	32.80	0.27	4.30	2.93	6.04	5.0	34.93	-0.67	4.23	2.70	6.53	7.5	-4.00	2.20	3.57	3.37	9.07
7.5	37.27	0.07	3.93	2.80	6.09	7.5	37.27	-0.13	4.00	2.80	6.36	11.5	15.20	0.27	5.80	4.77	21.20
10.0	40.53	-0.33	3.70	2.57	4.80	10.0	40.00	-0.20	3.57	2.60	4.49	15.5	34.00	-0.20	4.77	3.30	11.82
13.3	44.53	-0.53	2.87	2.03	2.00	13.3	44.80	-0.80	2.90	2.07	3.38	20.5	40.53	-0.27	3.73	2.53	5.96
16.6	48.00	-0.93	2.13	1.50	0.76	16.6	47.33	-0.93	1.93	1.40	0.53	25.5	45.60	-0.87	2.57	1.97	2.04
18.5	48.67	-0.87	1.33	1.07	0.53	18.5	47.93	-0.80	1.83	1.27	0.58	28.5	47.67	-0.80	1.67	1.17	0.27

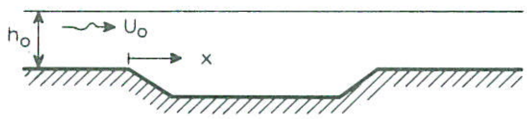
profile 4, x=0.4 m						profile 5, x=0.9 m						profile 6, x=1.4 m					
flow depth = 0.406 m						flow depth = 0.404 m						flow depth = 0.403 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.3	-4.93	1.80	2.57	1.30	0.71	1.7	-8.00	1.07	3.50	2.23	-0.49	2.2	-1.93	0.00	3.23	2.30	-2.09
3.5	-7.80	2.80	2.50	1.57	0.22	3.0	-8.07	1.53	3.83	2.80	0.71	3.5	-0.13	1.53	3.63	3.03	1.16
5.5	-8.00	3.07	2.53	1.83	0.58	5.0	-7.47	2.13	3.63	3.37	3.69	5.5	-0.60	2.13	4.10	3.63	3.02
9.5	-7.60	2.93	2.77	2.60	2.13	9.0	-3.47	1.33	4.47	3.93	9.47	9.5	0.47	3.47	4.97	4.23	7.96
14.5	-4.60	2.60	3.87	3.63	9.47	14.0	0.00	0.80	5.40	4.93	20.53	14.5	5.53	2.40	5.00	4.67	18.36
19.5	9.73	0.80	6.00	4.93	24.84	19.0	8.80	-0.13	5.87	5.43	27.64	19.5	9.33	0.87	5.73	5.13	25.07
26.5	34.27	-0.07	5.40	4.00	12.62	24.0	28.40	-0.93	5.80	4.93	19.38	26.5	23.93	-0.13	6.23	5.27	24.18
33.5	44.40	-0.53	3.30	2.23	2.31	33.0	42.93	-0.87	4.33	3.73	5.20	33.5	35.47	-0.40	5.40	3.97	16.27
38.5	47.47	-0.87	2.00	1.47	0.40	38.0	47.80	-0.73	2.33	1.67	0.80	38.5	40.80	-0.27	3.73	2.37	1.78

profile 7, x=1.6 m						profile 8, x=1.8 m						profile 9, x=2.2 m					
flow depth = 0.301 m						flow depth = 0.202 m						flow depth = 0.203 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.5	10.13	6.20	4.53	3.90	-2.31	2.0	35.80	9.33	5.13	4.40	4.13	1.6	28.87	-0.67	5.50	4.03	11.33
3.5	11.60	6.93	4.93	4.47	3.38	2.7	34.93	8.00	5.37	5.43	0.31	2.5	32.67	-0.47	5.57	4.13	11.96
5.0	12.87	8.20	4.77	4.90	11.02	3.7	34.67	9.13	4.97	5.67	12.70	3.5	34.40	0.67	5.50	4.37	15.20
8.0	15.07	5.80	5.70	5.60	26.98	-5.7	36.00	6.13	5.37	5.97	20.71	5.5	37.53	0.47	5.43	4.73	17.20
12.0	18.67	5.67	5.77	5.90	36.04	8.2	36.80	5.27	5.40	5.70	31.73	8.0	39.47	0.07	5.47	4.97	17.42
16.0	26.07	3.53	6.20	5.50	32.84	10.7	38.67	3.53	5.73	5.57	29.02	10.5	40.93	-0.53	5.60	5.00	23.29
21.0	37.40	0.53	5.63	4.60	23.73	14.0	40.67	2.40	5.43	5.17	27.07	13.8	32.87	0.00	5.63	4.97	23.42
26.0	41.60	0.00	4.90	3.50	10.62	17.3	47.47	-0.87	4.53	2.80	10.27	17.1	46.00	-0.80	4.93	4.10	11.24
28.0	42.53	-0.27	3.57	2.73	3.38	18.0	47.73	-0.87	4.33	3.30	6.31	18.0	46.60	-0.87	5.37	3.87	10.40

profile						profile						profile					
flow depth =						flow depth =						flow depth =					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$

Table 10 T8

Q = discharge = 0.063 m^3/s
h_o = upstream flow depth = 0.32 m
$\bar{u}_o$ = upstream flow velocity = 0.38 m/s
i_o = upstream surface slope = 3.4 10^{-4}
k = average roughness height = 0.006 m
z = height above under side of the roughness elements (10^{-2} m)
$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)
$\bar{w}$ = vertical flow velocity (10^{-2} m/s)
$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)
$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)
$\overline{u'w'}$ = shear stress correlation (10^{-4} m^2/s^2)



profile 1, x=-0.2 m						profile 2, x=0.2 m						profile 3, x=0.4 m					
flow depth = 0.320 m						flow depth = 0.423 m						flow depth = 0.522 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	18.07	0.53	3.93	2.27	4.18	2.2	-4.40	2.47	1.50	1.33	0.27	2.5	-4.27	1.40	2.23	1.27	0.22
2.3	24.53	0.47	4.37	2.53	5.87	3.7	-4.33	2.47	1.23	1.23	0.18	4.2	-5.07	2.00	2.20	1.63	0.80
3.8	28.20	0.53	4.07	2.60	5.33	5.7	-3.73	2.33	2.03	2.10	2.58	6.7	-5.40	2.40	2.33	2.00	0.58
7.0	34.33	0.53	3.53	2.50	4.84	10.0	8.13	0.73	4.83	3.57	9.96	12.0	-3.53	1.87	2.00	2.20	0.71
11.0	37.93	0.93	3.13	2.37	2.00	15.0	27.27	0.67	4.80	3.20	7.33	18.5	5.47	1.07	4.93	3.97	13.56
15.0	49.87	0.67	2.80	2.29	1.47	20.0	32.93	0.67	3.33	2.50	2.80	25.0	23.73	0.87	5.70	4.30	13.96
20.5	43.70					27.0	37.13	0.40	2.60	2.07	0.98	34.0	36.33	0.27	3.00	2.37	2.04
26.0	43.10					34.0	42.60					43.0	40.90				
29.3	42.90					39.5	41.20					49.3	40.50				

profile 4, x=0.71 m						profile 5, x=1.0 m						profile 6, x=1.30 m					
flow depth = 0.521 m						flow depth = 0.520 m						flow depth = 0.523 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.6	-6.47	0.80	2.80	1.63	0.27	1.3	-3.20	0.33	2.83	1.57	0.13	1.4	0.20	0.47	3.53	2.17	0.36
3.2	-7.33	0.87	3.07	2.37	1.51	3.0	-4.40	0.67	3.47	2.53	-0.13	3.0	0.20	0.80	3.93	2.87	-0.49
5.7	-6.40	1.27	3.67	2.93	1.96	5.5	-4.00	1.80	4.07	2.97	9.02	5.5	3.67	0.87	3.80	3.43	3.78
11.0	-5.00	1.47	3.60	3.27	8.84	10.5	-1.73	1.33	4.83	4.03	8.80	11.0	6.27	1.47	4.67	4.60	12.40
17.5	5.67	0.27	5.03	4.30	17.73	17.0	8.73	0.33	5.67	4.97	21.51	17.5	12.40	0.20	5.03	5.00	25.51
24.0	18.40	-0.73	5.67	4.83	19.29	23.5	19.67	-0.87	5.73	4.97	24.22	24.0	21.33	-0.67	5.40	5.03	20.44
33.0	33.33	-0.13	3.97	3.27	5.60	32.5	32.20	-0.87	3.77	3.43	6.71	33.0	31.73	-1.00	4.27	3.87	10.18
43.0	40.40					43.0	39.40					43.0	38.20				
49.4	40.40					49.4	38.40					49.5	37.30				

profile 7, x=1.75 m						profile 8, x=2.5 m						profile 9, x=3.60 m					
flow depth = 0.520 m						flow depth = 0.520 m						flow depth = 0.520 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	4.67	0.13	3.57	1.63	2.27	1.3	8.00	0.93	3.23	1.40	1.02	2.4	7.07	1.60	2.80	1.63	1.38
2.8	7.00	0.80	3.60	2.90	3.64	3.0	12.40	0.53	3.63	2.30	2.22	4.0	10.73	2.00	3.30	1.97	1.69
5.3	8.67	1.20	4.17	3.77	5.29	5.5	13.73	1.20	3.60	2.53	2.31	6.5	13.27	2.93	3.47	2.21	3.29
10.5	11.87	0.80	4.50	4.57	8.40	11.0	15.33	0.73	3.70	3.50	5.38	12.0	17.20	3.07	3.43	2.80	6.84
17.0	15.87	0.87	5.30	4.87	17.56	17.5	19.73	-0.20	4.70	3.93	9.24	18.5	21.33	2.87	4.00	3.43	5.96
23.5	23.20	-1.33	5.30	4.90	24.18	24.0	24.13	-1.07	4.40	3.93	13.91	25.0	25.73	2.07	4.43	3.53	9.47
32.5	28.67	-1.13	5.00	3.97	9.24	33.0	27.87	-0.93	4.30	3.77	9.51	34.0	30.53	0.73	3.97	3.57	4.80
43.0	37.20					42.0	36.70					43.0	35.60				
49.5	35.10					49.5	34.90					49.3	32.30				

profile 10, x=3.8 m						profile 11, x=4.0 m						profile 12, x=4.4 m					
flow depth = 0.417 m						flow depth = 0.313 m						flow depth = 0.313 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.2	18.53	9.00	3.33	2.53	-3.82	1.2	37.87	9.20	3.77	2.13	0.31	1.2	13.20	-0.27	5.13	2.97	11.42
3.7	20.93	8.40	3.37	2.90	-1.29	2.2	38.80	8.87	3.07	2.70	0.67	2.2	29.53	-0.27	5.10	3.20	9.11
5.7	20.53	7.47	4.57	4.13	-6.49	3.8	39.33	7.33	2.90	2.97	2.98	3.8	33.47	-0.40	4.70	2.97	7.96
10.0	24.67	6.53	4.23	3.90	2.36	7.0	38.20	5.27	3.27	3.43	8.13	7.0	38.67	-0.73	3.60	2.87	5.60
15.0	28.13	4.33	4.73	3.87	-1.20	11.0	39.33	3.07	3.37	3.43	7.82	11.0	40.47	-1.27	3.43	3.23	5.51
20.0	32.00	2.80	4.23	3.97	1.02	15.0	40.33	2.00	3.63	3.43	7.29	15.0	41.33	-1.33	3.27	3.23	4.93
27.0	35.33	1.40	4.03	3.77	-0.18	20.5	41.20					20.5	42.40				
34.0	37.80					26.0	40.70					26.0	41.40				
39.2						29.0	37.10					28.9	38.50				

Table 11 T9

Q	=	discharge	= 0.021 m^3/s
h_o	=	upstream flow depth	= 0.206 m
$\bar{u}_o$	=	upstream flow velocity	= 0.21 m/s
i_o	=	upstream surface slope	= 1.4 10^{-4}
k	=	average roughness height	= 0.006 m
z	=	height above under side of the roughness elements (10^{-2} m)	
$\bar{u}$	=	longitudinal flow velocity (10^{-2} m/s)	
$\bar{w}$	=	vertical flow velocity (10^{-2} m/s)	
$\tilde{u}$	=	longitudinal turbulence intensity (10^{-2} m/s)	
$\tilde{w}$	=	vertical turbulence intensity (10^{-2} m/s)	
$\overline{u'w'}$	=	shear stress correlation (10^{-4} m^2/s^2)	

profile 1, x=-0.2 m						profile 2, x=0.3 m						profile 3, x=0.6 m					
flow depth = 0.206 m						flow depth = 0.317 m						flow depth = 0.405 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	16.60		1.75			2.0	0.90		1.38			2.0	-1.40		1.20		
2.7	16.50		1.66			3.0	-0.70		1.06			3.5	-1.50		0.92		
3.7	17.00		1.56			4.5	-11.30		1.52			5.5	-1.90		1.01		
5.7	21.00		1.66			7.5	4.70		1.94			9.5	-0.20		1.11		
8.2	20.10		1.48			11.5	13.80		2.03			14.5	2.30		1.89		
10.7	21.50		1.48			15.5	17.60		1.84			19.5	9.60		2.12		
14.0	21.50		1.20			20.5	20.90		1.56			26.5	17.50		1.94		
17.3	24.20		1.11			25.5	22.80		1.11			33.5	21.80		1.56		
												38.0	23.80		0.83		

profile 4, x=0.8 m						profile 5, x=1.0 m						profile 6, x=1.5 m					
flow depth = 0.405 m						flow depth = 0.405 m						flow depth = 0.405 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	-2.20		1.20			2.0	-1.60		1.20			2.0	0.20		1.13		
3.5	-2.10		1.11			3.5	-1.90		1.24			3.5	0.40		1.24		
5.5	-1.90		1.29			5.5	-1.50		1.29			5.5	0.60		1.43		
9.5	-0.80		1.48			9.5	0.20		1.43			9.5	1.80		1.61		
14.5	2.40		1.84			14.5	2.60		1.98			14.5	2.90		2.12		
19.5	11.80		2.26			19.9	8.30		2.31			19.9	5.40		2.31		
26.5	16.90		2.31			26.5	13.90		2.44			26.5	13.50		2.26		
33.5	22.60		1.24			33.5	20.40		1.94			33.5	17.20		1.89		
38.0	22.80		0.97			37.5	22.30		1.66			37.5	20.60		1.24		

profile 7, x=2.6 m						profile 8, x=2.9 m						profile 9, x=3.2 m					
flow depth = 0.405 m						flow depth = 0.306 m						flow depth = 0.205 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	4.30		1.38			2.0	9.80		1.66			2.0	20.30		1.84		
3.5	5.10		1.48			3.0	10.20		1.71			2.7	19.30		1.80		
5.5	5.70		1.43			4.5	10.60		1.66			3.7	19.40		1.84		
9.5	6.50		1.84			7.5	12.00		1.66			5.7	19.20		1.89		
14.5	8.30		2.03			11.5	13.50		2.03			8.2	19.80		1.84		
19.9	11.00		2.21			15.5	14.70		2.26			10.7	20.40		1.84		
26.5	13.90		2.44			20.5	16.60		2.21			14.0	19.90		1.94		
33.5	17.20		2.21			25.5	16.70		2.17			17.3	20.00		1.94		
37.5	15.70		2.12			27.5	16.60		2.12								

profile 10, x=3.6 m						profile						profile					
flow depth = 0.205 m						flow depth =						flow depth =					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	19.30		1.98														
2.7	19.50		1.98														
3.7	19.90		1.89														
5.7	20.60		1.80														
8.2	19.90		1.80														
10.7	20.50		1.75														
14.0	21.00		1.80														
17.3	19.70		1.75														

Table 12 T10

Q = discharge = 0.032 m^3/s
h_o = upstream flow depth = 0.316 m
$\bar{u}_o$ = upstream flow velocity = 0.215 m/s
i_o = upstream surface slope = 1.2 10^{-4}
k = average roughness height = 0.006 m
z = height above under side of the roughness elements (10^{-2} m)
$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)
$\bar{w}$ = vertical flow velocity (10^{-2} m/s)
$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)
$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)
$\overline{u'w'}$ = shear stress correlation (10^{-4} m^2/s^2)

profile 1, x=-0.2 m						profile 2, x=0.3 m						profile 3, x=0.6 m					
flow depth = 0.316 m						flow depth = 0.415 m						flow depth = 0.515 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	15.90		1.98			2.0	-0.70		1.15			2.0	-1.40		0.97		
3.0	18.90		1.71			3.5	0.70		1.24			4.0	-1.60		0.92		
4.5	17.90		1.57			5.5	2.10		1.48			6.5	-1.50		0.92		
7.5	19.10		1.61			9.5	7.50		1.98			11.5	0.50		1.01		
11.5	19.70		1.66			14.5	15.00		1.66			18.0	4.80		1.89		
15.5	21.30		1.24			19.5	18.60		1.66			24.5	13.60		2.31		
21.0	23.50		1.06			26.5	21.10		1.06			33.5	18.90		1.84		
26.5	23.50		0.74			33.5	23.10		0.46			42.5	22.50		1.06		
28.5	23.10		0.51			38.5	22.60		0.46			48.5	22.40		0.64		

profile 4, x=0.8 m						profile 5, x=1.0 m						profile 6, x=1.5 m					
flow depth = 0.515 m						flow depth = 0.515 m						flow depth = 0.515 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	-1.70		1.01			2.0	-0.20		1.15			2.0	0.60		1.13		
4.0	-1.30		0.97			4.0	-0.80		1.20			4.0	0.40		1.20		
6.5	-0.90		1.24			6.5	-0.70		1.20			6.5	1.30		1.43		
11.5	0.20		1.38			11.5	1.30		1.71			11.5	1.80		1.52		
18.0	6.10		2.17			18.0	5.60		2.17			18.0	5.00		2.12		
24.5	16.30		1.94			24.5	12.40		2.17			24.5	11.70		2.26		
33.5	19.00		1.61			33.5	19.40		1.48			33.5	17.70		1.71		
42.5	21.80		1.01			42.5	21.80		0.74			42.5	20.70		1.11		
48.5	21.80		0.60			48.5	21.30		0.64			48.5	20.40		0.64		

profile 7, x=2.6 m						profile 8, x=2.9 m						profile 9, x=3.2 m					
flow depth = 0.515 m						flow depth = 0.417 m						flow depth = 0.315 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	5.20		1.29			2.0	10.00		1.48			2.0	18.40		1.80		
4.0	6.00		1.52			3.5	10.60		1.57			3.0	18.40		1.57		
6.5	6.80		1.71			5.5	10.50		1.43			4.5	18.80		1.61		
11.5	7.60		1.89			9.5	12.90		1.84			7.5	18.80		1.89		
18.0	10.50		2.08			14.5	14.50		2.17			11.5	19.60		1.94		
24.5	12.80		2.12			19.5	15.50		2.12			15.5	20.70		1.89		
33.5	17.20		1.80			26.5	18.60		2.03			21.0	22.30		1.75		
42.5	20.10		1.39			33.5	20.50		1.08			26.5	22.80		1.38		
48.5	19.20		1.20			38.5	19.60		1.38			28.5	21.80		1.38		

profile 10, x=3.6 m						profile						profile					
flow depth = 0.315 m						flow depth =						flow depth =					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	16.90		1.98														
3.0	16.90		1.84														
4.5	17.80		1.80														
7.5	19.10		1.84														
11.5	20.10		1.98														
15.5	22.20		1.80														
21.0	23.10		1.61														
26.5	22.40		1.52														
28.5	21.60		1.57														

Table 13 T11

Q	=	discharge	= 0.021 m^3/s
h_o	=	upstream flow depth	= 0.098 m
$\bar{u}_o$	=	upstream flow velocity	= 0.435 m/s
i_o	=	upstream surface slope	= $1.1 \ 10^{-3}$
k	=	average roughness height	= 0.006 m
z	=	height above under side of the roughness elements (10^{-2} m)	
$\bar{u}$	=	longitudinal flow velocity (10^{-2} m/s)	
$\bar{w}$	=	vertical flow velocity (10^{-2} m/s)	
$\tilde{u}$	=	longitudinal turbulence intensity (10^{-2} m/s)	
$\tilde{w}$	=	vertical turbulence intensity (10^{-2} m/s)	
$\overline{u'w'}$	=	shear stress correlation (10^{-4} m^2/s^2)	

profile 1, x=-0.2 m						profile 2, x=0.4 m						profile 3, x=0.8 m					
flow depth = 0.098 m						flow depth = 0.195 m						flow depth = 0.303 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
0.9	22.73	-0.87	5.60	3.73	13.38	1.7	-5.60	1.67	2.87	1.80	2.67	1.6	-5.60	0.73	2.67	1.60	0.40
1.2	29.13	-0.93	5.63	3.57	5.16	2.5	-4.13	1.53	3.60	2.73	3.96	2.6	-6.67	1.33	2.93	2.13	2.93
1.7	34.47	-0.73	5.40	3.40	9.38	3.5	-3.60	1.20	3.50	2.80	7.38	4.0	-3.27	1.07	2.90	2.13	4.49
2.7	39.67	-0.67	4.80	3.03	7.56	5.5	1.60	0.33	4.97	3.93	12.40	7.0	-3.20	0.33	3.53	3.50	8.71
4.0	43.87	-0.67	4.43	2.80	5.38	8.0	8.93	0.13	5.43	4.73	18.31	10.5	-2.27	0.93	5.17	4.27	12.09
5.3	47.33	-0.93	3.93	2.27	4.31	10.5	20.60	-1.40	5.87	4.83	25.02	14.0	7.73	-0.73	5.57	4.97	26.49
7.1	48.73	-0.60	3.50	2.17	1.38	14.0	36.13	-1.60	5.60	4.10	18.53	19.0	20.00	-1.47	5.80	5.10	28.49
8.5	51.07	-1.00	3.20	2.47	1.51	17.5	43.33	-1.27	3.93	2.57	3.60	24.0	31.60	-1.33	6.57	4.37	17.64
						19.0	45.80	-1.13	2.97	1.80	1.56	29.0	43.40	-1.53	4.10	2.57	2.40

profile 4, x=1.0 m						profile 5, x=1.55 m						profile 6, x=1.75 m					
flow depth = 0.303 m						flow depth = 0.303 m						flow depth = 0.303 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	-3.87	0.47	3.03	1.50	0.62	1.3	-1.20	0.80	3.33	1.80	2.93	1.3	2.27	0.33	3.23	1.97	1.33
2.3	-3.87	0.33	2.83	1.93	0.44	2.3	-1.07	0.73	3.50	2.47	3.69	2.3	3.33	0.13	3.37	2.77	4.36
3.8	-3.60	0.53	3.70	2.90	0.36	3.8	2.33	0.13	3.63	3.07	7.69	3.8	2.13	0.67	3.33	2.90	7.78
7.0	0.27	-1.27	4.40	3.67	11.16	7.0	3.73	0.27	4.30	4.00	10.44	6.8	3.07	-0.53	4.47	4.17	11.82
10.5	5.20	-0.87	5.27	4.67	21.38	10.5	6.00	0.00	5.27	4.47	17.69	10.3	8.80	-0.47	5.10	4.30	15.73
14.0	7.00	0.07	5.80	5.13	28.62	14.0	10.80	-0.93	5.10	4.63	22.36	13.8	11.67	-0.87	5.20	4.50	14.98
19.0	18.60	-1.33	5.83	5.07	31.02	19.0	18.80	-1.60	5.97	4.93	22.80	18.8	18.27	-2.00	5.77	5.13	24.71
24.0	28.80	-1.40	6.10	4.67	17.91	24.0	28.20	-1.53	6.00	4.80	17.33	23.8	26.87	-1.93	5.83	4.70	14.18
29.2	38.53	-1.40	4.93	3.07	8.93	29.3	-	-1.07	5.30	3.43	1.02	29.0	30.53	-1.13	5.60	3.57	5.96

profile 7, x=2.25 m						profile 8, x=3.2 m						profile 9, x=3.6 m					
flow depth = 0.303 m						flow depth = 0.303 m						flow depth = 0.203 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.0	3.13	0.27	2.33	1.27	0.36	2.0	8.27	0.53	2.93	1.57	1.29	1.8	15.20	3.53	3.27	1.43	-0.18
2.0	7.27	0.20	3.53	2.20	1.91	3.0	8.73	-0.20	3.30	2.20	1.42	2.5	18.53	4.33	2.63	1.47	-0.22
3.5	9.53	0.00	3.93	2.93	5.78	4.5	12.80	0.20	3.30	2.10	3.47	3.5	19.67	4.33	2.43	1.83	0.27
6.5	10.47	-0.40	4.13	3.80	5.96	6.5	12.87	-0.07	3.27	2.47	2.00	5.5	20.47	3.07	2.40	2.23	0.18
10.0	12.67	-0.67	4.50	4.10	13.51	11.0	15.20	-0.13	3.73	3.03	3.07	8.0	21.07	2.67	2.27	2.60	1.24
13.5	15.13	-0.60	5.00	4.43	16.98	14.5	15.27	-0.47	3.63	3.17	5.16	10.5	21.53	2.00	2.50	2.60	0.89
18.5	18.60	-1.93	5.33	4.70	13.16	19.5	16.93	-0.33	3.50	3.17	2.22	14.0	21.20	0.87	2.50	2.53	0.84
23.5	22.60	-1.47	5.50	4.67	8.31	24.5	16.33	-0.33	3.67	2.67	0.93	17.5	20.80	0.47	2.30	2.23	0.18
29.0	21.87	-0.87	5.30	3.40	1.73	29.5	15.87	-0.27	3.53	2.03	-0.53	19.5	20.87	-0.07	2.70	1.77	-0.04

profile 10, x=4.0 m						profile 11, x=4.4 m						profile					
flow depth = 0.093 m						flow depth = 0.095 m						flow depth =					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	38.40	4.33	4.63	2.77	4.49	1.3	28.33	-1.27	5.70	3.63	12.93						
1.5	41.80	4.53	3.20	1.90	1.33	1.6	32.13	-1.07	5.60	3.53	10.27						
2.0	43.13	4.00	2.10	1.87	0.09	2.1	38.27	-0.93	5.43	3.27	9.91						
3.0	42.87	3.33	1.67	2.03	0.27	3.0	44.80	-0.93	4.07	2.53	4.44						
4.3	43.27	2.40	1.57	2.33	0.44	4.3	46.33	-0.73	2.27	1.97	0.62						
5.6	43.00	1.00	1.47	2.43	0.13	5.6	48.00	-0.93	1.43	1.90	0.44						
7.4	42.87	0.07	1.60	2.43	0.18	7.4	48.13	-0.93	1.50	1.80	0.00						
9.0	41.87	-1.00	1.77	1.87	-0.18	9.0	48.00	-0.80	1.40	1.70	-0.18						

Table 14 T12

Q = discharge = 0.042 m^3/s
h_o = upstream flow depth = 0.206 m
$\bar{u}_o$ = upstream flow velocity = 0.395 m/s
i_o = upstream surface slope = 5.4 10^{-4}
k = average roughness height = 0.006 m
z = height above under side of the roughness elements (10^{-2} m)
$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)
$\bar{w}$ = vertical flow velocity (10^{-2} m/s)
$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)
$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)
$\overline{u'w'}$ = shear stress correlation (10^{-4} m^2/s^2)

profile 1, x=-0.20 m						profile 2, x=0.4 m						profile 3, x=0.8 m					
flow depth = 0.206 m						flow depth = 0.310 m						flow depth = 0.410 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	19.87	-0.27	4.80	2.80	6.49	1.5	-5.00	1.40	2.63	1.63	0.98	1.8	-4.67	1.60	2.03	1.13	1.20
2.0	25.47	0.20	4.73	2.80	4.44	2.5	-3.67	1.20	3.20	2.63	2.76	3.0	-5.60	2.13	2.13	1.67	1.20
3.0	27.67	0.53	4.47	2.80	5.73	4.0	-3.33	1.27	3.30	2.87	6.84	5.0	-4.40	1.73	2.70	2.23	4.80
5.0	32.33	0.40	4.27	2.73	5.02	7.0	2.53	1.07	4.73	3.93	18.93	9.0	-1.20	1.13	3.77	3.27	20.98
7.5	36.27	0.33	3.77	2.57	4.00	11.0	14.53	0.20	5.50	4.50	22.89	14.0	6.67	0.60	5.13	4.13	24.89
10.0	41.00	0.13	3.37	2.40	3.47	15.0	26.40	-0.13	5.17	3.73	17.51	19.0	15.87	0.87	5.43	4.67	24.93
13.5	43.60	0.13	3.10	2.33	1.69	20.0	35.07	-0.07	3.53	2.70	2.49	25.5	27.73	0.21	5.00	3.83	16.80
17.0	46.93	-0.20	2.00	1.83	0.76	25.0	40.00	-0.20	2.93	2.23	1.47	32.0	37.73	-0.13	2.97	2.33	2.44
18.5	47.33	0.00	2.10	1.93	0.89	28.5	43.40	-0.60	2.17	1.63	0.53	38.0	41.40	-0.40	2.23	1.67	0.53

profile 4, x=1.0 m						profile 5, x=1.55 m						profile 6, x=1.75 m					
flow depth = 0.410 m						flow depth = 0.410 m						flow depth = 0.410 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.7	-5.47	0.60	2.83	1.80	0.09	1.4	-0.73	0.40	3.00	1.40	0.98	1.1	0.93	0.33	2.87	1.37	0.93
3.0	-4.87	0.60	2.80	2.13	1.64	3.0	1.47	0.80	3.37	2.50	0.58	2.5	3.40	0.53	3.57	2.37	0.13
5.0	-4.80	1.40	3.40	2.73	5.60	5.0	2.33	1.07	3.87	3.10	3.64	4.5	5.00	1.00	3.73	3.33	2.44
9.0	-2.00	0.27	4.00	3.37	18.62	9.0	4.60	0.80	4.57	4.07	11.51	8.5	5.47	1.60	4.57	3.97	7.38
14.0	4.27	-0.13	5.00	4.13	18.76	14.0	7.27	0.27	5.30	4.60	18.40	13.5	8.00	1.53	4.83	4.27	14.40
19.0	12.60	0.27	5.50	4.63	19.87	19.0	10.40	1.00	5.30	4.87	22.13	18.5	12.00	0.53	5.70	4.97	22.58
26.0	24.80	-0.27	5.13	4.50	17.78	26.0	21.13	-0.47	5.57	4.83	23.91	25.5	21.40	-0.93	5.40	4.67	20.31
33.0	36.00	-0.40	3.97	3.70	3.64	33.0	30.40	-0.73	5.20	4.03	11.02	32.5	29.80	-1.07	5.00	3.67	13.87
39.0	44.40	-0.60	2.97	1.77	0.58	39.0	38.73	-0.73	3.10	2.07	3.29	38.5	34.13	-1.33	2.90	1.97	4.98

profile 7, x=2.25 m						profile 8, x=3.2 m						profile 9, x=3.6 m					
flow depth = 0.410 m						flow depth = 0.410 m						flow depth = 0.309 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	9.87	0.67	3.30	1.87	2.22	2.0	9.87	0.67	3.30	1.87	2.22	1.8	19.33	4.87	3.33	1.80	0.22
3.5	13.07	0.13	3.47	2.27	2.71	3.5	13.07	0.13	3.47	2.27	2.71	2.8	20.93	5.13	2.97	2.03	1.78
5.5	13.47	1.20	3.37	2.47	3.69	5.5	13.47	1.20	3.37	2.47	3.69	4.3	22.60	4.87	3.33	2.83	2.36
9.5	14.27	1.53	3.73	3.03	4.04	9.5	14.27	1.53	3.73	3.03	4.04	7.5	24.00	4.20	3.53	3.33	5.20
14.5	18.00	0.53	3.87	3.47	6.22	14.5	18.00	0.53	3.87	3.47	6.22	11.5	26.13	3.13	3.77	3.67	6.62
19.5	20.13	0.60	4.30	3.67	8.44	19.5	20.13	0.60	4.30	3.67	8.44	15.5	26.73	2.87	3.93	3.63	11.87
26.5	24.80	0.27	4.63	3.80	12.40	26.5	24.80	0.27	4.63	3.80	12.40	20.5	28.80	1.27	3.57	3.33	6.40
33.5	27.27	0.93	3.87	3.40	5.69	33.5	27.27	0.93	3.87	3.40	5.69	25.5	30.13	0.13	3.53	3.33	2.98
38.5	26.60	0.67	3.83	2.83	0.44	38.5	26.60	0.67	3.83	2.83	0.44	28.5	30.00	-0.47	3.43	2.67	1.24

profile 10, x=4.0 m						profile 11, x=4.4 m						profile					
flow depth = 0.214 m						flow depth = 0.208 m						flow depth =					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	33.07	3.47	4.87	2.53	3.78	1.4	19.73	-0.73	4.80	2.73	5.73						
2.0	38.00	3.93	3.47	2.00	0.98	2.0	27.93	-0.67	5.20	3.10	8.49						
3.0	40.00	3.93	2.93	2.37	1.78	3.0	34.20	-0.93	5.03	2.87	8.27						
5.0	40.07	2.80	2.97	2.80	2.27	5.0	40.20	-1.13	3.17	2.40	3.60						
7.5	40.13	2.27	2.80	3.40	4.58	7.5	40.80	-1.07	2.60	2.70	2.22						
10.0	39.93	1.73	3.13	3.50	6.40	10.0	41.60	-1.33	2.70	3.20	2.18						
13.5	40.33	0.27	2.77	3.30	2.89	13.5	41.47	-1.47	2.37	2.83	1.87						
17.0	40.27	-0.80	2.63	2.90	0.93	17.0	41.40	-1.60	2.47	2.53	0.22						
18.5	40.20	-0.87	3.07	2.53	0.31	18.5	41.33	-1.60	2.60	2.40	-0.18						

Table 15 T13

Q = discharge = 0.064 m^3/s

h_o = upstream flow depth = 0.317 m

$\bar{u}_o$ = upstream flow velocity = 0.40 m/s

i_o = upstream surface slope = 3.5 10^{-4}

k = average roughness height = 0.006 m

z = height above under side of the roughness elements (10^{-2} m)

$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)

$\bar{w}$ = vertical flow velocity (10^{-2} m/s)

$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)

$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)

$\overline{u'w'}$ = shear stress correlation (10^{-4} m^2/s^2)

profile 1, x=-0.2 m — flow depth = 0.317 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.0	16.00	0.47	4.47	2.67	6.49
2.0	23.80	0.00	4.23	2.47	5.11
3.5	27.73	0.20	4.13	2.57	5.29
6.5	34.73	0.27	3.63	2.67	5.24
10.5	38.40	-0.40	3.57	2.43	4.49
14.5	42.93	-0.87	3.07	2.23	3.82
20.5	47.10				
26.0	45.90				
29.0	43.30				

profile 2, x=0.4 m — flow depth = 0.419 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.8	-2.47	0.87	2.83	1.97	1.60
3.0	-1.33	0.93	3.00	2.53	5.73
5.0	1.20	0.47	3.83	3.23	10.31
9.0	9.53	0.07	5.03	3.40	12.84
14.0	24.00	-0.67	5.07	3.50	11.02
19.0	32.93	-1.07	3.80	2.60	4.76
26.0	39.73	-1.47	2.87	2.03	2.71
33.5	44.80				
39.0	41.50				

profile 3, x=0.8 m — flow depth = 0.520 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.6	-4.53	0.80	2.30	1.30	0.71
3.5	-4.67	0.80	2.27	1.90	1.51
6.0	-2.13	0.60	2.80	2.27	5.82
11.0	1.20	1.07	3.97	3.33	9.60
17.5	11.73	-0.00	5.17	4.33	17.47
24.0	23.47	-0.93	5.30	4.10	13.82
33.0	35.73	-1.60	3.17	2.43	3.78
41.5	42.90				
49.0	40.70				

profile 4, x=1.0 m — flow depth = 0.520 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	-2.80	0.67	2.23	1.07	0.09
3.0	-0.73	0.20	2.83	2.00	4.49
5.5	0.13	0.67	3.37	2.97	5.73
10.5	5.20	-0.07	4.87	3.87	10.58
17.0	10.60	-0.33	5.10	4.30	18.44
23.5	22.40	-0.87	5.40	4.23	19.91
32.5	33.33	-1.47	4.00	2.90	4.31
41.5	41.50				
49.0	39.40				

profile 5, x=1.55 m — flow depth = 0.520 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	1.53	0.33	2.93	1.50	1.96
3.0	4.47	0.80	3.50	2.77	2.76
5.5	5.20	1.07	3.70	3.30	5.24
10.5	6.80	0.47	4.27	3.93	8.44
17.0	11.27	0.27	4.77	4.43	20.36
23.5	19.73	0.80	5.37	4.27	18.89
32.5	33.93	-2.13	4.20	3.23	7.47
41.5	40.20				
49.0	38.60				

profile 6, x=1.75 m — flow depth = 0.520 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	4.53	0.20	3.70	1.83	1.33
3.0	6.33	0.67	3.60	2.70	2.18
5.5	8.00	0.47	4.00	3.43	6.22
10.5	10.00	0.27	4.80	4.70	11.51
17.0	12.60	0.47	4.83	4.37	12.67
23.5	22.13	-1.33	5.00	4.20	14.13
32.5	32.60	-2.00	4.13	3.03	8.76
41.5	40.20				
49.0	37.80				

profile 7, x=2.25 m — flow depth = 0.520 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.2	7.13	-0.20	3.47	2.20	1.82
3.0	8.80	0.07	3.70	2.47	2.13
5.5	11.67	0.73	3.60	3.13	4.84
10.5	13.93	0.53	4.10	3.73	7.78
17.0	16.47	0.40	5.03	4.33	12.62
23.5	22.67	-0.67	5.40	4.13	13.24
32.5	30.93	-1.20	4.63	3.40	7.07
41.5	39.30				
49.0	36.00				

profile 8, x=3.2 m — flow depth = 0.522 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.8	7.60	0.00	2.83	1.63	0.71
3.5	12.53	0.87	3.17	2.27	2.71
6.0	13.53	1.47	3.20	2.50	4.04
11.0	17.07	1.20	3.70	3.27	8.98
17.5	21.47	0.27	4.13	3.53	8.18
24.0	24.67	-0.27	4.93	4.07	12.93
33.0	32.80	-0.27	4.47	3.17	8.18
41.5	38.10				
49.0	33.30				

profile 9, x=3.6 m — flow depth = 0.423 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.6	18.00	5.07	3.50	1.83	-0.13
3.0	21.73	4.60	3.30	2.43	0.53
5.0	22.13	4.80	3.03	2.67	2.89
9.0	23.87	4.07	3.83	3.40	7.91
14.0	27.67	3.13	4.27	3.67	9.20
19.0	32.53	1.47	4.40	3.77	11.51
26.0	37.00	0.60	4.00	3.07	6.89
33.5	38.20				
39.0	33.50				

profile 10, x=4.0 m — flow depth = 0.317 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	31.33	2.67	4.43	2.27	3.51
2.3	36.13	3.40	3.40	2.10	1.51
3.8	37.47	3.13	3.23	2.87	1.20
7.0	38.13	3.33	3.70	3.40	6.00
11.0	38.53	2.60	3.87	3.43	10.89
15.0	41.93	1.53	4.13	3.50	9.69
20.5	44.80				
26.0	42.60				
28.5	38.20				

profile 11, x=4.4 m — flow depth = 0.317 m

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
1.3	17.07	-0.93	5.10	3.10	9.11
2.3	28.33	-0.53	5.13	3.27	8.31
3.8	33.87	-0.47	4.80	2.77	6.44
7.0	39.20	-0.67	3.97	2.83	5.16
11.0	40.40	-0.53	3.47	2.97	8.22
15.0	42.80	-1.60	3.73	3.13	7.29
20.5	45.80				
26.0	42.20				
28.5	39.00				

profile — flow depth =

z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$

Table 16 T14

Q	= discharge	= 0.041 m^3/s
h_o	= upstream flow depth	= 0.20 m
$\bar{u}_o$	= upstream flow velocity	= 0.395 m/s
i_o	= upstream surface slope	= 7.8 10^{-4}
k	= average roughness height	= 0.011 m
z	= height above under side of the roughness elements (10^{-2} m)	
$\bar{u}$	= longitudinal flow velocity (10^{-2} m/s)	
$\bar{w}$	= vertical flow velocity (10^{-2} m/s)	
$\tilde{u}$	= longitudinal turbulence intensity (10^{-2} m/s)	
$\tilde{w}$	= vertical turbulence intensity (10^{-2} m/s)	
$\overline{u'w'}$	= shear stress correlation (10^{-4} m^2/s^2)	

profile 1, x=-0.2 m						profile 2, x=0.4 m						profile 3, x=0.8 m					
flow depth = 0.200 m						flow depth = 0.271 m						flow depth = 0.337 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.35	22.60		3.30			2.50	1.00		2.44			2.75	-0.40		1.61		
3.25	28.40		3.57			3.40	5.00		2.81			3.40	-2.00		2.08		
5.35	32.50		3.66			4.75	9.90		3.86			5.10	-0.70		2.41		
7.95	36.60		3.50			7.45	19.80		4.73			8.50	4.30		3.46		
10.60	41.80		3.13			10.95	28.80		4.05			12.80	12.60		4.46		
14.10	47.70		2.64			14.45	33.40		3.38			17.10	20.10		5.18		
17.60	48.00		1.97			18.85	40.50		3.12			22.90	35.20		3.83		
18.80	47.90		1.58			23.35	43.90		2.01			28.70	40.00		2.83		
						25.50	42.50		1.29			32.55	41.30		1.60		

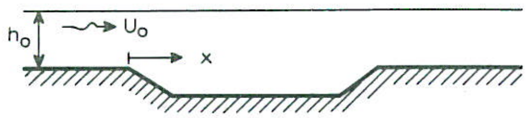
profile 4, x=1.2 m						profile 5, x=1.5 m						profile 6, x=1.75 m					
flow depth = 0.404 m						flow depth = 0.404 m						flow depth = 0.404 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.45	-1.30		1.34			2.45	0.00		1.41			2.	0.10		1.14		
3.75	-1.50		1.53			3.75	0.60		1.71			3.	1.10		1.39		
5.85	-1.10		1.64			5.85	1.00		1.62			5.	2.30		2.35		
9.95	1.80		2.63			9.95	3.50		2.59			9.	3.10		2.59		
15.15	0.90		3.37			15.15	7.60		3.44			15.	8.40		4.08		
20.35	15.40		4.88			20.35	12.80		4.62			20.	17.00		4.99		
27.15	28.20		5.02			27.15	28.20		5.05			27.	25.80		5.30		
33.95	38.50		3.30			33.95	34.50		3.52			33.	36.20		3.98		
39.45	37.70		1.90			39.45	37.50		1.94			39.	36.30		2.16		

profile 7, x=2.25 m						profile 8, x=2.80 m						profile 9, x=3.40 m					
flow depth = 0.401 m						flow depth = 0.402 m						flow depth = 0.298 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.30	2.30		1.88			2.50	6.30		1.44			2.55	17.00		2.56		
3.60	4.80		2.52			3.80	7.40		2.10			3.65	20.80		2.62		
5.70	5.60		2.57			5.90	9.60		2.71			5.15	22.10		2.99		
9.80	6.60		3.18			10.00	12.20		2.99			8.25	23.90		3.36		
15.00	10.50		4.25			15.20	15.60		3.97			12.05	26.80		3.75		
20.20	14.50		4.89			20.40	18.00		4.33			15.35	29.00		4.04		
27.00	31.70		5.45			27.20	28.10		4.67			21.05	30.70		3.84		
33.80	36.90		3.30			34.00	32.20		3.36			26.25	31.50		2.90		
39.30	32.70		3.17			39.50	28.10		3.60			29.15	29.00		2.76		

profile 10, x=4.0 m						profile						profile					
flow depth = 0.195 m						flow depth =						flow depth =					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.50	34.50		3.42														
3.20	37.50		3.00														
4.30	38.70		2.66														
6.40	39.40		2.57														
7.70	39.90		2.71														
9.00	41.60		2.57														
12.50	41.80		2.44														
16.00	41.30		2.09														
18.55	38.90		1.95														

Table 17 T15

Q = discharge = 0.0405 m^3/s
h_o = upstream flow depth = 0.20 m
$\bar{u}_o$ = upstream flow velocity = 0.39 m/s
i_o = upstream surface slope = 7.4 10^{-4}
k = average roughness height = 0.011 m
z = height above under side of the roughness elements (10^{-2} m)
$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)
$\bar{w}$ = vertical flow velocity (10^{-2} m/s)
$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)
$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)
$\overline{u'w'}$ = shear stress correlation (10^{-4} m^2/s^2)



profile 1, x=-0.2 m						profile 2, x=0.4 m						profile 3, x=0.8 m					
flow depth = 0.200 m						flow depth = 0.243 m						flow depth = 0.295 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.6	22.90		3.06			2.7	9.60		3.68			3.0	4.30		2.63		
3.3	25.00		3.11			3.6	11.20		4.29			4.1	5.10		2.84		
4.3	28.60		3.69			4.9	19.10		4.16			5.7	8.30		3.22		
5.4	33.70		3.58			7.5	25.80		4.71			8.8	18.40		4.74		
7.9	39.30		3.80			10.7	31.70		3.86			12.6	22.80		4.26		
10.4	43.90		3.34			13.9	38.30		3.44			16.4	29.50		4.67		
13.9	47.30		2.69			18.2	41.50		3.25			21.6	38.40		3.14		
17.4	46.80		1.87			22.5	43.60		2.11			26.8	39.60		2.30		
18.4	45.60		1.48			23.5	42.80		1.61			28.8	39.10		2.00		

profile 4, x=1.2 m						profile 5, x=1.6 m						profile 6, x=2.0 m					
flow depth = 0.345 m						flow depth = 0.396 m						flow depth = 0.398 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.7	2.40		1.79			2.8	0.00		1.45			2.9	2.40		1.83		
3.9	3.00		2.00			4.1	1.30		1.36			4.2	2.10		1.48		
5.7	4.70		2.50			6.1	1.40		1.61			6.2	2.80		1.98		
9.3	7.10		3.24			10.2	5.20		3.23			10.3	4.70		2.64		
13.8	11.90		3.64			15.3	7.20		3.12			15.4	10.10		3.96		
18.3	25.30		4.32			20.4	18.40		3.89			20.5	19.00		4.57		
24.3	33.40		4.17			26.6	29.10		4.32			26.7	26.80		4.46		
30.3	39.60		2.27			32.8	34.00		3.58			32.9	32.40		3.68		
33.5	37.50		1.59			38.6	36.00		1.71			38.7	34.50		2.29		

profile 7, x=2.4 m						profile 8, x=3.2 m						profile 9, x=4.0 m					
flow depth = 0.402 m						flow depth = 0.292 m						flow depth = 0.198 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
3.3	3.50		1.85			2.5	18.40		2.53			2.6	34.80		2.88		
4.6	3.50		1.68			3.6	18.40		2.43			3.3	36.40		2.83		
6.6	5.30		2.20			5.2	19.80		2.64			4.3	40.20		3.00		
10.7	6.50		2.62			8.3	21.90		2.97			6.4	40.10		2.57		
15.8	9.20		3.27			12.1	24.90		3.50			8.9	41.20		2.66		
20.9	19.80		4.95			15.9	28.70		4.14			11.4	41.70		2.56		
27.1	24.60		4.67			21.1	31.70		3.58			14.9	40.20		2.39		
33.3	33.10		3.40			26.3	30.80		3.04			18.4	38.90		2.06		
39.1	31.70		2.63			28.3	30.20		2.75			19.4	31.90		2.07		

profile						profile						profile					
flow depth =						flow depth =						flow depth =					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$

Table 18 T16

Q = discharge = 0.042 m^3/s
h_o = upstream flow depth = 0.207 m
$\underline{u}_o$ = upstream flow velocity = 0.405 m/s
i_o = upstream surface slope = 5.4 10^{-4}
k = average roughness height = 0.006 m
z = height above under side of the roughness elements (10^{-2} m)
$\bar{u}$ = longitudinal flow velocity (10^{-2} m/s)
$\bar{w}$ = vertical flow velocity (10^{-2} m/s)
$\tilde{u}$ = longitudinal turbulence intensity (10^{-2} m/s)
$\tilde{w}$ = vertical turbulence intensity (10^{-2} m/s)
$\overline{u'w'}$ = shear stress correlation (10^{-4} m^2/s^2)

profile 1A						profile 1B						profile 1C					
flow depth = 0.212 m						flow depth = 0.212 m						flow depth = 0.212 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	33.10					2.0	34.30					2.0	33.20				
2.7	35.40					2.7	36.30					2.7	34.20				
3.7	37.80					3.7	38.90					3.7	37.10				
5.7	40.50					5.7	42.10					5.7	40.80				
8.2	40.50					8.2	44.80					8.2	42.50				
10.7	40.50					10.7	47.70					10.7	46.60				
14.0	40.80					14.0	49.40					14.0	47.80				
17.3	39.60					17.3	46.10					17.3	46.70				

profile 2A						profile 2B						profile 2C					
flow depth = 0.412 m						flow depth = 0.412 m						flow depth = 0.412 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	-2.40					2.0	-5.40					2.0	8.30				
3.5	-1.30					3.5	-5.40					3.5	-7.10				
5.5	-0.40					5.5	-4.10					5.5	-5.90				
9.5	2.60					9.5	-0.40					9.5	-4.60				
14.5	8.20					14.5	6.50					14.5	5.40				
19.5	24.50					19.5	20.60					19.5	16.60				
26.5	40.70					26.5	40.50					26.5	36.90				
33.5	39.80					33.5	48.10					33.5	46.30				
37.5	37.40					37.5	44.30					37.5	45.90				

profile 3A						profile 3B						profile 3C					
flow depth = 0.412 m						flow depth = 0.412 m						flow depth = 0.412 m					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$
2.0	5.70					2.0	6.10					2.0	3.80				
3.5	5.50					3.5	8.10					3.5	4.30				
5.5	5.30					5.5	9.40					5.5	4.30				
9.5	9.90					9.5	11.00					9.5	8.80				
14.5	12.20					14.5	18.50					14.5	10.90				
19.5	17.60					19.5	20.20					19.5	16.90				
26.5	22.60					26.5	31.20					26.5	27.00				
33.5	20.20					33.5	37.00					33.5	34.40				
37.5	16.70					37.5	30.40					37.5	35.10				

profile						profile						profile					
flow depth =						flow depth =						flow depth =					
z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$	z	$\bar{u}$	$\bar{w}$	$\tilde{u}$	$\tilde{w}$	$\overline{u'w'}$

Table 19 T17

Test 1

profile 2		profile 3		profile 4		profile 5		profile 6		profile 7	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	-0.15	1.5	0.17	1.5	0.90	1.5	1.49	1.5	2.31	1.5	3.18
10.2	-0.24	10.2	-0.13	10.2	0.65	10.2	1.09	10.2	2.00	10.2	2.94
20.4	-0.30	20.4	-0.21	20.4	0.59	20.4	1.16	20.4	1.94	20.4	2.70
30.5	-0.02	30.5	0.20	30.5	0.81	30.5	1.30	30.5	2.15	30.5	2.88

Test 1

profile 8		profile 9		profile 10		profile 11		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	3.90	1.5	3.97	1.5	4.04	3.86					
10.3	3.68	10.1	3.86	10.1	3.98	3.80					
20.6	3.63	20.3	3.89	20.3	3.97	3.78					
30.8	3.48	30.4	3.84	30.4	3.98	3.74					

Test 2

profile 2		profile 3		profile 4		profile 5		profile 6		profile 7	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	0.05	1.5	0.12	1.5	0.14	1.5	0.39	1.5	0.57	1.5	0.82
5.2	0.08	7.6	0.08	7.6	0.05	7.6	0.27	7.6	0.50	7.6	0.78
10.3	0.10	15.3	0.02	15.2	0.01	15.2	0.18	15.2	0.45	15.2	0.69
15.5	0.14	22.9	0.07	22.8	0.04	22.7	0.24	22.7	0.44	22.8	0.71

Test 2

profile 8		profile 9		profile		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	0.93	1.5	0.95								
7.6	0.91	7.6	0.91								
15.2	0.86	15.3	0.87								
22.8	0.84	22.9	0.83								

z = height above underside of the grains (10^{-2} m)

Δh = static pressure difference with respect to profile 1 (10^{-3} m)

Table 20 T1, T2

Test 3

profile 2		profile 4		profile 5		profile 6		profile 7		profile 8	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	0.09	1.5	0.09	1.5	0.30	1.5	0.62	1.5	0.72	1.5	0.94
10.0	0.02	10.0	0.00	10.0	0.19	10.0	0.46	10.0	0.64	10.0	0.86
20.0	-0.02	20.0	-0.04	20.0	0.16	20.0	0.39	20.0	0.67	20.0	0.82
30.0	-0.01	30.0	0.02	30.0	0.19	30.0	0.42	30.0	0.62	30.0	0.79

Test 3

profile 9		profile		profile		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	1.07										
10.0	0.98										
20.0	0.87										
30.0	0.80										

Test 4

profile 3		profile 4		profile 5		profile 6		profile 7		profile 8	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	0.10	1.5	0.09	1.5	0.30	1.5	0.55	1.5	0.70	1.5	0.82
13.2	0.02	13.2	0.04	13.2	0.21	13.2	0.41	13.0	0.56	13.0	0.73
26.4	0.05	26.4	0.09	26.4	0.22	26.4	0.43	26.0	0.60	26.0	0.69
39.5	0.01	39.5	0.11	39.5	0.24	39.5	0.53	39.0	0.62	39.0	0.71

Test 4

profile 9		profile		profile		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	0.90										
13.1	0.76										
26.2	0.65										
39.2	0.58										

z = height above underside of the grains (10^{-2} m)

Δh = static pressure difference with respect to profile 1 (10^{-3} m)

Table 21 T3, T4

Test 5

profile 2		profile 4		profile 5		profile 6		profile 7		profile 8	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	0.08	1.5	0.42	1.5	1.29	1.5	2.53	1.5	3.54	1.5	4.09
7.5	-0.01	7.5	0.03	7.5	0.88	7.5	2.47	7.5	3.29	7.5	3.86
15.0	-0.26	15.0	-0.14	15.0	0.84	15.0	2.17	15.0	3.16	15.0	3.74
22.4	-0.13	22.4	-0.20	22.4	1.00	22.4	2.23	22.4	3.14	22.4	3.72

Test 5

profile 9		profile		profile		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	4.32										
7.5	3.86										
15.0	3.67										
22.4	3.56										

Test 6

profile		profile 3		profile 4		profile 5		profile 6		profile 7	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
		1.5	0.07	1.5	0.42	1.5	1.43	1.5	2.78	1.5	3.20
		10.1	-0.06	10.1	0.05	10.1	0.90	10.1	2.50	10.1	2.98
		20.2	-0.08	20.2	-0.01	20.2	0.77	20.2	2.24	20.2	2.66
		30.2	0.28	30.2	0.55	30.2	1.21	30.2	2.51	30.2	2.79

Test 6

profile 8		profile 9		profile		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	3.89	1.5	4.48								
10.1	3.72	10.1	4.02								
20.2	3.64	20.2	3.64								
30.2	3.59	30.3	3.44								

z = height above underside of the grains (10^{-2} m)

Δh = static pressure difference with respect to profile 1 (10^{-3} m)

Table 22 T5, T6

Test 7

profile 3		profile 5		profile 6		profile 7		profile 8		profile 9	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
2.5	-0.39	2.5	0.13	2.5	0.91	2.5	2.43	2.5	2.74	2.5	3.93
10.0	-0.56	10.0	-0.11	10.0	0.47	10.0	2.17	10.0	2.59	10.0	3.49
20.0	-0.74	20.0	-0.27	20.0	0.23	20.0	1.98	20.0	2.39	20.0	3.40
30.0	-0.33	30.0	0.25	30.0	0.73	30.0	2.07	30.0	2.64	30.0	3.25

Test 7

profile 10		profile 11		profile 12		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
2.5	4.47	2.5	2.01	2.5	-4.20						
10.0	4.12	7.6	2.13	4.9	-4.24						
20.0	3.85	15.2	1.55	9.7	-2.94						
30.0	3.60	22.8	2.34	14.6	-2.12						

Test 9

		profile 3		profile 4		profile 5		profile 6		profile 7	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
		1.5	0.10	1.5	0.26	1.5	1.24	1.5	2.13	1.5	2.98
		13.1	0.00	13.0	0.03	13.0	0.78	13.1	1.70	13.0	2.52
		26.1	0.14	26.1	0.33	26.0	1.04	26.2	1.80	26.0	2.51
		39.2	0.25	39.1	0.47	39.0	1.31	39.2	2.21	39.0	2.85

Test 9

profile 8		profile 9		profile		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	3.39	1.5	3.95								
13.0	3.14	13.0	3.50								
26.0	3.09	26.0	3.10								
39.0	3.25	39.0	2.87								

z = height above underside of the grains (10^{-2} m)

Δh = static pressure difference with respect to profile 1 (10^{-3} m)

Table 23 T7, T9

Test 12

profile 2		profile 3		profile 4		profile 5		profile 6		profile 7	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	2.09	1.5	2.79	1.5	3.69	1.5	4.54	1.5	5.19	1.5	5.69
4.9	2.00	7.6	2.44	7.6	3.54	7.6	4.34	7.6	5.04	7.6	5.59
9.8	1.99	15.2	2.39	15.2	3.34	15.2	4.04	15.2	4.64	15.2	5.54
14.6	2.14	22.7	2.34	22.7	3.39	22.7	4.04	22.7	4.59	22.7	5.34

Test 13

profile 2		profile 3		profile 4		profile 5		profile 6		profile 7	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	1.52	1.5	2.25	1.5	2.52	1.5	3.27	1.5	3.97	1.5	4.32
7.8	1.54	10.3	2.34	10.3	2.32	10.3	2.97	10.3	3.52	10.3	4.12
15.5	1.72	20.5	2.32	20.5	2.27	20.5	3.00	20.5	3.47	20.5	4.07
23.3	1.74	30.8	2.30	30.8	2.32	30.8	3.12	30.8	3.52	30.8	4.12

Test 14

profile 2		profile 3		profile 4		profile 5		profile 6		profile 7	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
1.5	1.12	1.5	1.72	1.5	2.42	1.5	2.92	1.5	3.24	1.5	3.67
10.5	1.12	13.0	1.47	13.0	2.17	13.0	2.67	13.0	3.02	13.0	3.37
21.0	1.10	26.0	1.67	26.0	2.17	26.0	2.64	26.0	3.02	26.0	3.27
31.4	1.12	39.0	1.57	39.0	2.34	39.0	2.70	39.0	3.07	39.0	3.37

Test 15

profile 2		profile 3		profile 4		profile 5		profile 6		profile 7	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
2.5	1.48	2.5	2.49	2.5	3.05	2.5	3.62	2.5	3.98	2.5	4.57
6.8	1.43	8.4	2.66	10.1	2.88	10.1	3.53	10.1	3.69	10.0	4.32
13.6	1.54	16.9	2.69	20.2	3.02	20.2	3.21	20.2	3.72	20.1	4.18
20.3	1.70	25.3	2.47	30.3	3.18	30.3	3.23	30.3	3.86	30.1	3.98

z = height above underside of the grains (10^{-2} m)

Δh = static pressure difference with respect to profile 1 (10^{-3} m)

Table 24 T12, T13, T14, T15

Test 16

profile 2		profile 3		profile 4		profile 5		profile 6		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh
2.5	1.29	2.5	2.47	2.5	3.23	2.5	3.70	2.5	4.11		
6.1	1.25	7.4	2.38	8.6	3.08	9.9	3.55	10.0	3.95		
12.2	1.35	14.8	2.41	17.3	3.02	19.9	3.40	19.9	3.90		
18.2	1.36	22.1	2.50	25.9	3.17	29.7	3.62	29.9	4.01		

Test

profile		profile		profile		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh

Test

profile		profile		profile		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh

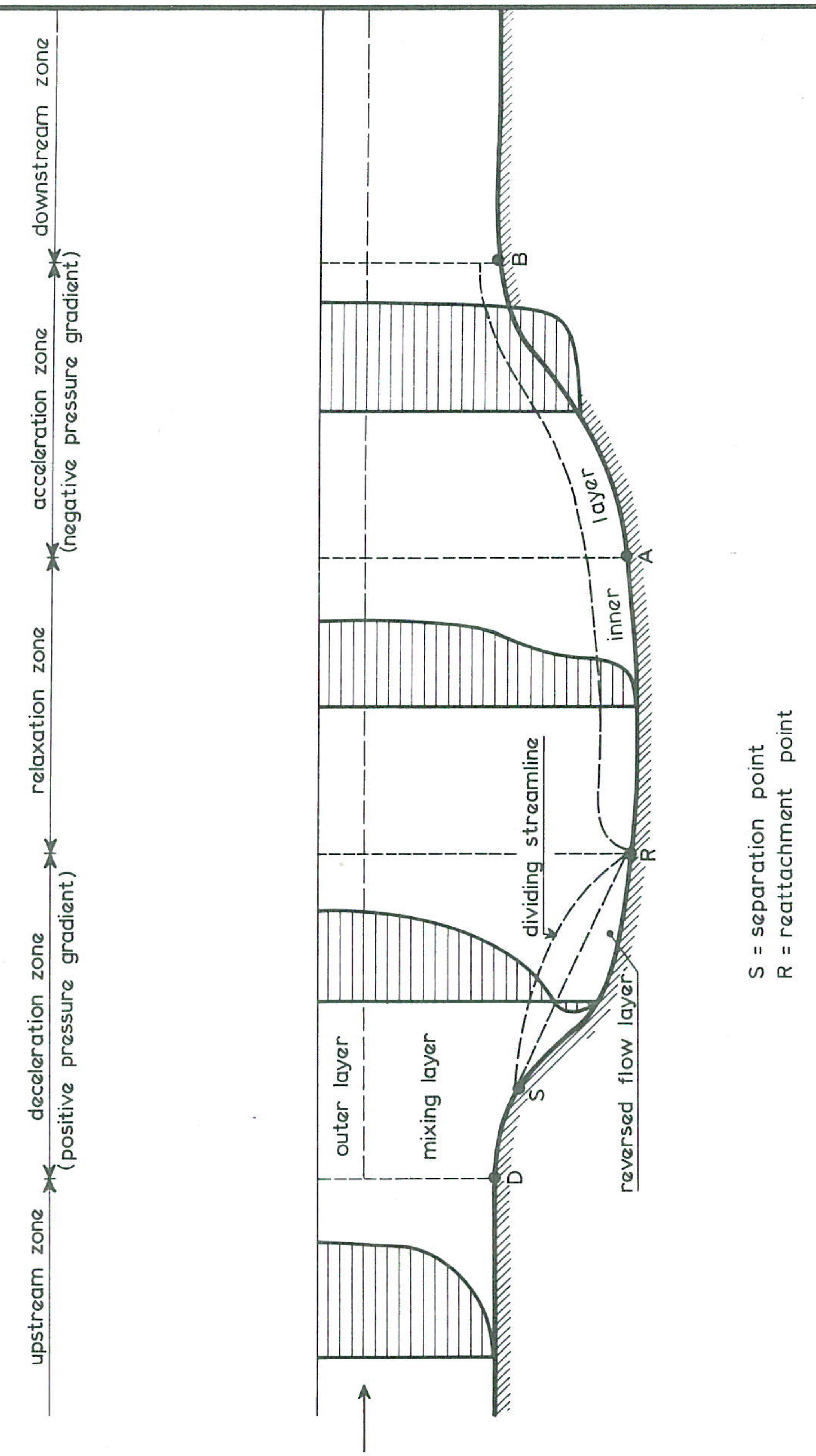
Test

profile		profile		profile		profile		profile		profile	
z	Δh	z	Δh	z	Δh	z	Δh	z	Δh	z	Δh

z = height above underside of the grains (10^{-2} m)

Δh = static pressure difference with respect to profile 1 (10^{-3} m)

Table 25 T16

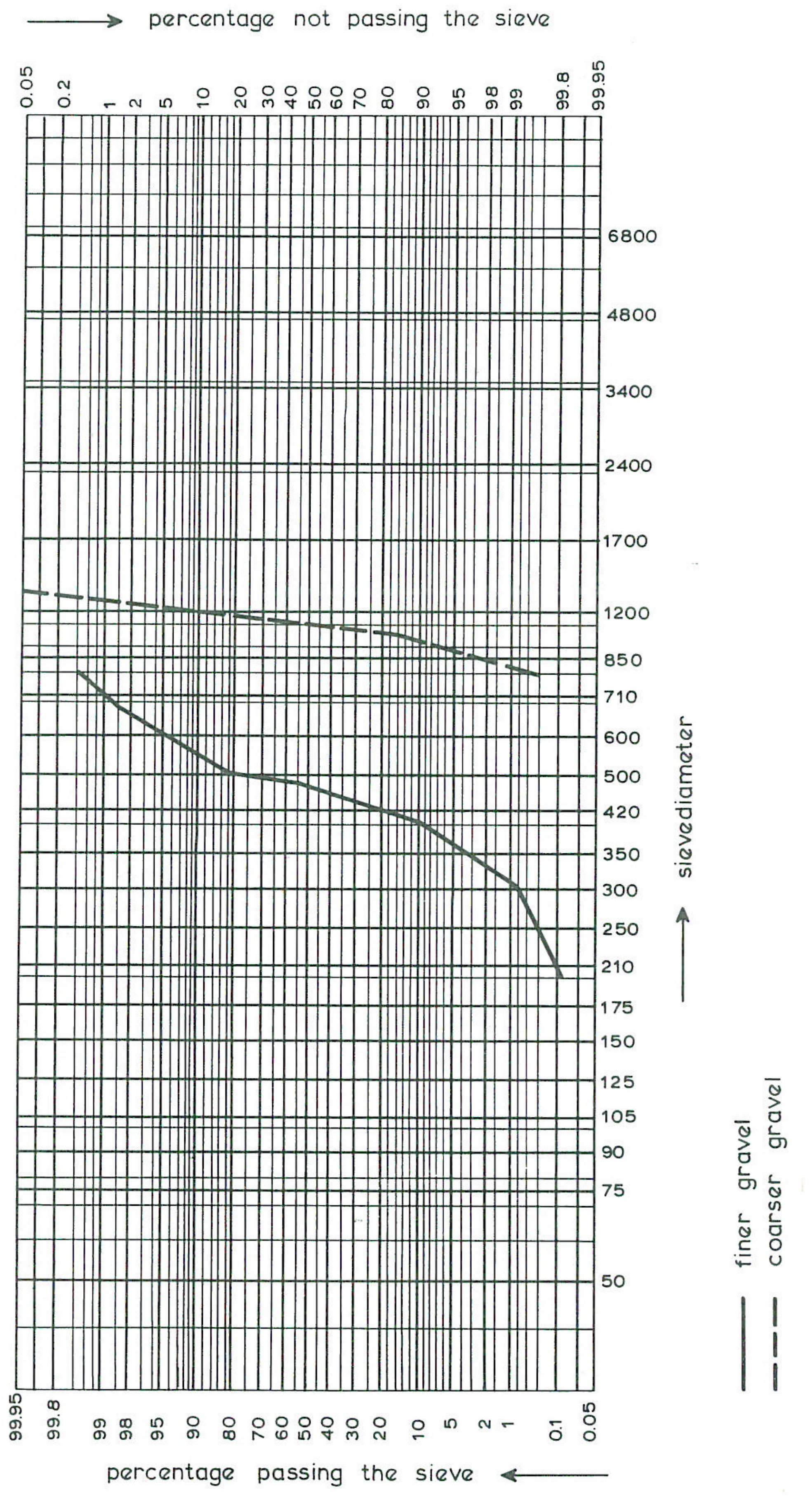


SKETCH OF FLOW VELOCITY PROFILES

DELFT HYDRAULICS LABORATORY

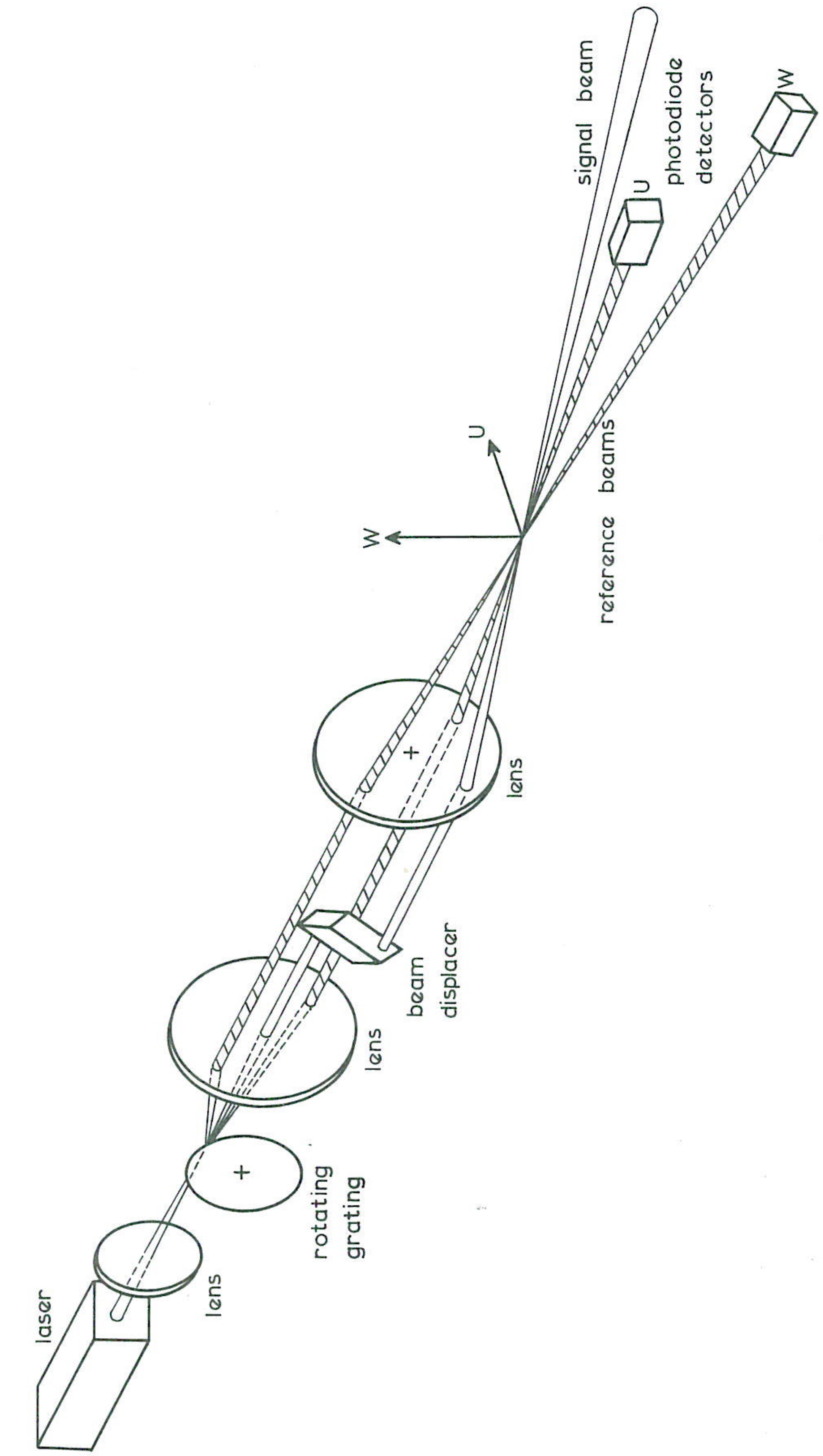
R1267-III/M1536

FIG. 1



SIZE DISTRIBUTIONS OF GRAVEL

DELFT HYDRAULICS LABORATORY | R1267-III/M1536 | FIG. 2

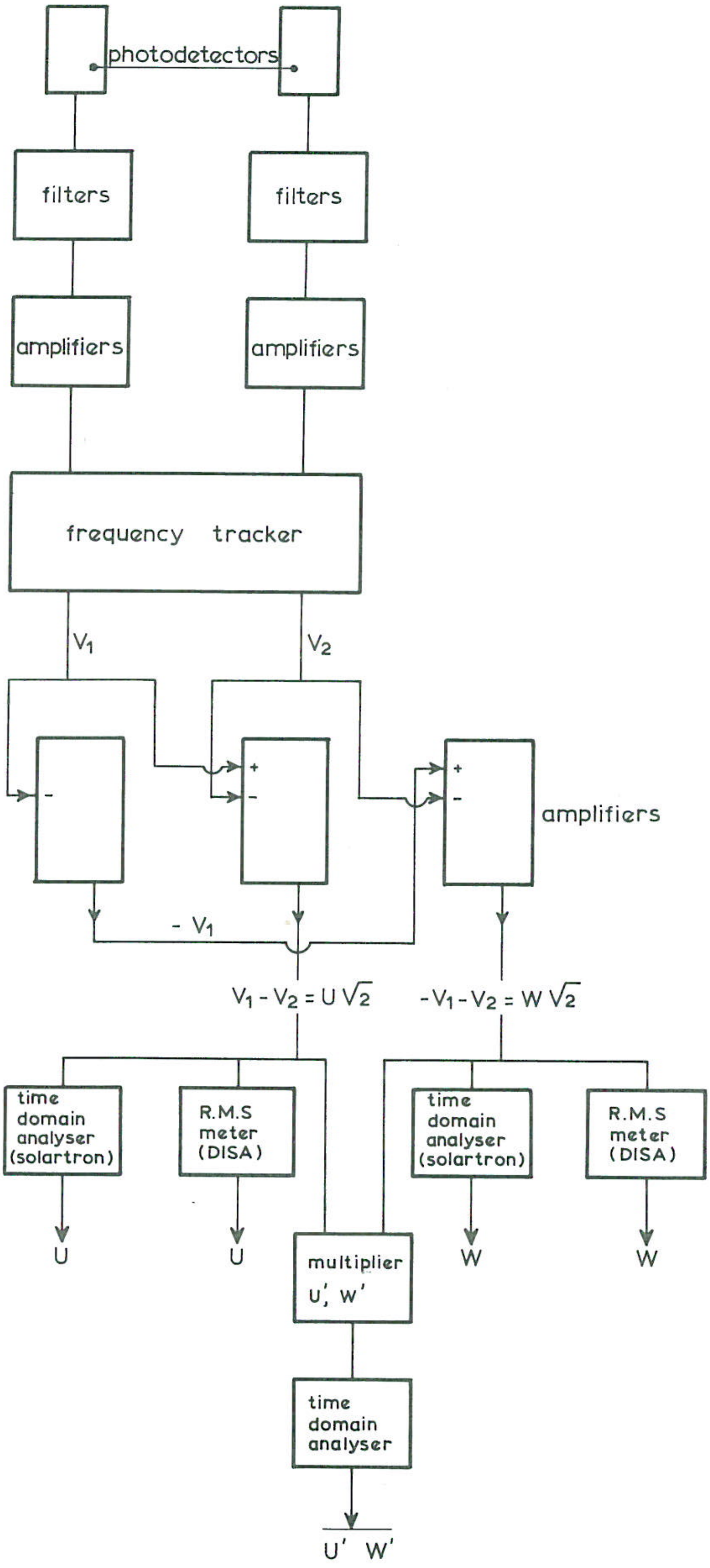


BEAM CONFIGURATION OF LASER DOPPLER VELOCITY METER

DELFT HYDRAULICS LABORATORY

R1267-III/M1536

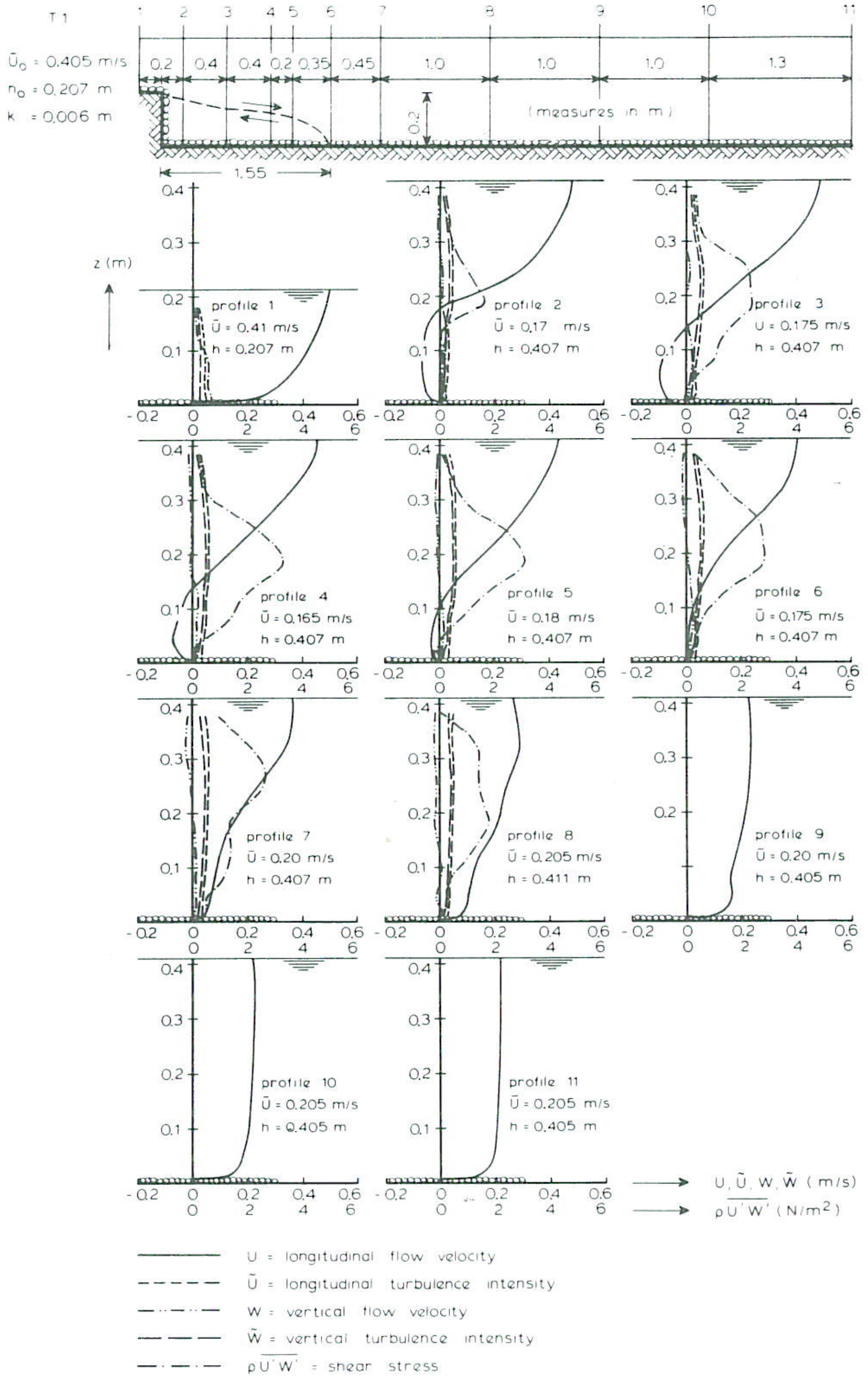
FIG. 3



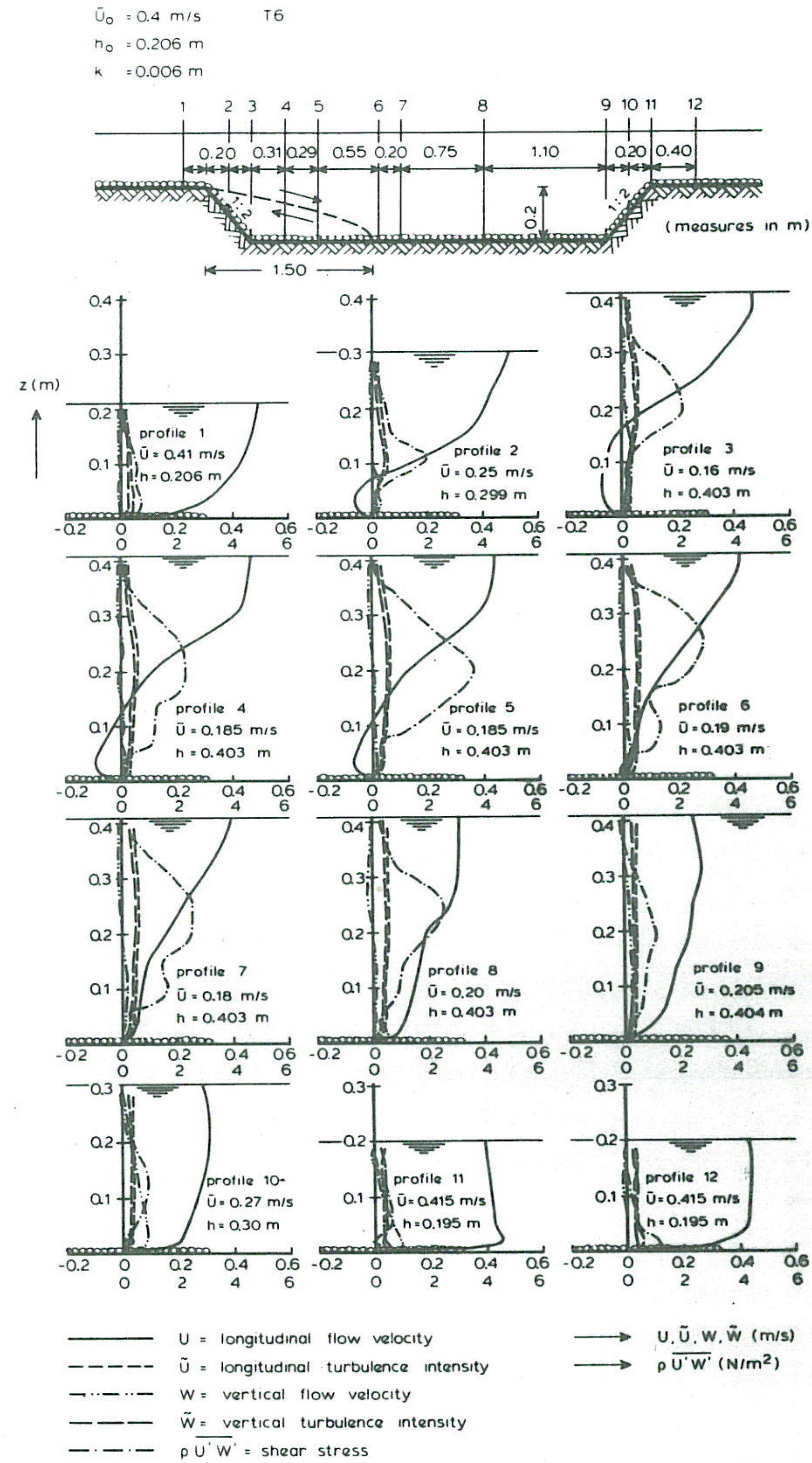
SCHEME OF SIGNAL CONVERTING EQUIPMENT

DELFT HYDRAULICS LABORATORY

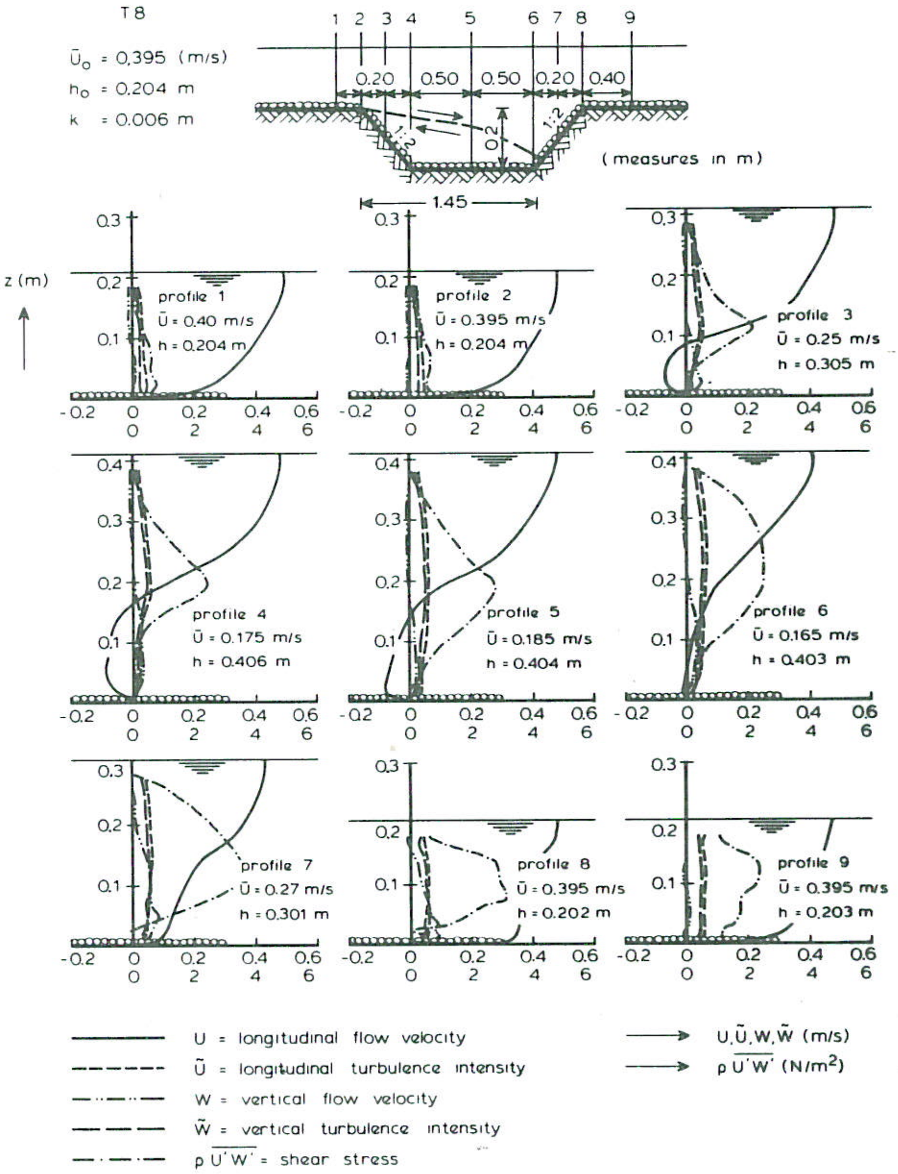
R1267-III/M1536 FIG. 4



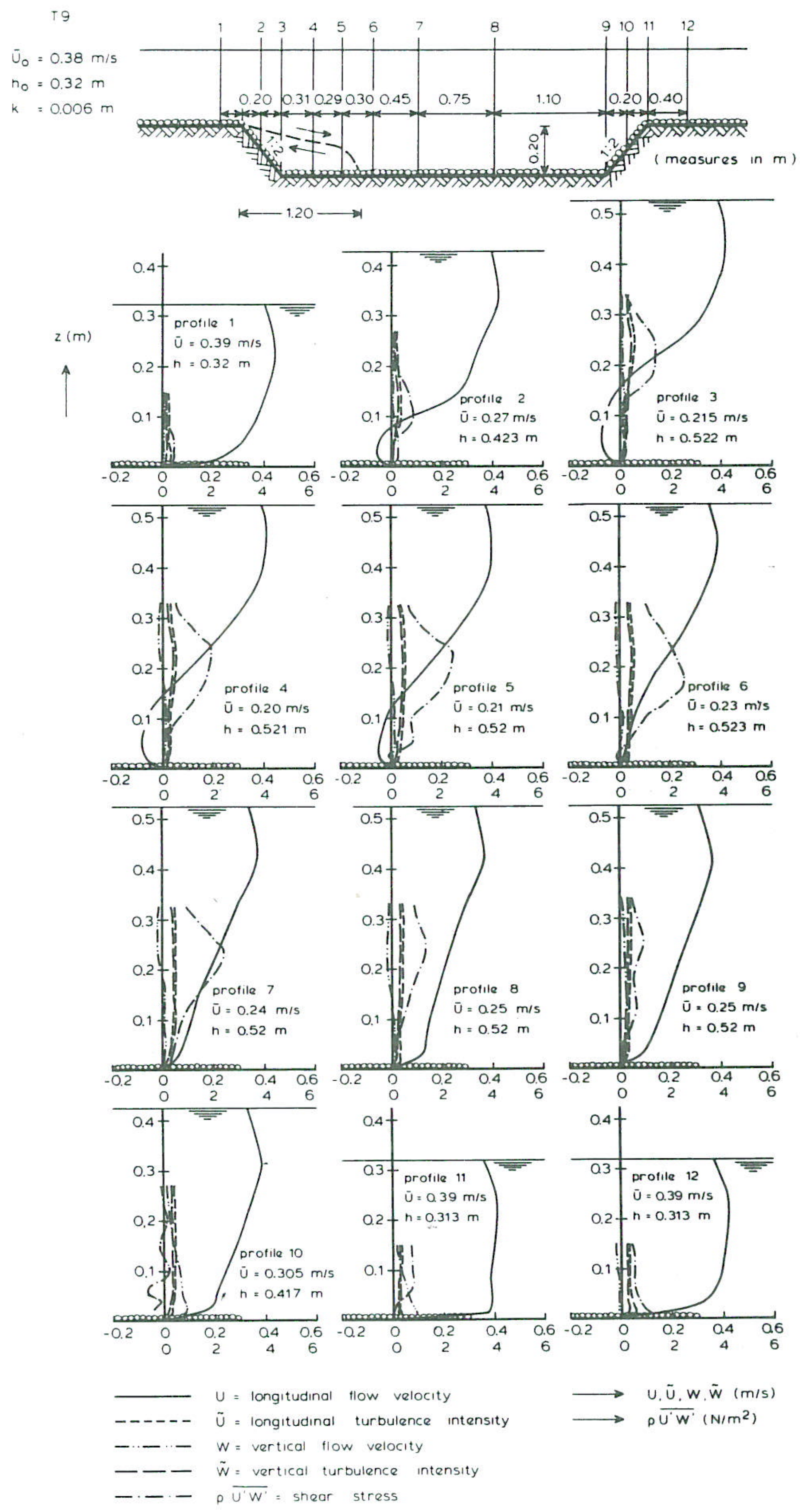
LONGITUDINAL DISTRIBUTION OF FLOW VELOCITIES, TURBULENCE INTENSITIES AND SHEAR STRESSES	T 1	
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 5



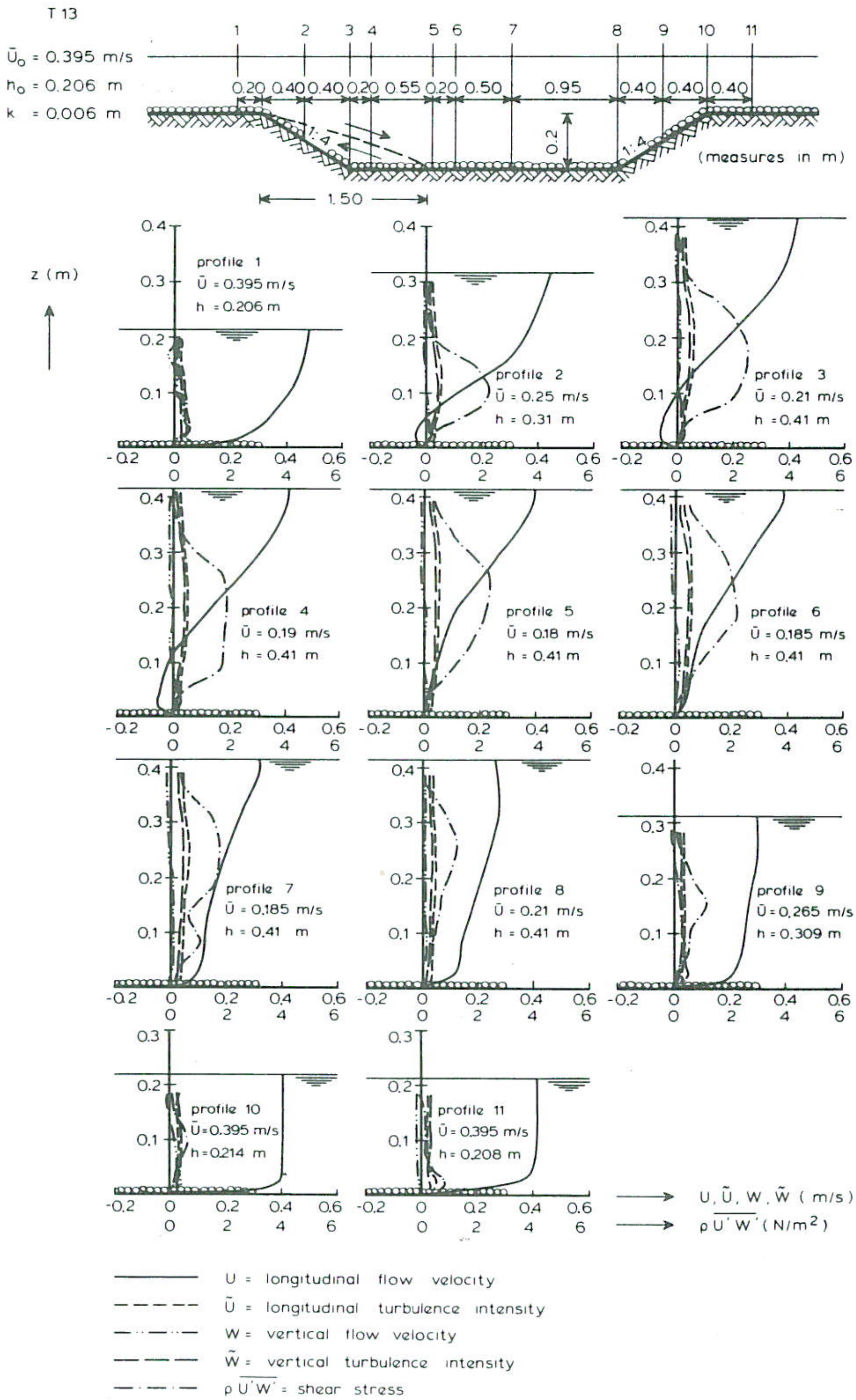
LONGITUDINAL DISTRIBUTION OF FLOW VELOCITIES, TURBULENCE INTENSITIES AND SHEAR STRESSES	T6
DELFT HYDRAULICS LABORATORY	R1267-III/M1536 FIG. 6



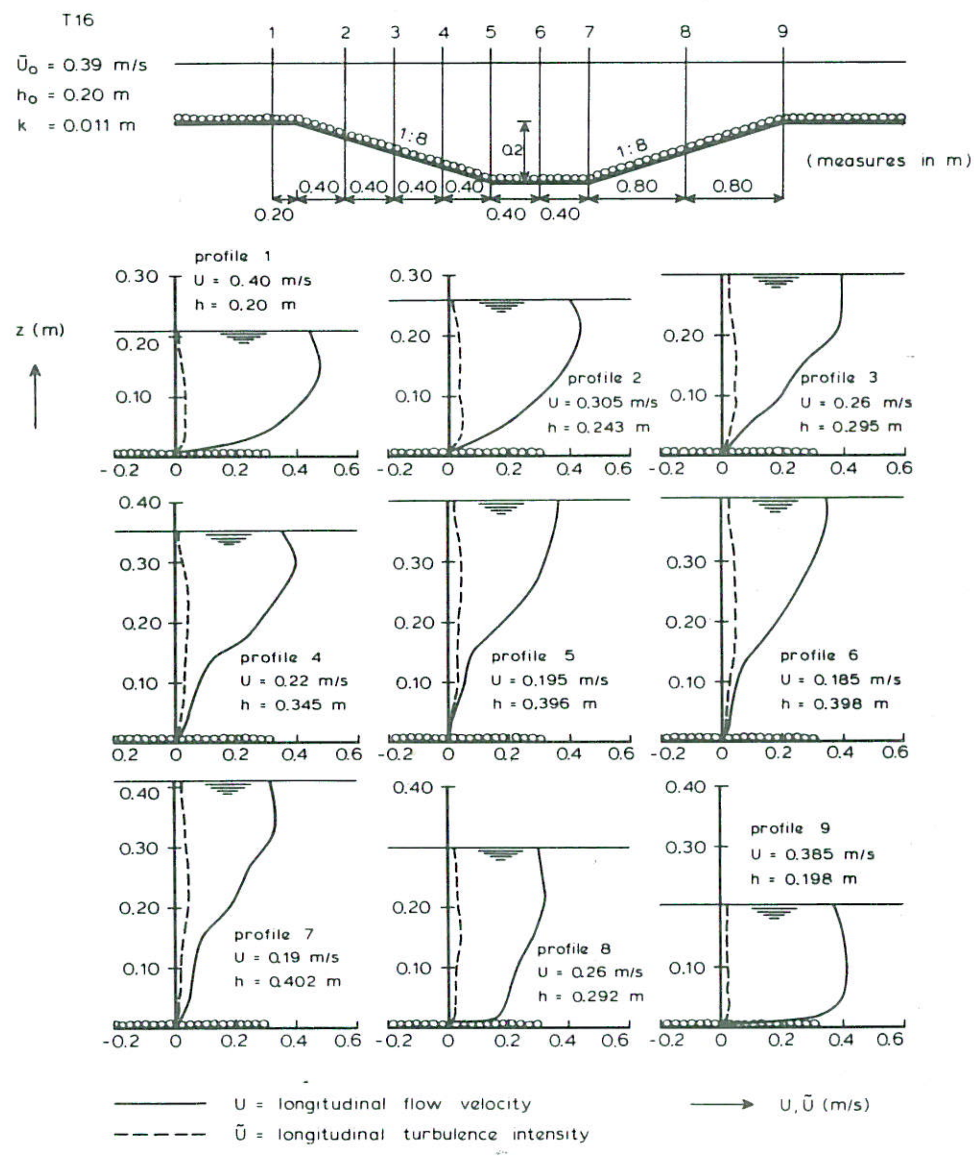
LONGITUDINAL DISTRIBUTION OF FLOW VELOCITIES, TURBULENCE INTENSITIES AND SHEAR STRESSES	T 8	
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 7



LONGITUDINAL DISTRIBUTION OF FLOW VELOCITIES, TURBULENCE INTENSITIES AND SHEAR STRESSES	T9	
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 8



LONGITUDINAL DISTRIBUTION OF FLOW VELOCITIES, TURBULENCE INTENSITIES AND SHEAR STRESSES	T 13	
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 9



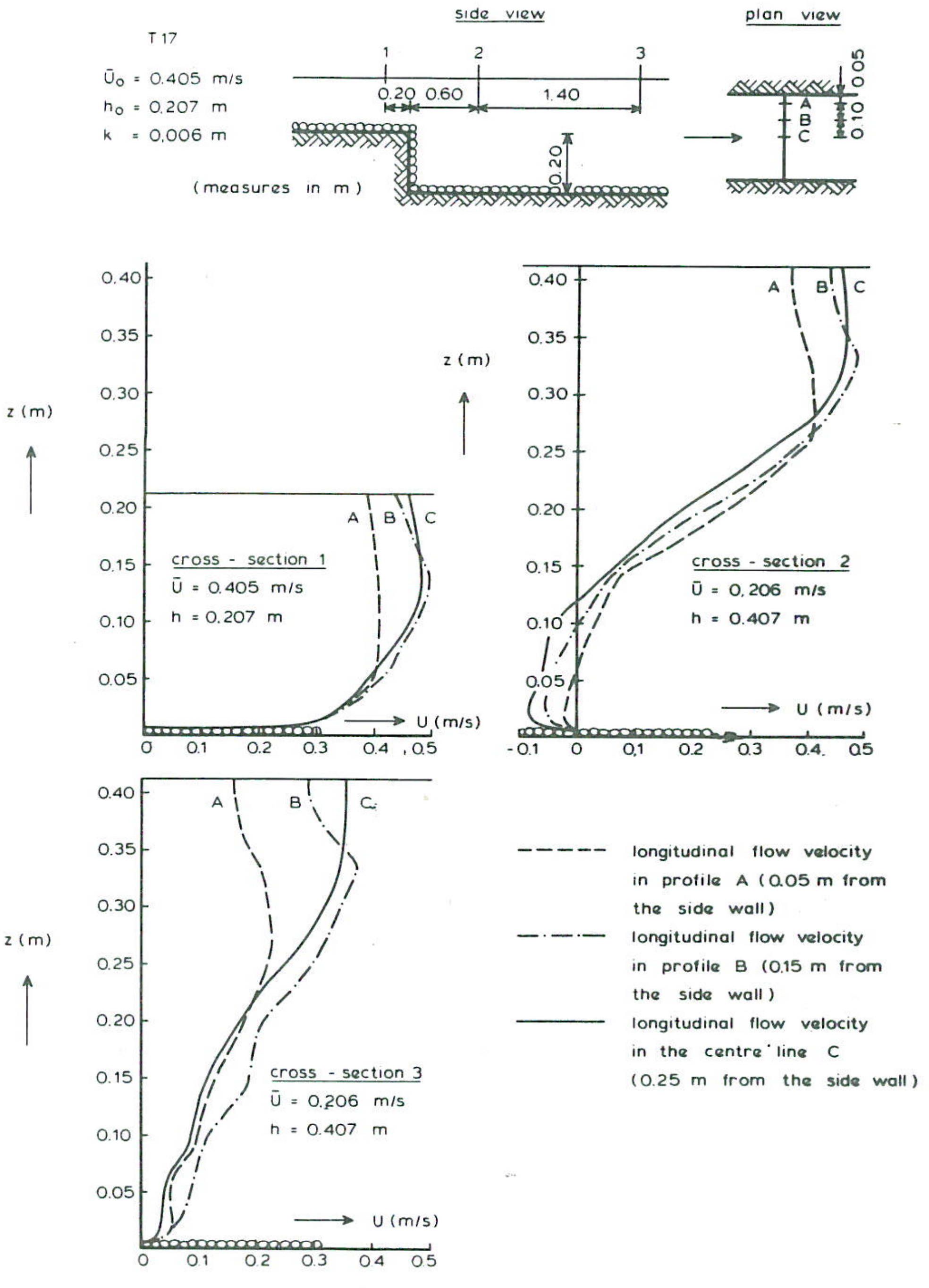
LONGITUDINAL DISTRIBUTION OF FLOW VELOCITIES, TURBULENCE INTENSITIES AND SHEAR STRESSES

T 16

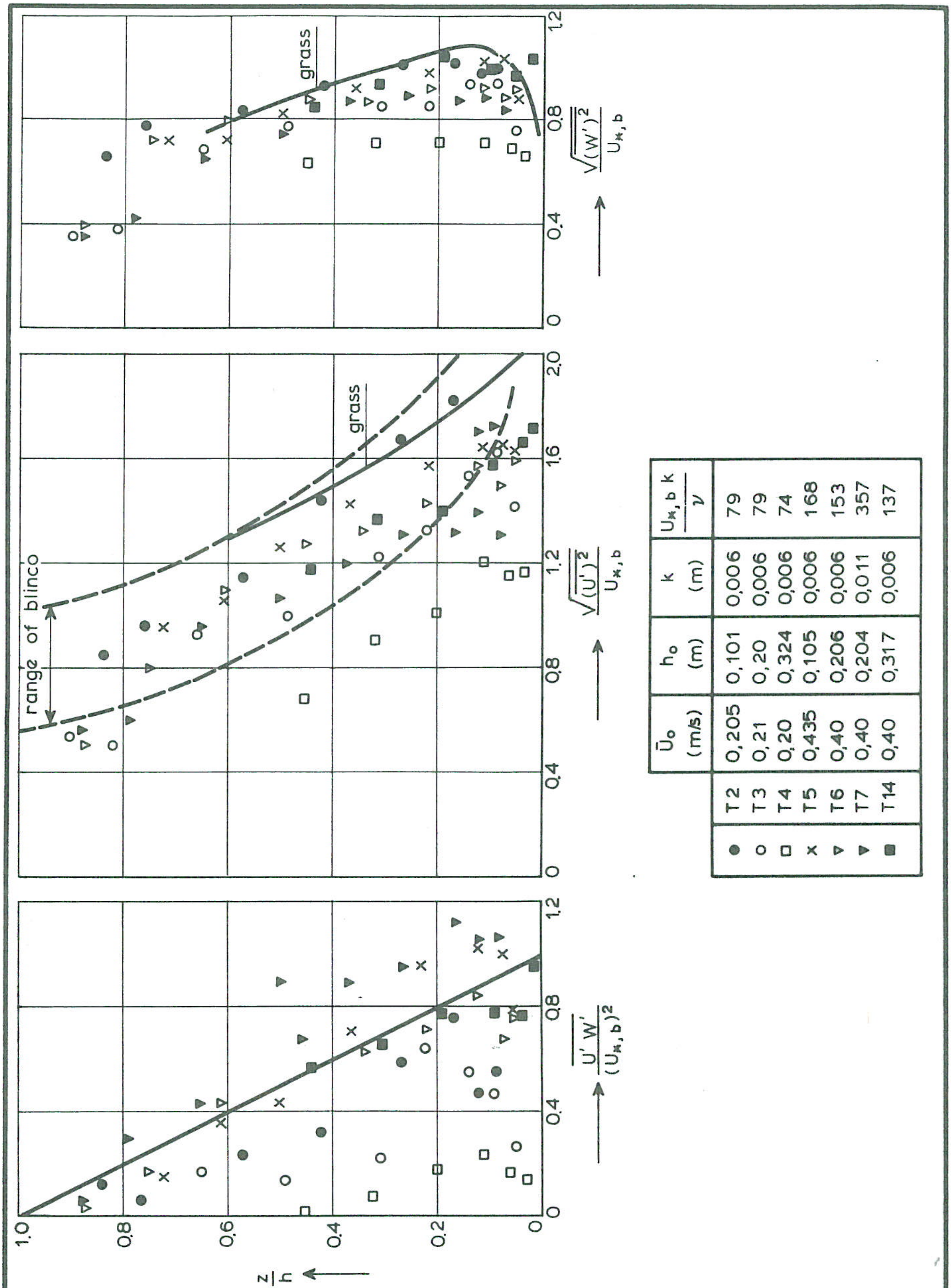
DELFT HYDRAULICS LABORATORY

R1267-III/M1536

FIG. 10



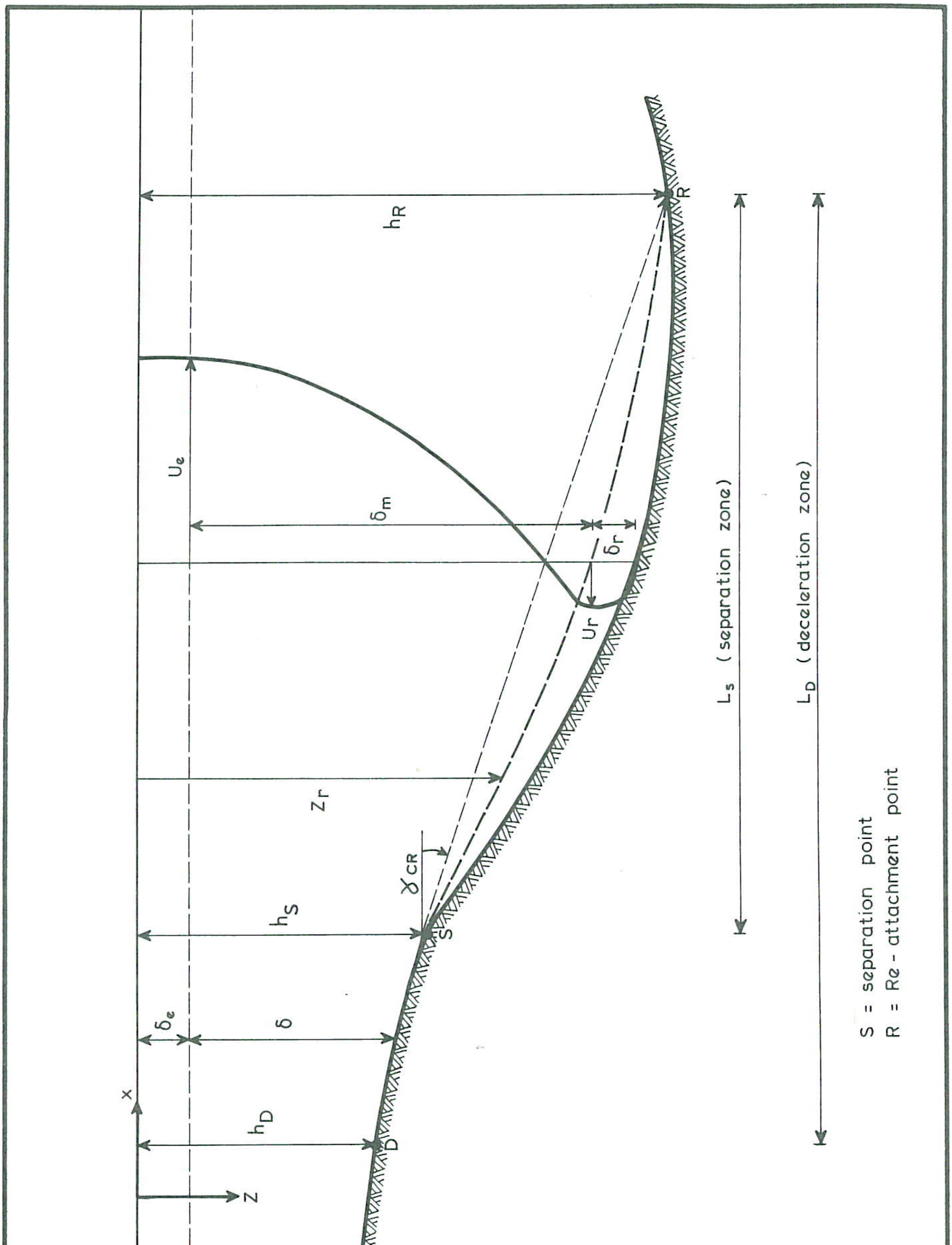
LATERAL DISTRIBUTION OF FLOW VELOCITIES	T 17	
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 11



		$\bar{U}_o$ (m/s)	h_o (m)	k (m)	$\frac{U_{*,b}\,k}{\nu}$
●	T2	0,205	0,101	0,006	79
○	T3	0,21	0,20	0,006	79
□	T4	0,20	0,324	0,006	74
×	T5	0,435	0,105	0,006	168
▷	T6	0,40	0,206	0,006	153
▶	T7	0,40	0,204	0,011	357
■	T14	0,40	0,317	0,006	137

VERTICAL DISTRIBUTION OF SHEAR STRESSES AND TURBULENCE INTENSITIES IN EQUILIBRIUM CONDITIONS

DELFT HYDRAULICS LABORATORY | R1267-III/M1536 | FIG. 12

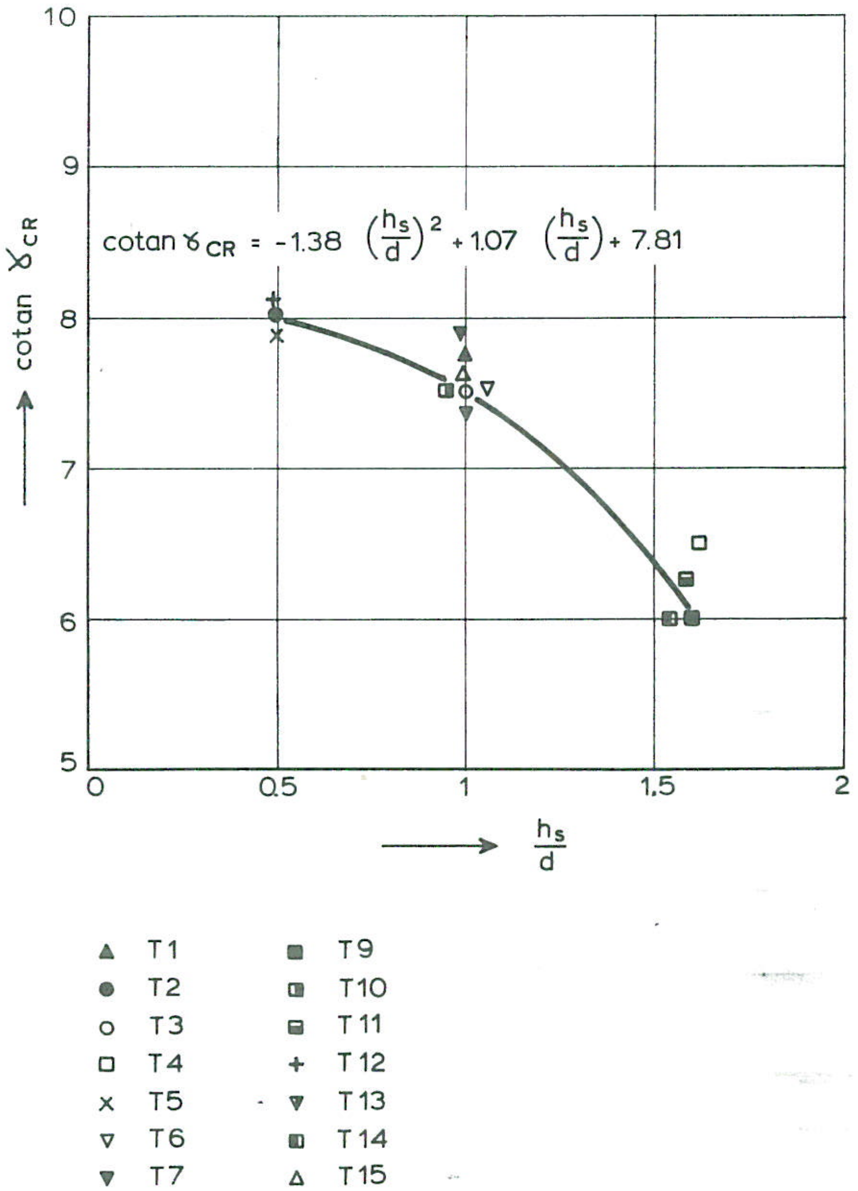


DEFINITION SKETCH OF DECELERATION ZONE

DELFT HYDRAULICS LABORATORY

R1267-III/M1536

FIG. 13

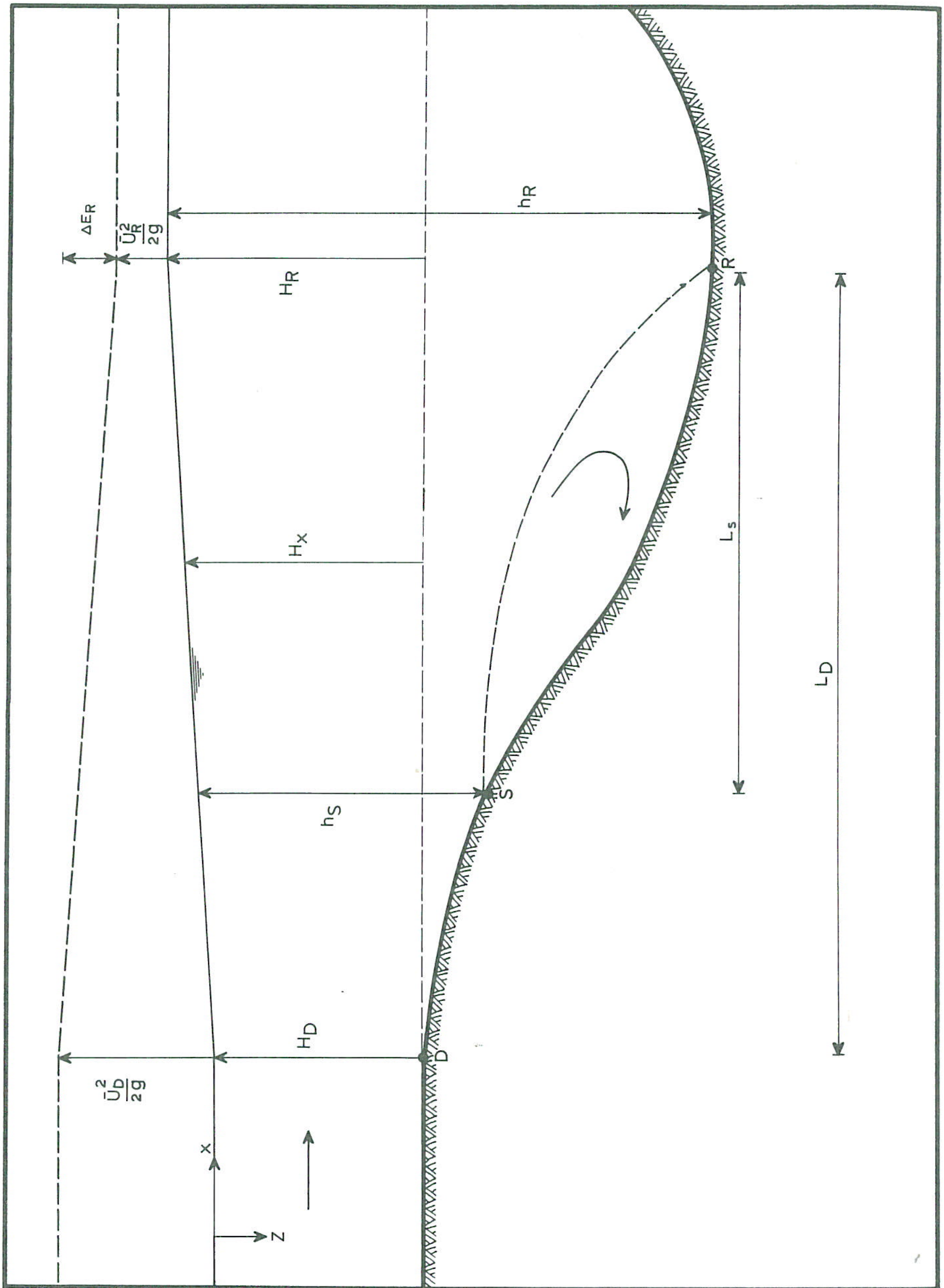


CRITICAL SIDE SLOPES

DELFT HYDRAULICS LABORATORY

R1267-III/M1536

FIG. 14

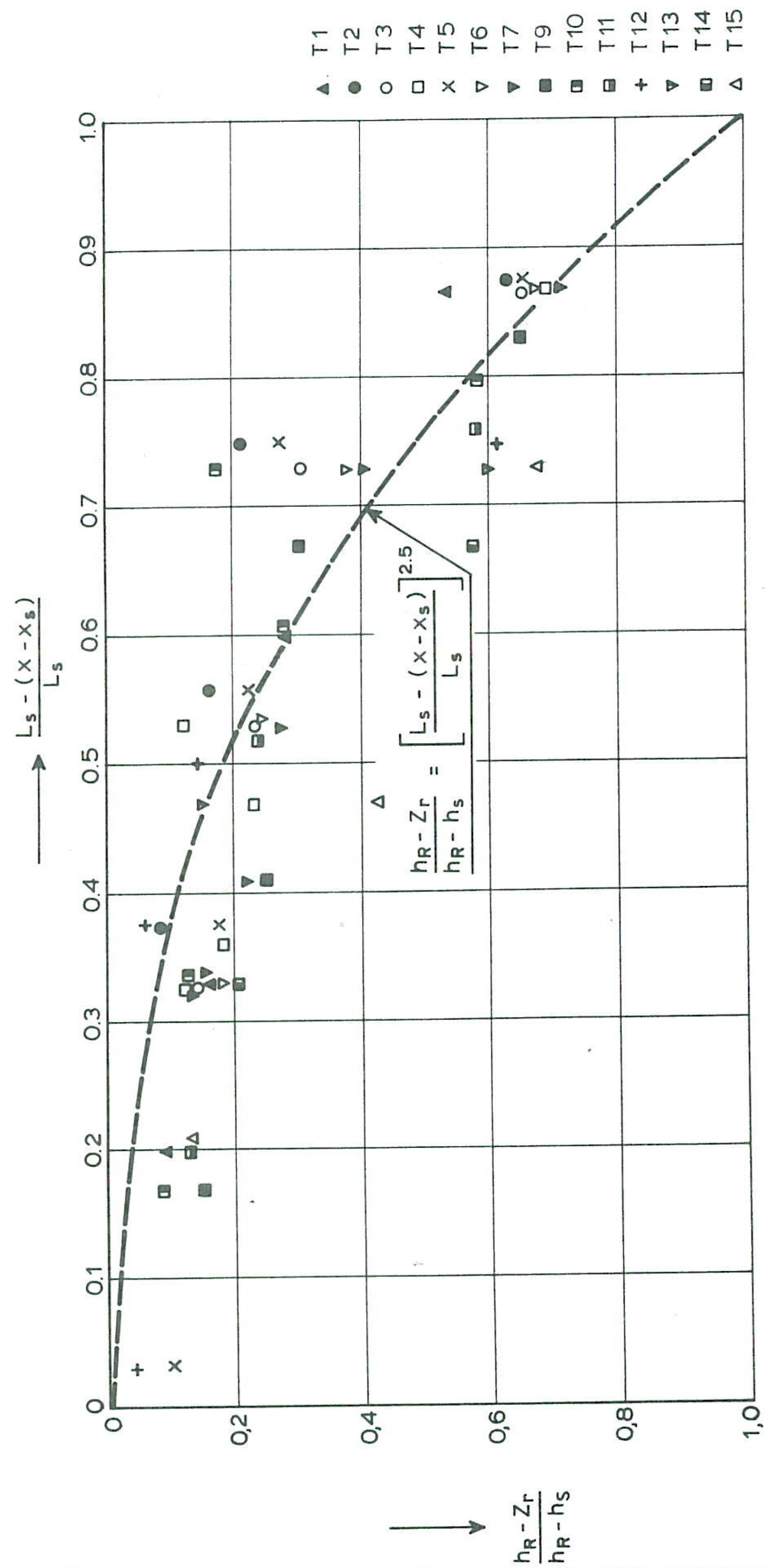


ENERGY BALANCE FOR DECELERATION ZONE

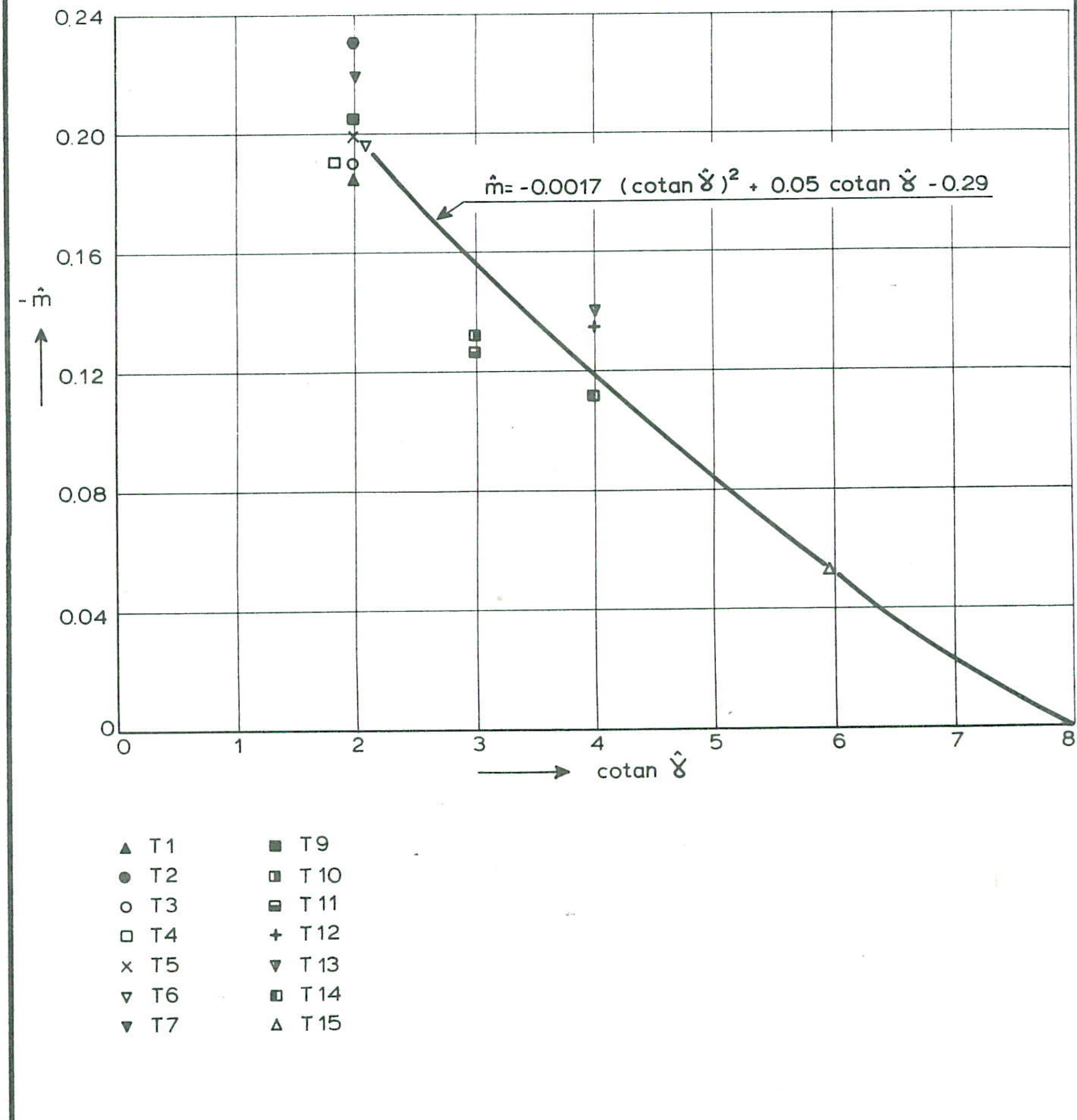
DELFT HYDRAULICS LABORATORY

R1267-III/M1536

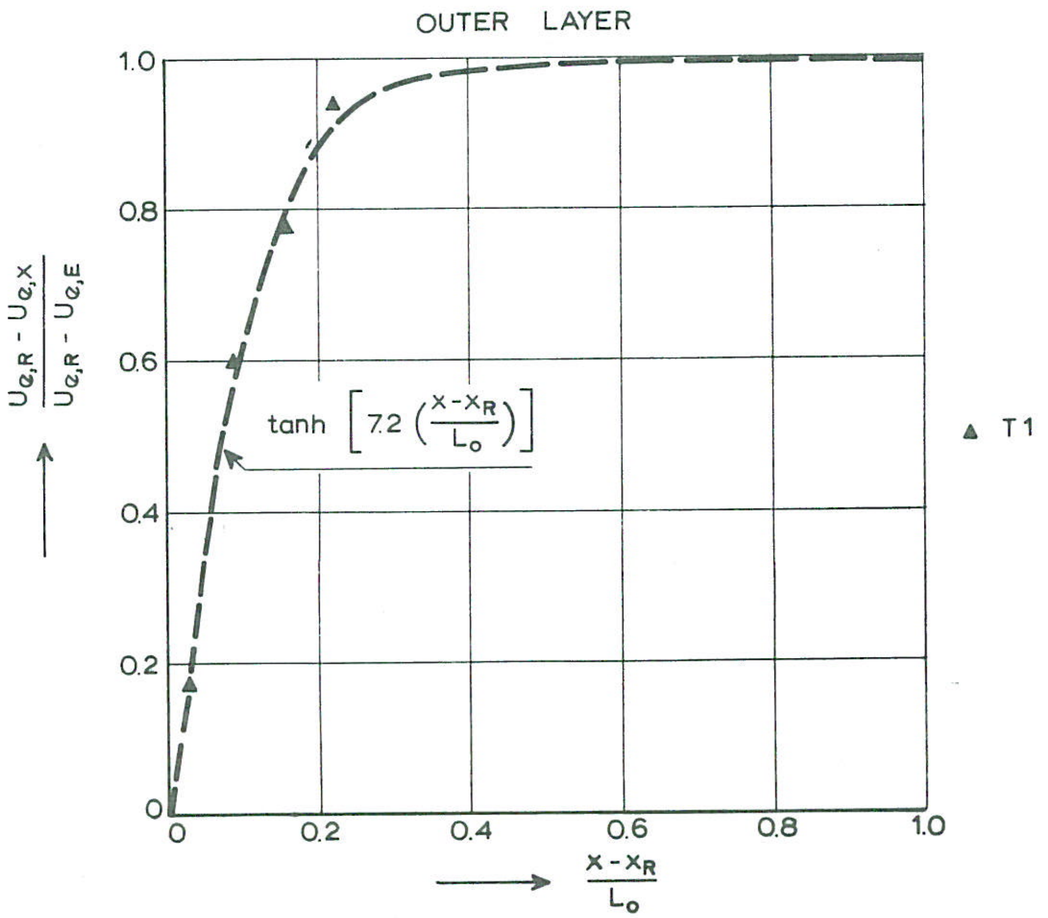
FIG. 15

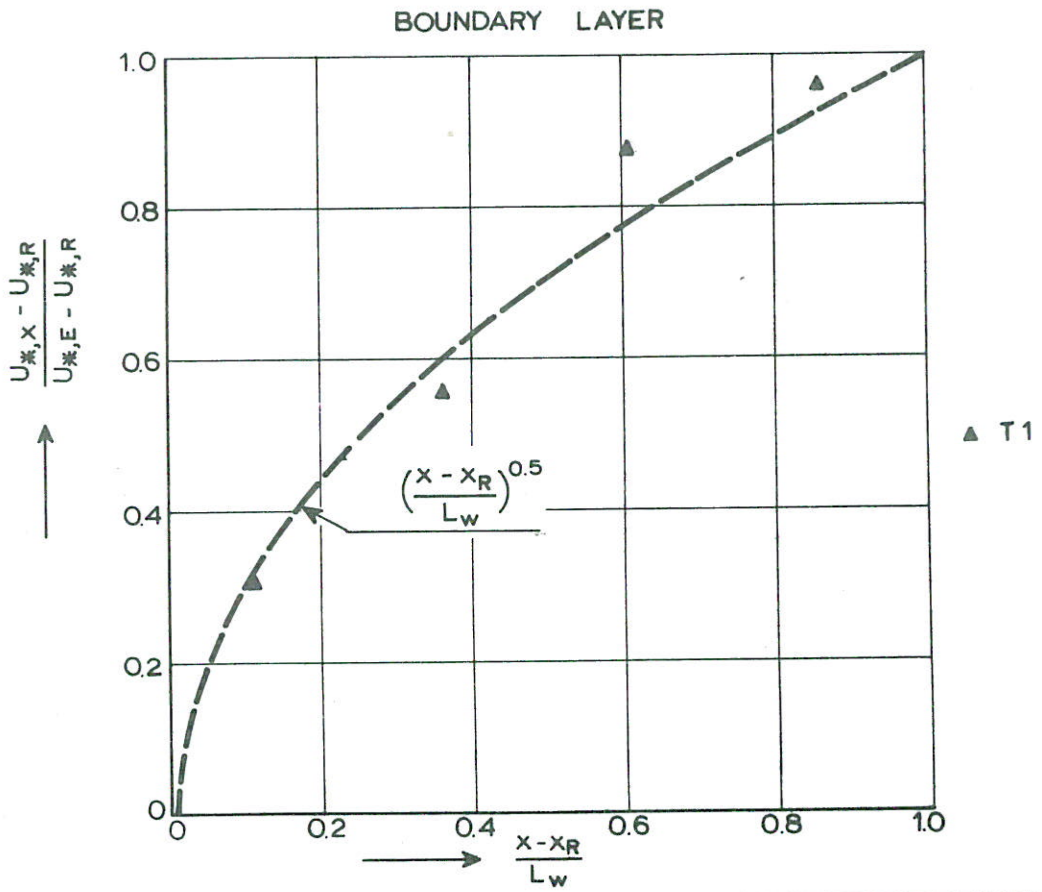


LINE OF MAXIMUM REVERSED FLOW VELOCITIES		
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 16



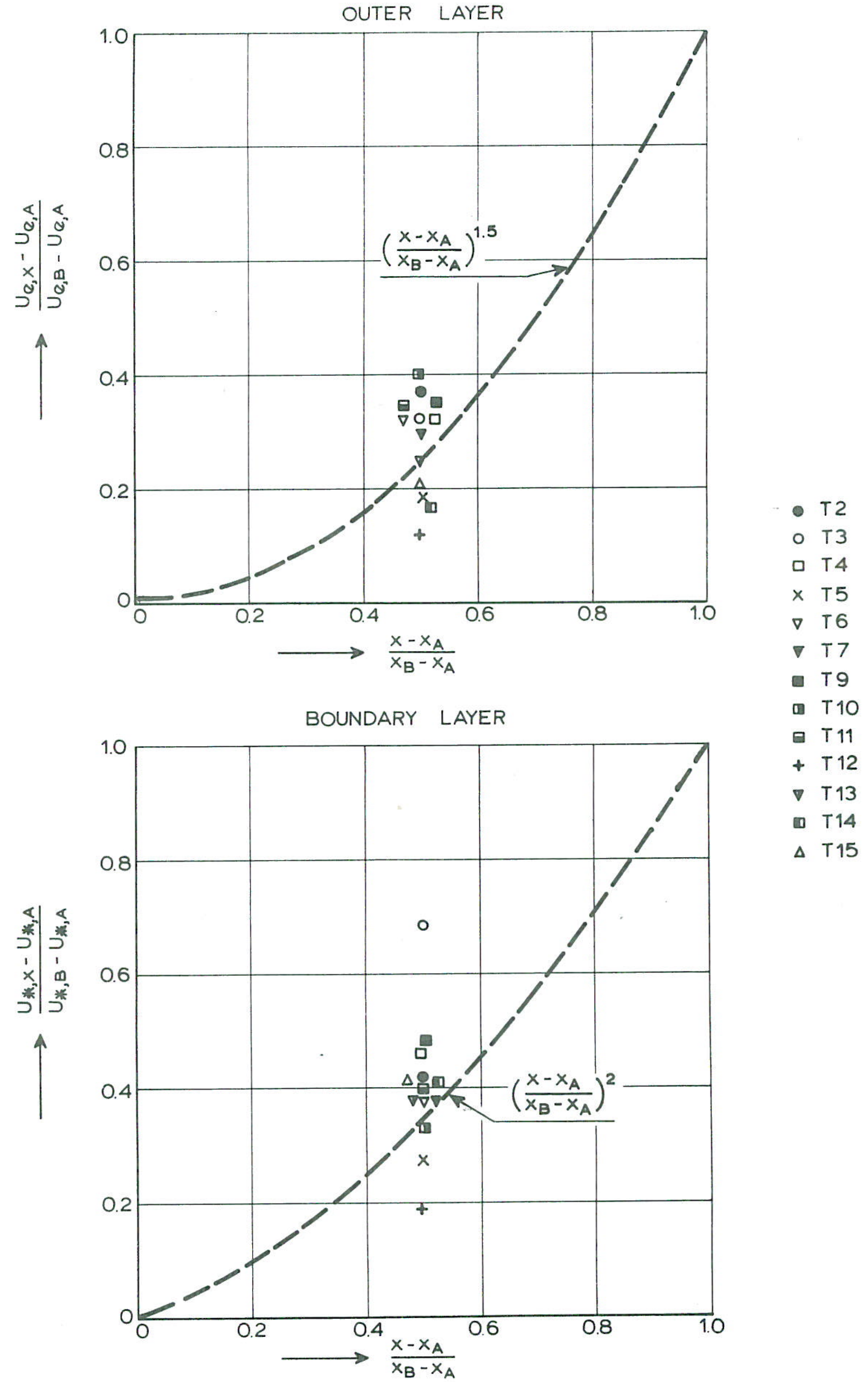
MAXIMUM RATIO OF REVERSED AND OUTER FLOW VELOCITY		
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 17





RELAXATION FUNCTIONS FOR RELAXATION ZONE

DELFT HYDRAULICS LABORATORY | R1267-III/M1536 | FIG. 18

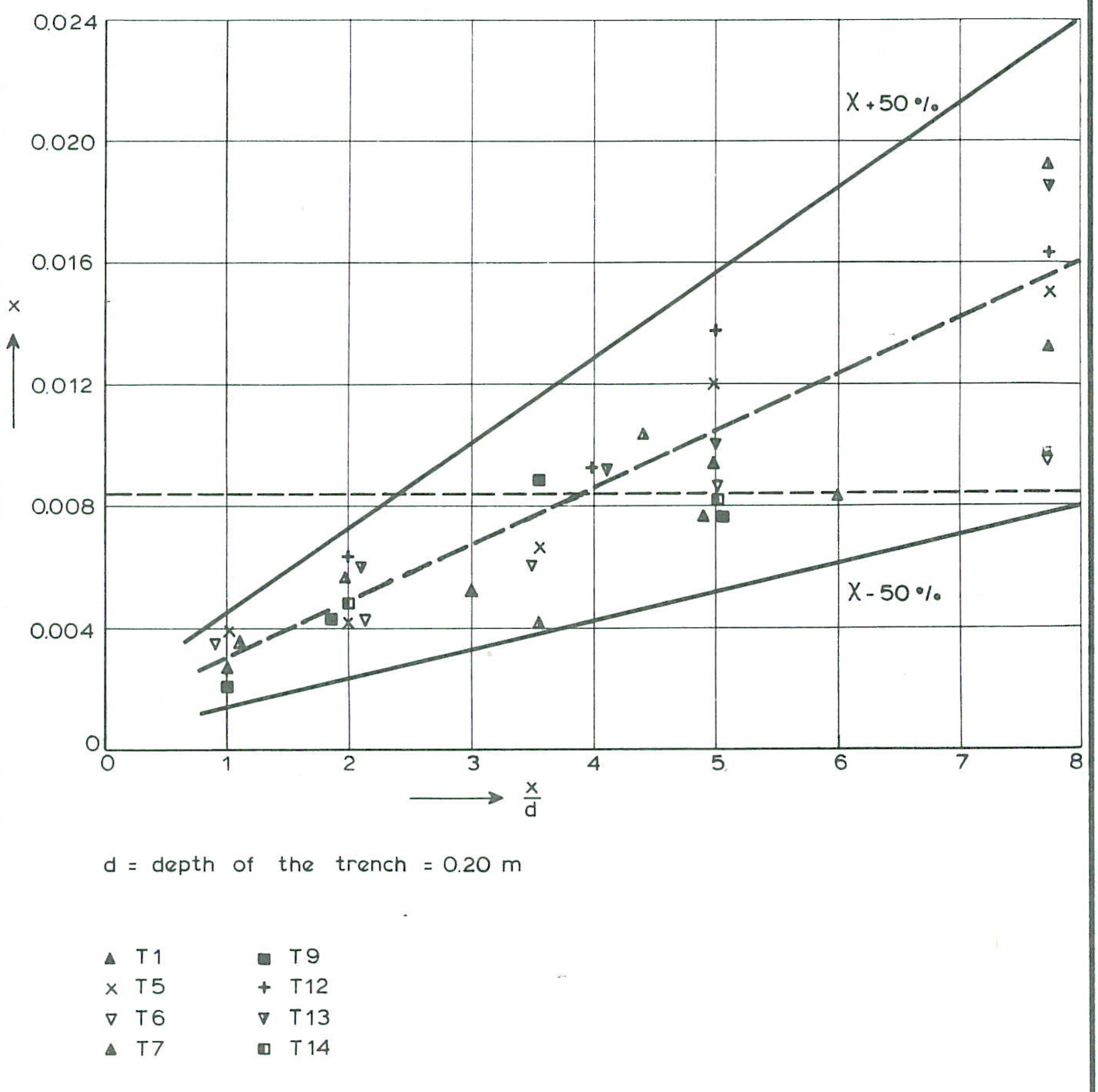


RELAXATION FUNCTIONS FOR ACCELERATION ZONE

DELFT HYDRAULICS LABORATORY

R1267-III/M1536

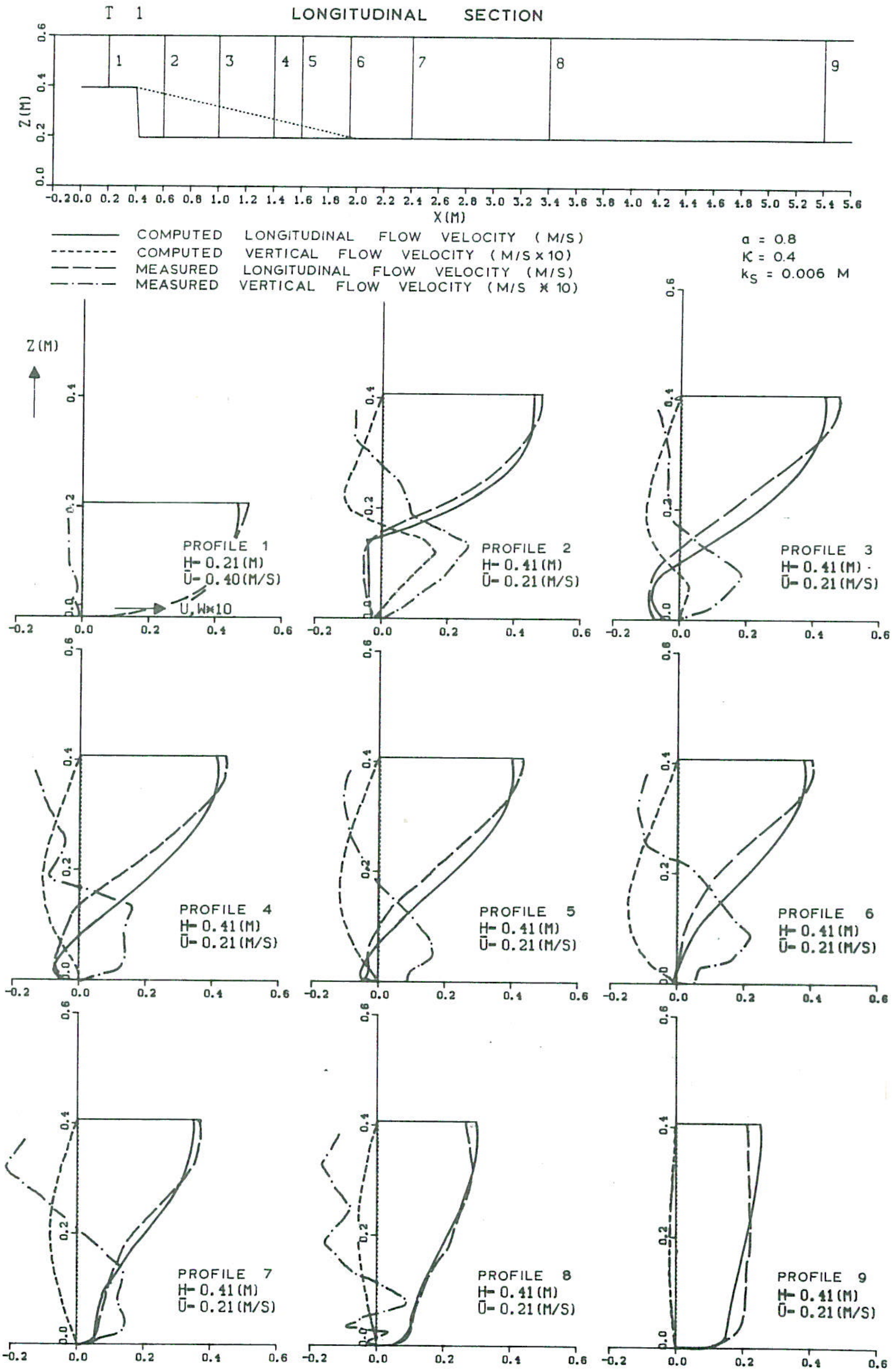
FIG. 19



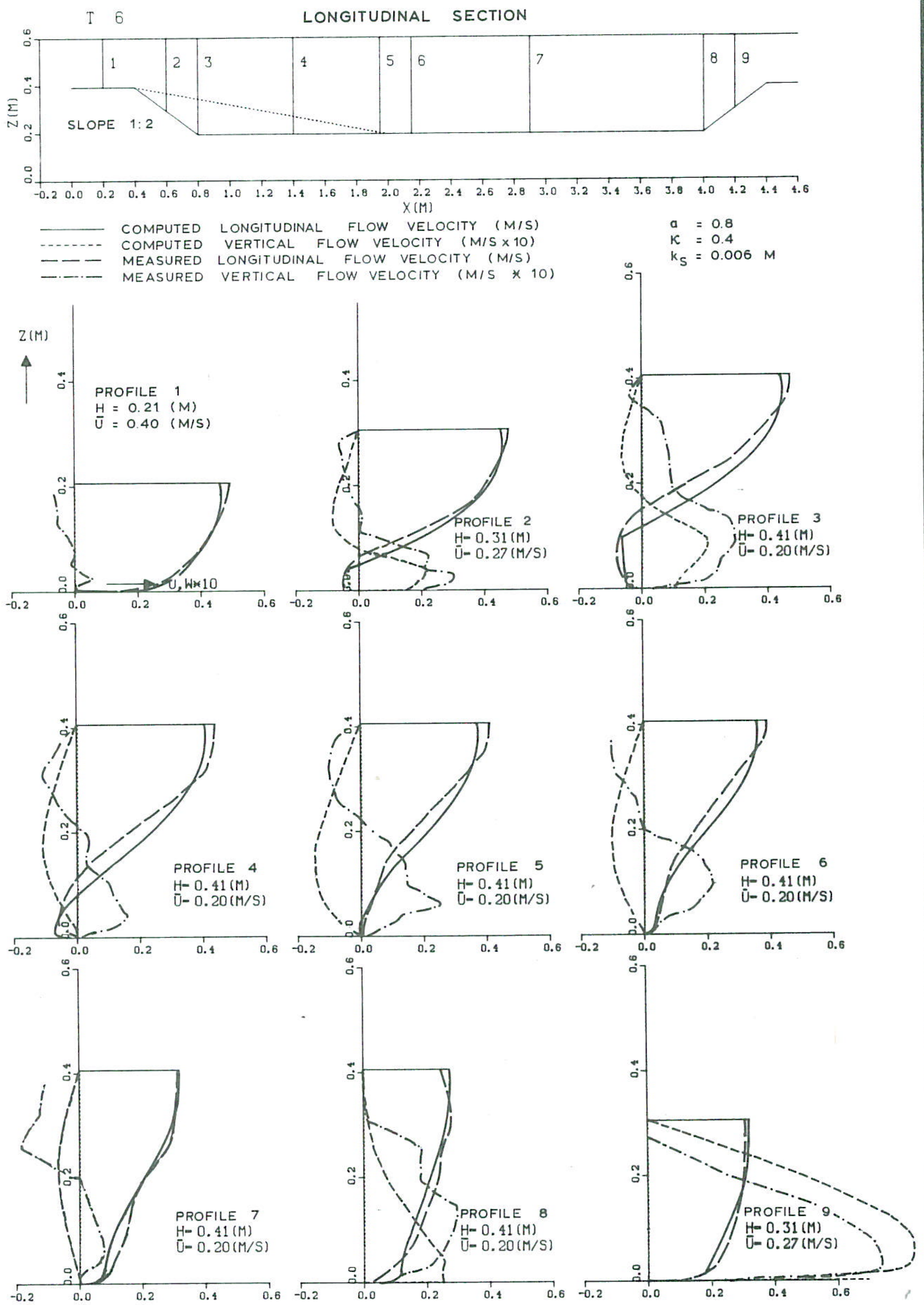
EMPIRICAL CONSTANT FOR DIFFUSION COEFFICIENT

DELFT HYDRAULICS LABORATORY

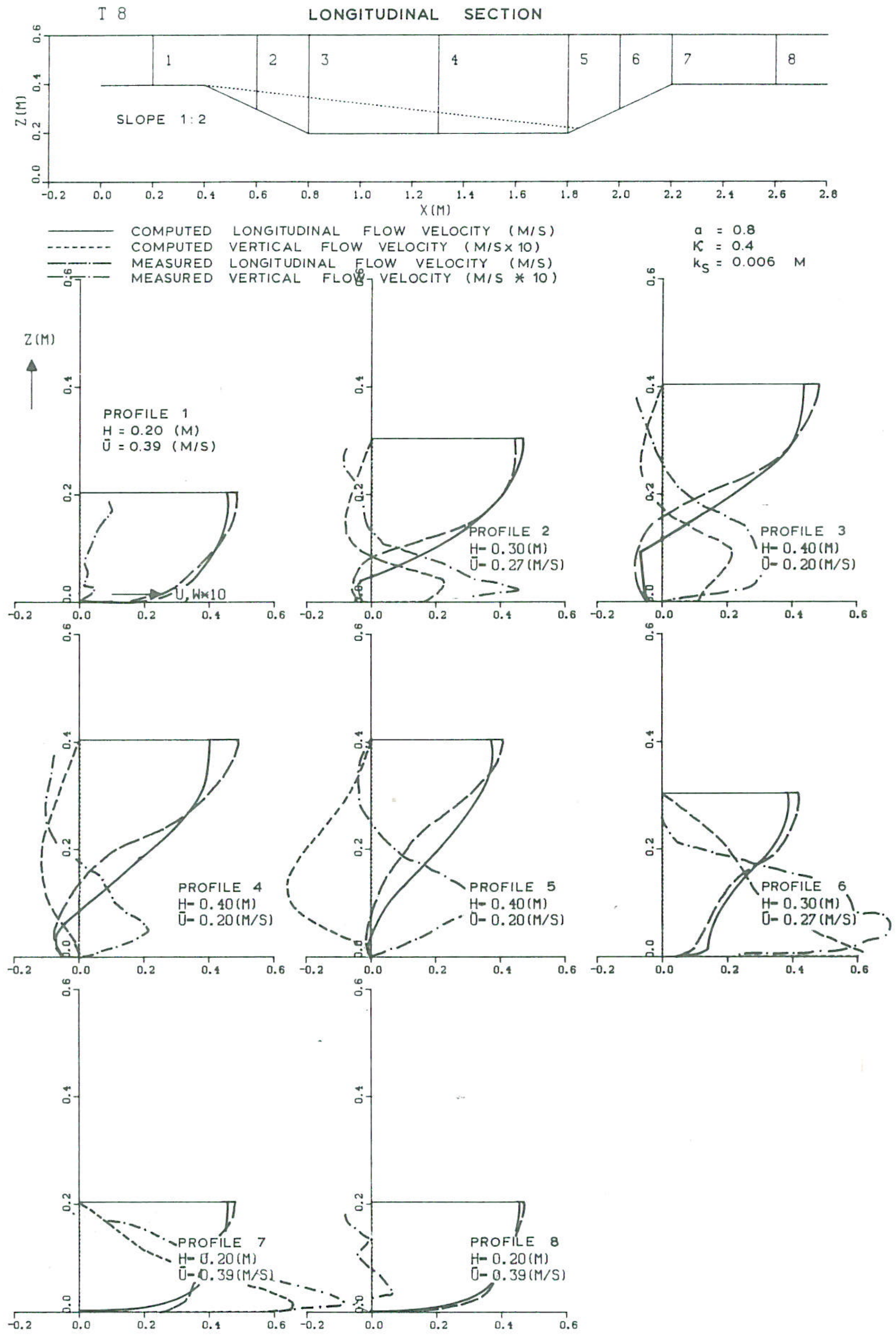
R1267-III/M1536 FIG. 20



LONGITUDINAL DISTRIBUTION OF MEASURED AND COMPUTED FLOW VELOCITIES	T 1	
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 21



LONGITUDINAL DISTRIBUTION OF MEASURED AND COMPUTED FLOW VELOCITIES	T 6	
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 22



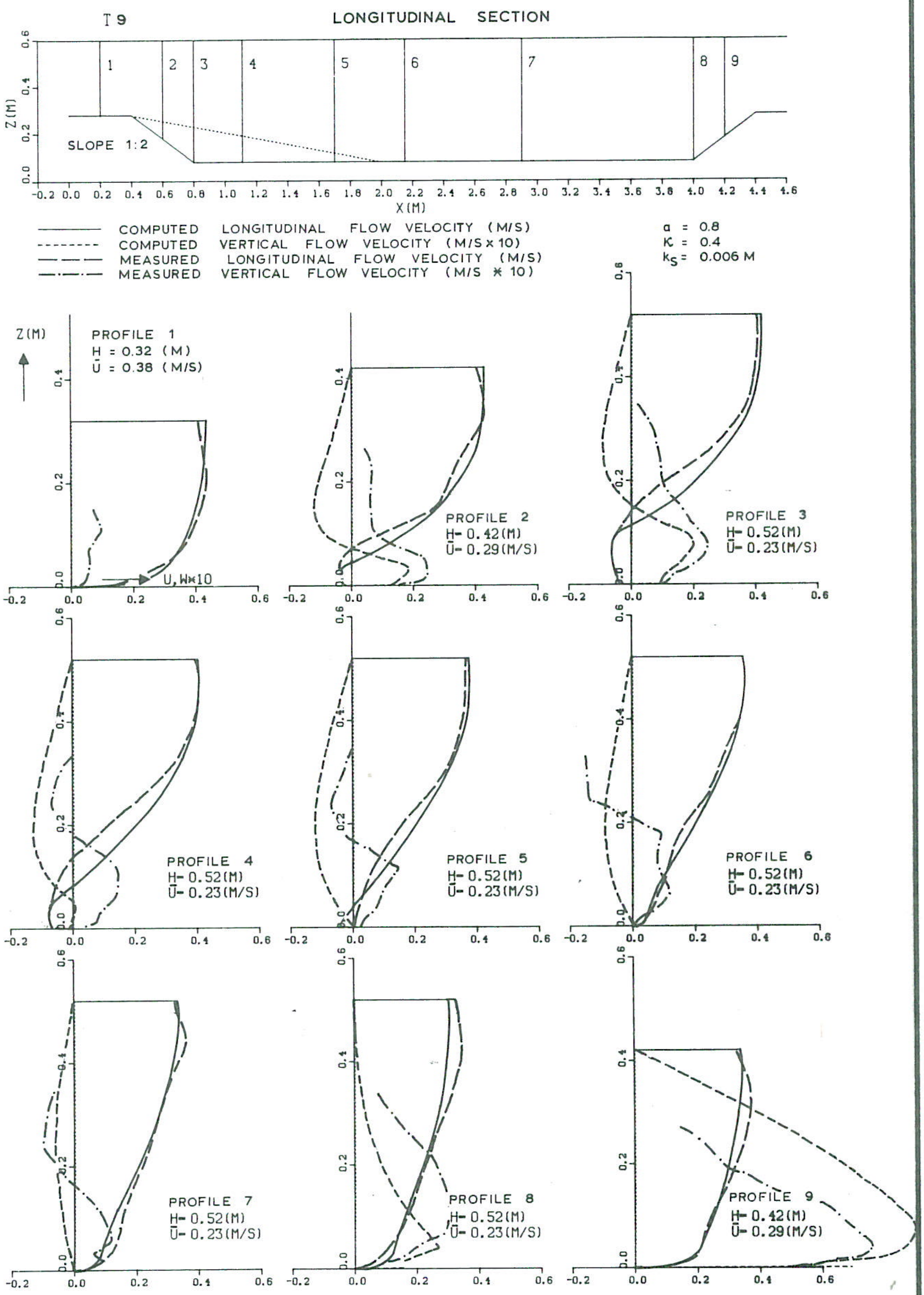
LONGITUDINAL DISTRIBUTION OF MEASURED AND COMPUTED FLOW VELOCITIES

T8

DELFT HYDRAULICS LABORATORY

R1267-III/M1536

FIG. 23



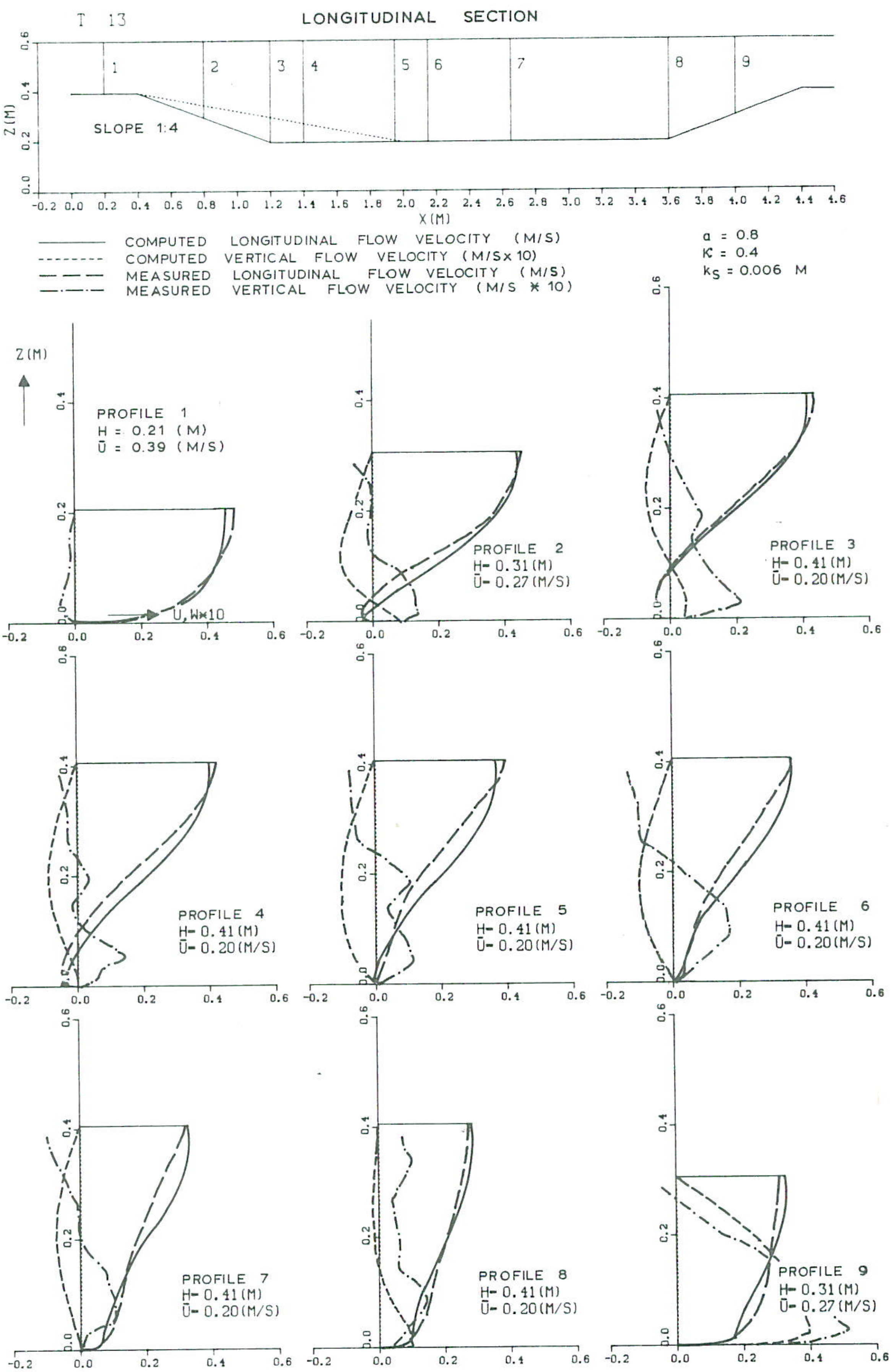
LONGITUDINAL DISTRIBUTION OF MEASURED AND COMPUTED FLOW VELOCITIES

T 9

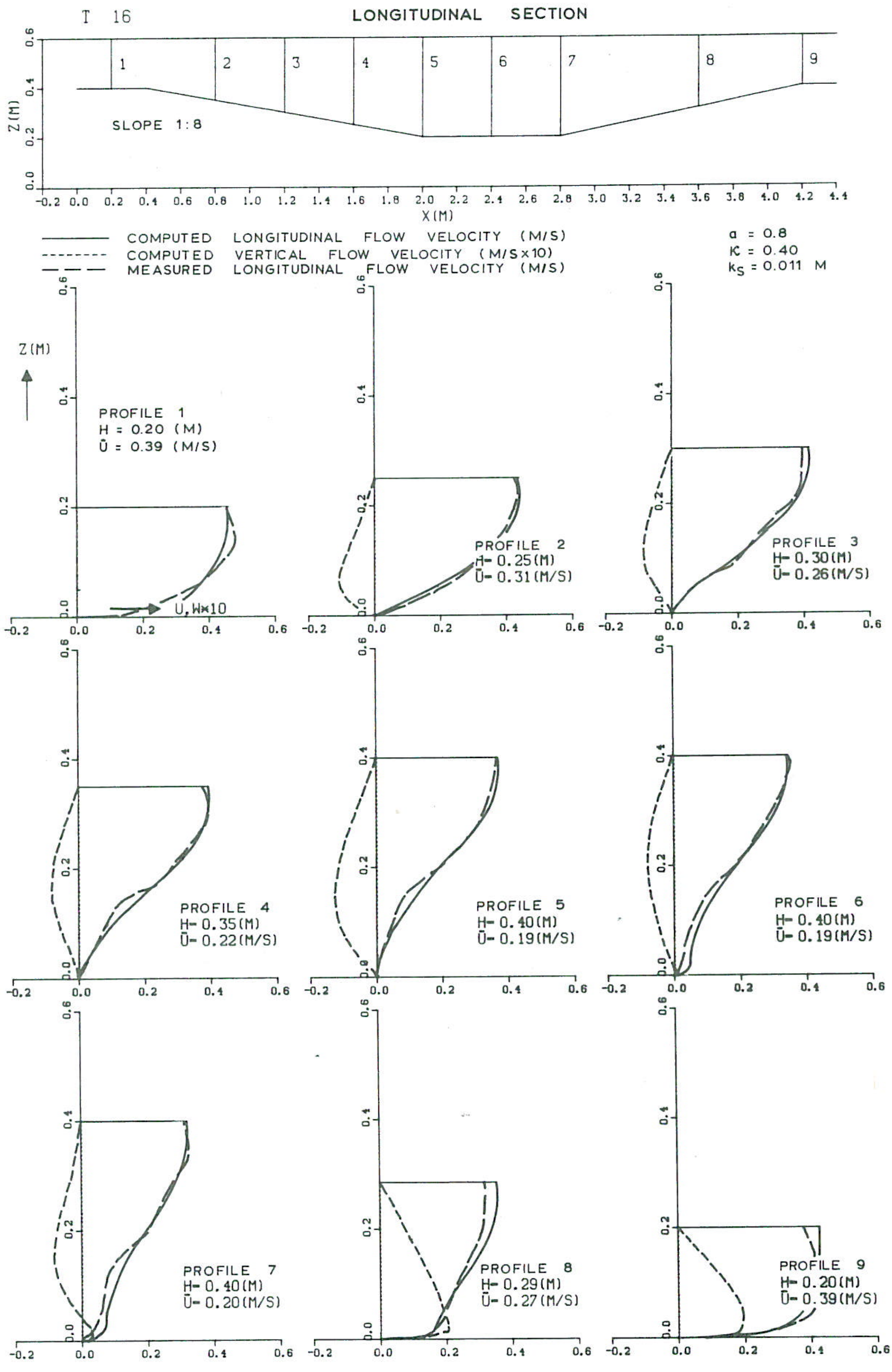
DELFT HYDRAULICS LABORATORY

R1267-III/M1536

FIG. 24



LONGITUDINAL DISTRIBUTION OF MEASURED AND COMPUTED FLOW VELOCITIES	T 13	
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 25



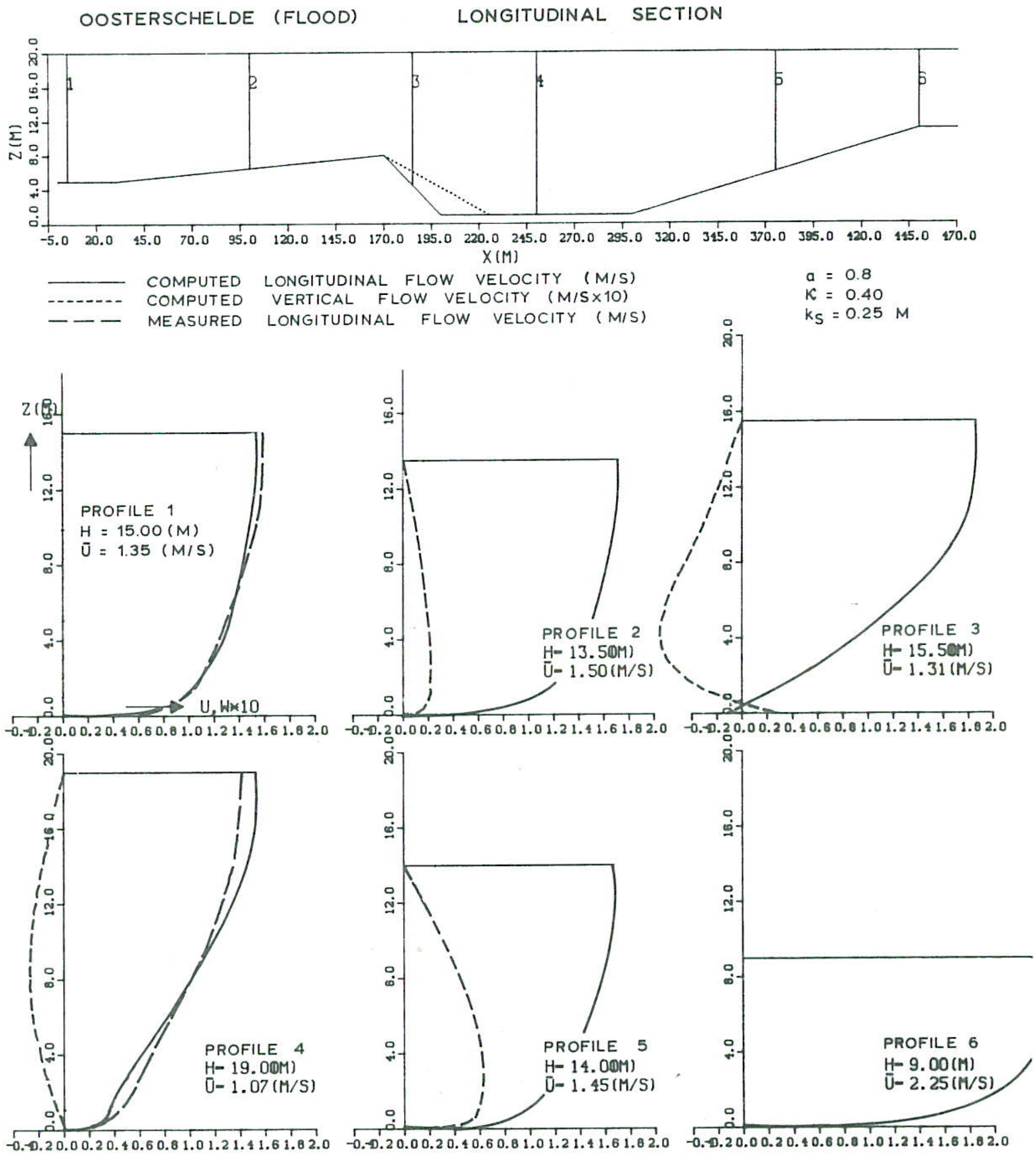
LONGITUDINAL DISTRIBUTION OF MEASURED AND COMPUTED FLOW VELOCITIES

T 16

DELFT HYDRAULICS LABORATORY

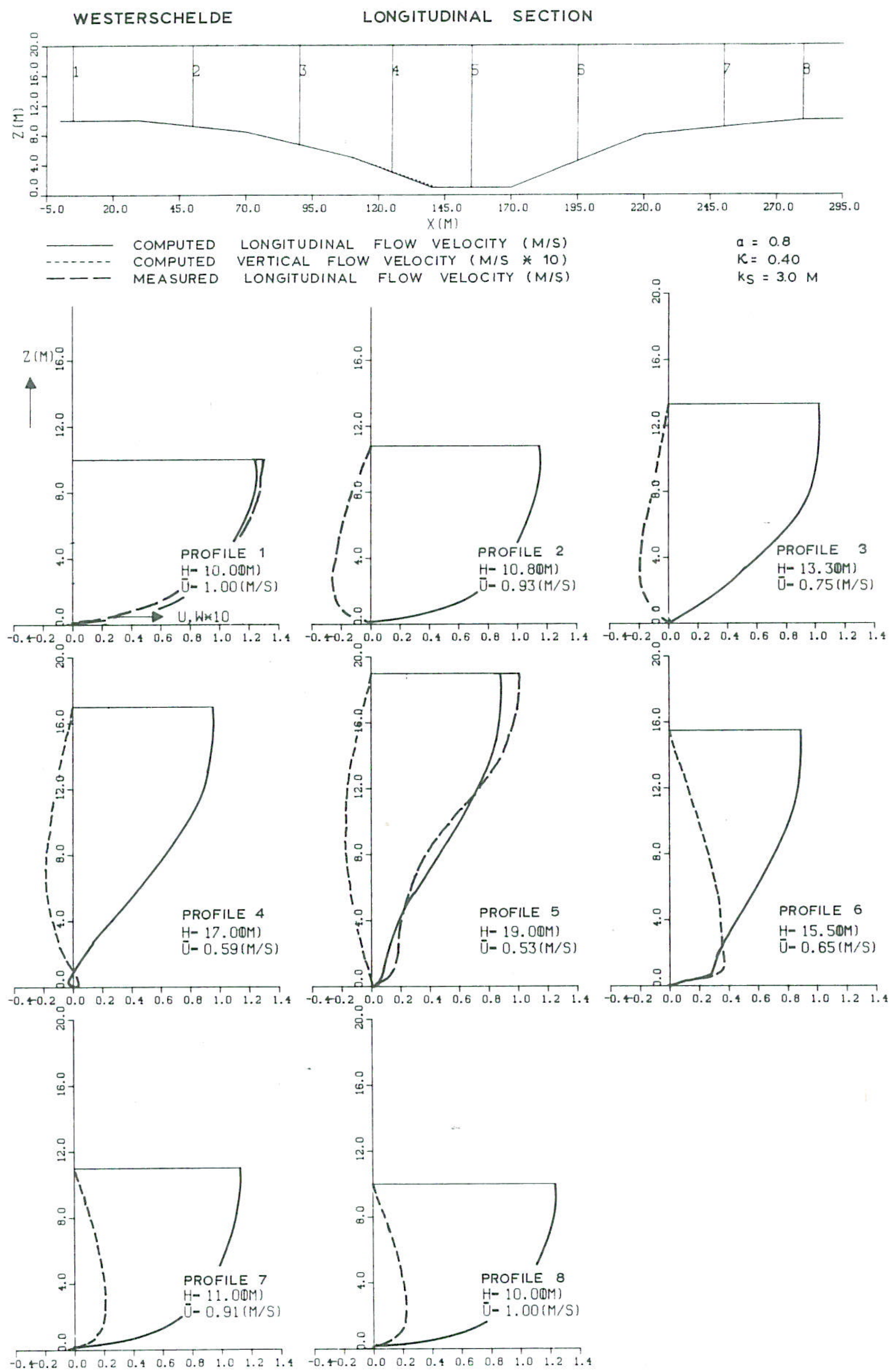
R1267-III/M1536

FIG. 26

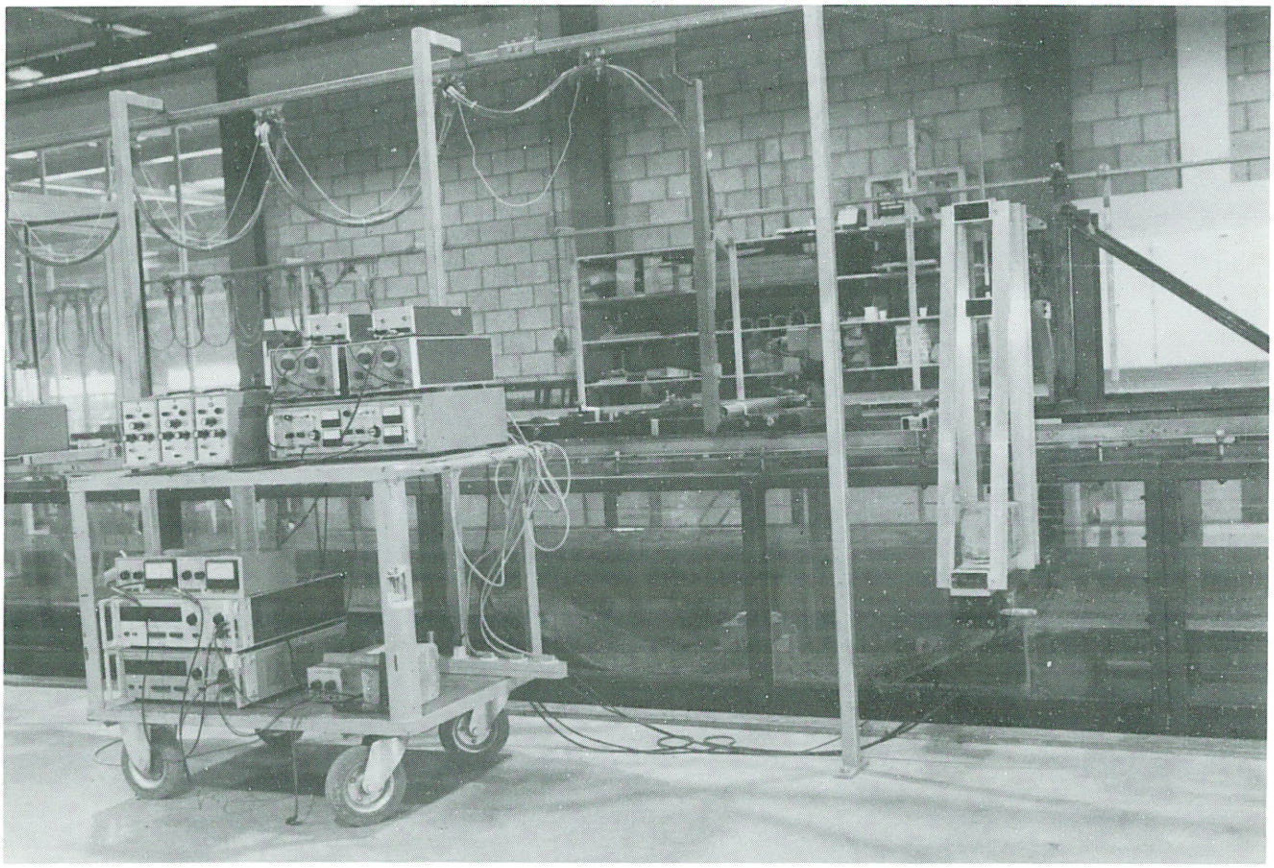


OOSTERSCHELDE , ROOMPOT 29 NOVEMBER 1977 (FLOOD)

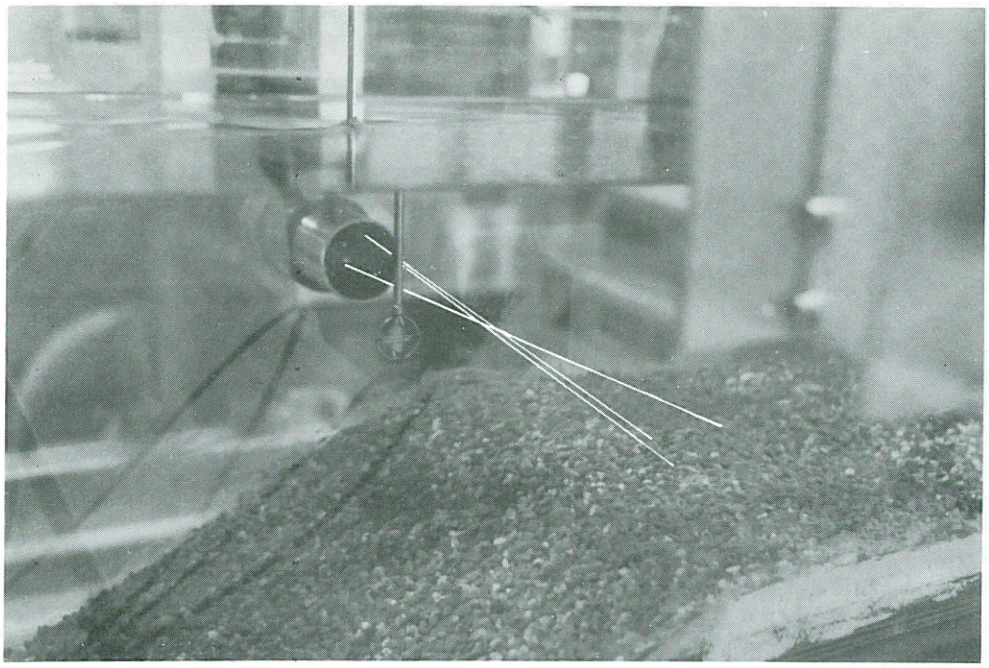
DELFT HYDRAULICS LABORATORY | R1267-III/M1536 | FIG. 27



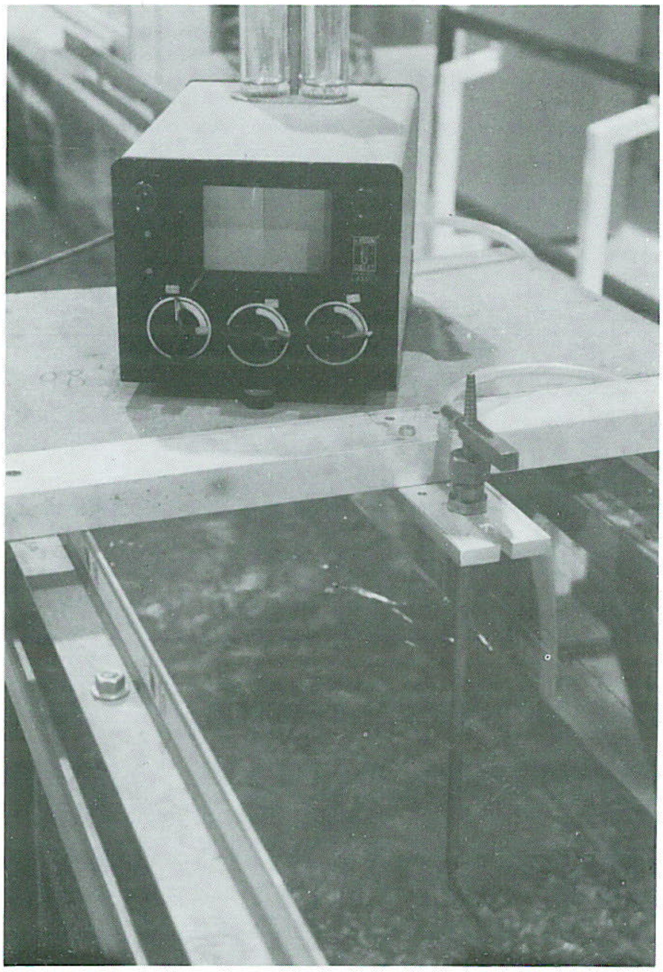
WESTERSCHELDE, VAARWATER BOVEN BATH, MAY 1965 (FLOOD)		
DELFT HYDRAULICS LABORATORY	R1267-III/M1536	FIG. 28



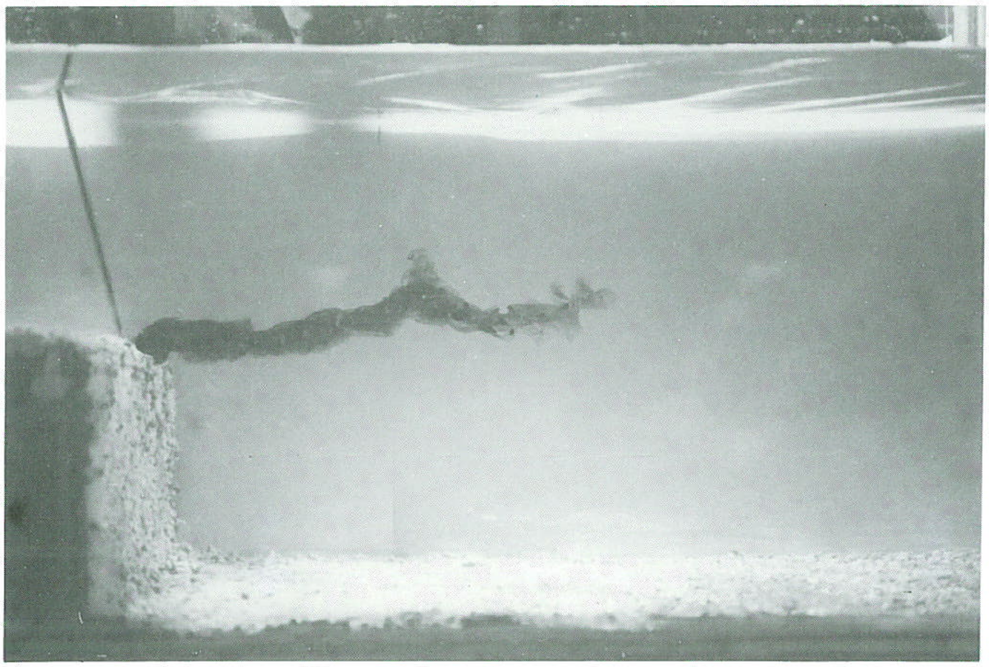
1 Flume trench and Laser Doppler equipment



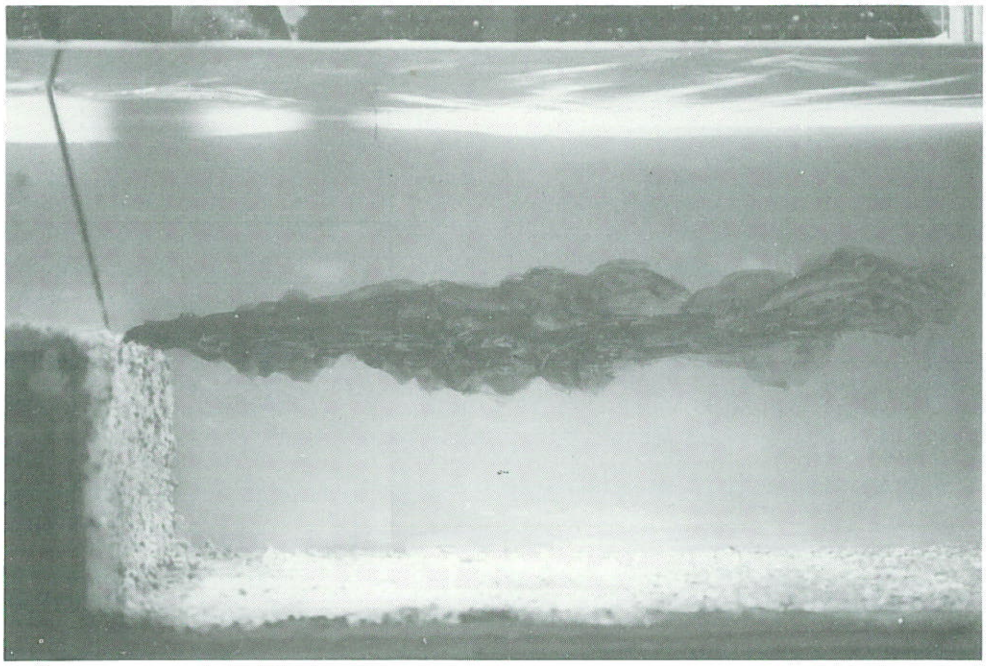
2 Beam configuration of Laser Doppler equipment; micro propeller meter



3 Pressure difference meter; Pitot-tube

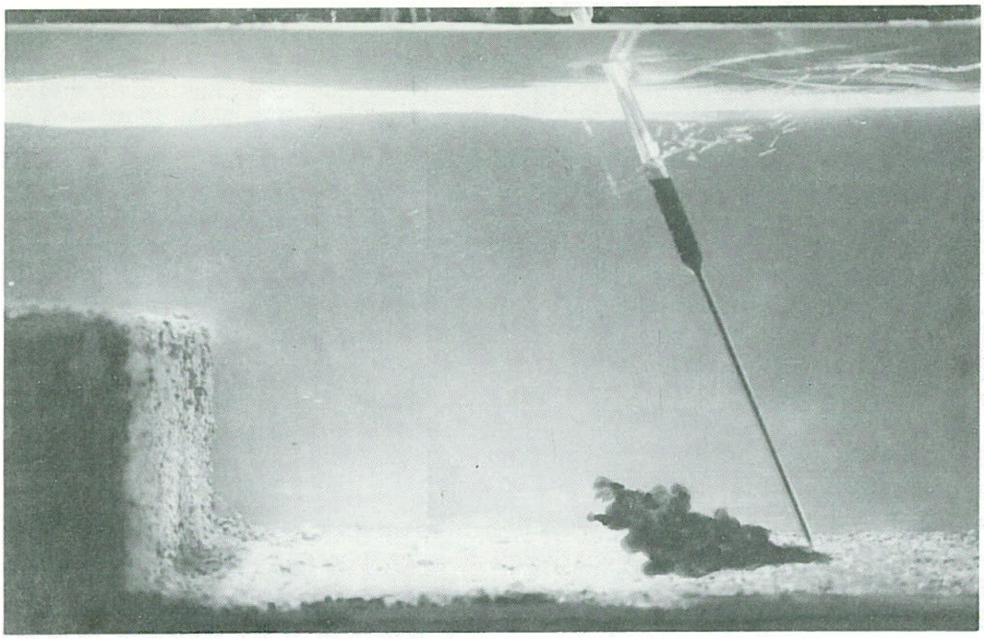


4

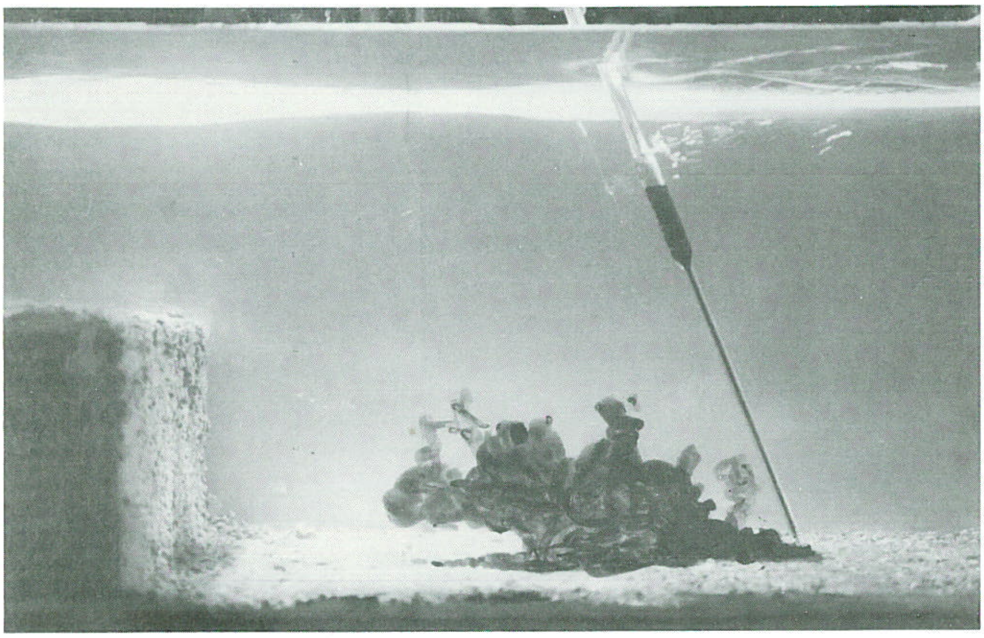


5

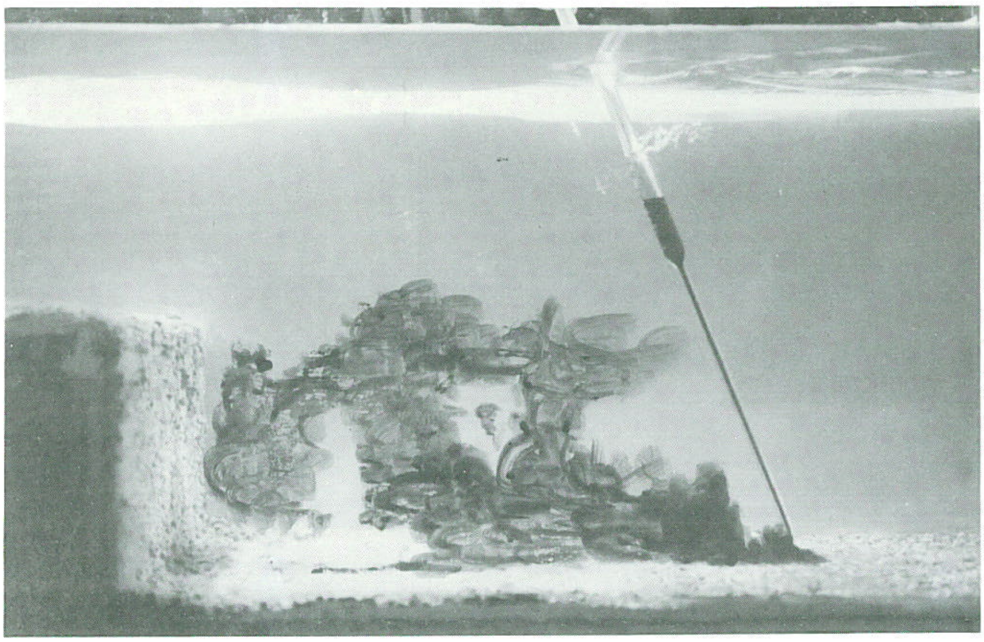
4,5 Visualization of mixing layer (T1)



6



7



8

6,7,8 Visualization of reverred flow (T1)

Appendix A Energy balance for the deceleration zone

From the energy balance the following expression can be derived (Figure 15):

$$\frac{\bar{u}_D^2}{2g} = \Delta E_R + \frac{\bar{u}_R^2}{2g} + (H_R - H_D) \qquad \text{(A.1)}$$

in which

$\bar{u}_D$ = depth-averaged flow velocity in point D

$\bar{u}_R$ = depth-averaged flow velocity in point R

ΔE_R = energy loss in the deceleration zone

Suppose that:

$$\Delta E_R = \xi \left(\frac{\bar{u}_D^2 - \bar{u}_R^2}{2g}\right) \qquad \text{(A.2)}$$

in which

ξ = energy loss coefficient

The substitution of equation (A.2) in (A.1) yields:

$$\Delta H = H_R - H_D = (1 - \xi) \left(\frac{\bar{u}_D^2 - \bar{u}_R^2}{2g}\right) = \left(\frac{1 - \xi}{2g}\right) q^2 \left(\frac{1}{h_D^2} - \frac{1}{h_R^2}\right) \qquad \text{(A.3)}$$

Appendix B. Errors in measuring turbulent shear stresses

General

The turbulent shear stress is defined as:

$$\frac{\tau}{\rho} = \overline{u'w'} \qquad \text{(B.1)}$$

in which u' and w' represent the velocity fluctuations (deviations) with respect to the mean flow velocities of the longitudinal and vertical velocity components U(t) and W(t). The time-averaging period is supposed to be infinitely long. If U(t) and W(t) are considered as realisations of two stationary, ergodic processes with mean values μ_U and μ_W, the shear stress can be expressed as the covariance of U and W:

$$\frac{\tau}{\rho} = E\left[\{U_{(t)} - \mu_U\} \ \{W_{(t)} - \mu_W\}\right] = \text{cov }(U,W) \qquad \text{(B.2)}$$

or

$$\frac{\tau}{\rho} = \gamma_{UW}\ (\Theta = 0) \qquad \text{(B.3)}$$

in which

$\gamma_{UW}\ (\Theta)$ = cross-covariance function

Θ = time shift

In the case of a limited measuring time (T), only an estimate ($\hat{\underline{\tau}}$) of the shear stress (τ) can be determined.

Measuring methods

Two methods can be distinguished:

One-phase method

During a one-time period (T) the components $U_{(t)}$ and $W_{(t)}$ are measured. It is assumed that any errors in the measurements of these components are negligibly small. The turbulent shear stress can be estimated by:

$$\frac{\hat{\underline{\tau}}}{\rho} = \left\{\frac{t}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} \underline{U}_{(t)} \, \underline{W}_{(t)} \, dt\right\} - \underline{u} \, \underline{w} \tag{B.4}$$

in which:

$\hat{\underline{\tau}}$ = estimate of the turbulent shear stress

$\underline{u} = \frac{1}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} \underline{U}_{(t)} \, dt$ = measured mean longitudinal flow velocity

$\underline{w} = \frac{1}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} \underline{W}_{(t)} \, dt$ = measured mean vertical flow velocity

The expected systematic error in $\hat{\underline{\tau}}$ can be represented by the bias of $\hat{\underline{\tau}}$:

$$\text{Bias}\left(\frac{\hat{\underline{\tau}}}{\rho}\right) = E\left(\frac{\hat{\underline{\tau}}}{\rho}\right) - \frac{\tau}{\rho} \tag{B.5}$$

The expected stochastic error in $\hat{\underline{\tau}}$ can be represented by the variance (σ^2) of $\hat{\underline{\tau}}$:

$$\text{Var}\left(\frac{\hat{\underline{\tau}}}{\rho}\right) = E\left\{\frac{\hat{\underline{\tau}}}{\rho} - E\left(\frac{\hat{\underline{\tau}}}{\rho}\right)\right\}^2 \tag{B.6}$$

To determine the bias and variance (σ^2) of $\hat{\underline{\tau}}$, equation (B.4) is described as:

$$\frac{\hat{\underline{\tau}}}{\rho} = \underbrace{\left[\frac{1}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} \{\underline{U}_{(t)} - \mu_U\} \{\underline{W}_{(t)} - \mu_W\} \, dt\right]}_{\text{I}} - \underbrace{(\mu_U - \underline{u}) \, (\mu_W - \underline{w})}_{\text{II}} \tag{B.7}$$

in which:

$$\underline{u} = \frac{1}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} \underline{U}_{(t)} \, dt$$

$$\underline{w} = \frac{1}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} \underline{W}(t) \, dt$$

It can be shown that:

$$\text{Bias } \left(\frac{\hat{\tau}}{\rho}\right) = E\left(\frac{\hat{\tau}}{\rho}\right) - \frac{\tau}{\rho} = -\frac{1}{T} \int_{-T}^{T} \left(1 - \frac{|t|}{T}\right) \gamma_{UW} (t) \, dt \qquad \text{(B.8)}$$

$$\text{Var } \left(\frac{\hat{\tau}}{\rho}\right) = \text{var (I)} + \text{var (II)} - 2 \text{ cov (I, II)} \qquad \text{(B.9)}$$

in which:

$$\text{Var (I)} = \frac{1}{T} \int_{-T}^{T} \{\gamma_{UU} (t) \, \gamma_{WW} (t) + \gamma_{UW} (t) \, \gamma_{UW} (-t)\} \left(1 - \frac{|t|}{T}\right) dt \qquad \text{(B.10)}$$

γ_{UU} (t) = auto-covariance function of U

γ_{WW} (t) = auto-covariance function of W

If the time period is sufficiently large, the contributions of var (II) and cov (I,II) can be neglected with respect to var (I) since these terms are of the order $o\left(\frac{1}{T^2}\right)$, $O\left(\frac{1}{T^3}\right)$ and higher.

Therefore:

$$\text{var } \left(\frac{\hat{\tau}}{\rho}\right) \approx \frac{1}{T} \int_{-\infty}^{\infty} \{\gamma_{UU} (t) \, \gamma_{WW} (t) + \gamma_{UW} (t) \, \gamma_{UW} (t)\} \, dt \qquad \text{(B.11)}$$

Two-phase method

During the first phase the mean flow velocities (u_1, w_1) are determined. During the second phase the turbulent shear stress is determined as:

$$\frac{\hat{\tau}}{\rho} = \frac{1}{T} \int_{-\frac{1}{2}T}^{+\frac{1}{2}T} \{\underline{U}_2 (t) - \underline{u}_1\} \{\underline{W}_2 (t) - \underline{w}_1\} \, dt \qquad \text{(B.12)}$$

in which:

$$\underline{u}_1 = \frac{1}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} \underline{U}_1 (t) \, dt$$

$$\underline{w}_1 = \frac{1}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} \underline{W}_1 (t) \, dt$$

Equation (B.12) can be described as:

$$\frac{\hat{\underline{\tau}}}{\rho} = \{\frac{1}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} (\underline{U}_2 (t) - \mu_U) (W_2 (t) - \mu_W) \, dt\} + (\underline{u}_2 - \underline{u}_1)(\underline{w}_2 - \underline{w}_1) + (\mu_U - \underline{u}_2) (\mu_W - \underline{w}_2) \qquad \text{(B.13)}$$

If the measurements during the first and second phases are considered to be independent, then:

$$\text{Bias } (\frac{\hat{\underline{\tau}}}{\rho}) = \frac{1}{T} \int_{-T}^{T} (1 - \frac{|t|}{T}) \gamma_{UW} (t) \, dt \qquad \text{(B.14)}$$

The variance $(\hat{\underline{\tau}})$ can be described by equation (B.11) because the extra terms resulting in equation (B.13) are negligibly small $\left[(\frac{1}{T^2}) \right]$.

Comparison of one-phase and two-phase methods

Both methods are compared from experimental results of Antonia and Atta [1]:

For sufficiently large measuring times (T), the bias-terms of $\hat{\underline{\tau}}$ can be described by:

$$\text{Bias } (\hat{\underline{\tau}}) = \pm \frac{\rho}{T} \int_{-\infty}^{\infty} \gamma_{UW} (t) \, dt \qquad \text{(B.15)}$$

Using the results of Antonia (Figure 5 of Antonia) the cross-covariance function γ_{UW} (t) can be approximated by:

$$\gamma_{UW}(t) = \gamma_{UW}(o)\, e^{-\alpha |t|} , \quad \gamma_{UW}(o) < 0 \tag{B.16}$$

in which:

$\alpha \approx 2\, u_o/\delta$

u_o = flow velocity in (equilibrium) outer layer

δ = thickness of boundary layer

Substitution of (B.16) in B(15) yields:

$$\text{Bias}\ (\hat{\underline{\tau}}) = \pm \frac{2\,\rho\,\gamma_{UW}(o)}{\alpha\, T} = \pm \frac{2\tau}{\alpha T} \tag{B.17}$$

To describe the variance of $\hat{\underline{\tau}}$ it is assumed that U and W are Gaussian stationary processes. This yields:

$$\gamma_{UU}(\Theta)\,\gamma_{WW}(\Theta) + \gamma_{UW}(\Theta)\,\gamma_{UW}(-\Theta) = E\,\{u'(t)w'(t)\ u'(t+\Theta)\ w'(t+\Theta)\} -$$

$$- \left[E\,\{u'(t)w'(t)\}\right]^2 \triangleq \gamma_{u'.w'}(\Theta) \tag{B.18}$$

in which:

$\gamma_{u'.w'}$ = auto-covariance function of the product of u'(t) and w'(t)

For sufficiently large measuring time periods (T):

$$\text{Var}\ (\hat{\underline{\tau}}) \approx \frac{\rho^2}{T} \int_{-\infty}^{\infty} \gamma_{u'.w'}(\Theta)\, d\,\Theta = \frac{\sigma_U^{\,2}\,\sigma_W^{\,2}\,\rho^2}{T} \int_{-\infty}^{\infty} \frac{\gamma_{u'.w'}(\Theta)\, d\Theta}{\sigma_U^{\,2}\,\sigma_W^{\,2}} \tag{B.19}$$

The function $\dfrac{\gamma_{u'.w'}(\Theta)}{\sigma_U^{\,2}\,\sigma_W^{\,2}}$ is identical to Antonia's (measured) function

$R_{UW - (UW)}$ (Θ), so that:

$$Var\ (\hat{\underline{\tau}}) = \frac{\rho^2\ \sigma_U^{\ 2}\ \sigma_W^{\ 2}}{T} \int_{-\infty}^{\infty} R_{UW - (UW)}\ \Theta\ d(\Theta)$$

$$= \frac{\rho^2\ \sigma_U^{\ 2}\ \sigma_W^{\ 2}}{T}\ R_{UW - (UW)}\ (o) \int_{-\infty}^{\infty} \frac{R_{UW - (UW)}\ (\Theta)}{R_{UW - (UW)}\ (o)}\ d\Theta$$

$$\triangleq \frac{2\rho^2\ \sigma_U^{\ 2}\ \sigma_W^{\ 2}}{T}\ R_{UW - (UW)}\ (o)\ \Lambda_{u'.w'} \qquad (B.20)$$

in which

$\Lambda_{u'.w'}$ = time integral scale of the produkt of u' and w'

$$R_{UW - (UW)}\ (o) = \frac{\gamma_{u'.w'}\ (o)}{\sigma_U^{\ 2}\ \sigma_W^{\ 2}} = \frac{\gamma_{UU}\ (o)\ \gamma_{WW}\ (o) + \gamma_{UW}^{\ 2}(o)}{\sigma_U^{\ 2}\ \sigma_W^{\ 2}}$$

$$= 1 + \frac{\tau^2}{\rho^2\ \sigma_U^{\ 2}\ \sigma_W^{\ 2}} \qquad (B.21)$$

Finally, there can be derived:

$$Var\ (\hat{\underline{\tau}}) = \frac{2\rho^2\ \sigma_U^{\ 2}\ \sigma_W^{\ 2}}{T}\ (1 + \frac{\tau^2}{\rho^2\ \sigma_U^{\ 2}\ \sigma_W^{\ 2}})\ \Lambda_{u'.w'}$$

$$= \frac{2\Lambda_{u'.w'}}{T}\ (\rho^2\ \sigma_U^{\ 2}\ \sigma_W^{\ 2} + \tau^2) \qquad (B.22)$$

From Antonia's Figure 5 it can be derived that:

$$\Lambda_{u'.w'} \approx 0.1\ \frac{\delta}{u_o} \qquad (B.23)$$

Assuming:

$$\sigma_U^2 \approx 9\, u_*^2 = 9\,\frac{\tau}{\rho}$$

$$\sigma_W^2 \approx u_*^2 = \frac{\tau}{\rho}$$

then:

$$\text{Var}\,(\hat{\underline{\tau}}) = \frac{0.2\delta}{T\, u_o}\,(9\,\tau^2 + \tau^2) = \frac{2\,\delta\,\tau^2}{T\, u_o} \qquad \text{(B.24)}$$

The relative error in the turbulent shear stress will be:

$$\frac{\sigma_\tau}{\tau} = \left(\frac{2\delta}{T\, u_o}\right)^{\frac{1}{2}} \qquad \text{(B.25)}$$

The relative systematic error, expressed by equation (B.17), will be:

$$\frac{\text{Bias}\,(\tau)}{\tau} = -\,\frac{\delta}{u_o\, T} \quad \text{for the one-phase method}$$

$$\text{(B.26)}$$

$$\frac{\text{Bias}\,(\tau)}{\tau} = +\,\frac{\delta}{u_o\, T} \quad \text{for the two-phase method}$$

in which:

δ = thickness of boundary layer (m)

u_o = flow velocity in outer layer (m/s)

T = measuring-time period (s)

Generally, the values measured by the one-phase method will be systematically too low, while for the two-phase method the measured values will be systematically too high.

p.o. box 177 2600 mh delft the netherlands