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A suspended-load experiment in a straight flume at Delft Hydraulics

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ABSTRACT

A suspended sediment transport experiment in a straight flume with a mobile bed is reported. The bed topography is non-horizontal. The flow is steady. Due to an obstruction in the entrance a steady bed oscillation is generated.

The bed topography is measured by means of manual bed soundings (by Delft Hydraulics). Suspended sediment concentrations are measured by siphoning (by Delft University).

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LIST OF SYMBOLS

a	local ensemble mean water depth	[m]
a'	local fluctuation of bed level	[m]
a_0	overall mean water depth	[m]
c	local concentration	[g/l]
c_r	concentration at reference level	[g/l]
$\bar{c}$	local depth averaged concentration	[g/l]
$\bar{c}_{tr}$	total transport concentration; $\bar{c}_{tr} = Q_s/Q_w\ 10^{-3}$	[g/l]
C	Chézy coefficient, with $d=a_0$; $C = \bar{u}/\surd(di)$	[$m^{0.5}$/s]
D_{gr}	dimensionless grain diameter; $D_{gr} = D_{50}(\Delta g/\nu^2)^{1/3}$	[-]
D_g	geometric mean grain diameter; $D_g = \surd(D_{84}/D_{16})$	[m]
D_p	grain size for which p% of the grains is smaller than D_p	[-]
D_{50}	median grain size	[m]
D_s	sedimentation diameter	[m]
Fr	Froude number, with $d=a_0$, $Fr = \bar{u}/\surd(gd)$	[-]
G	coefficient in gravitation term	[-]
H	depth of the flume	[m]
i	water surface slope	[-]
y	coordinate in transverse direction	[m]
Q_w	water discharge	[m^3/s]
Q_s	sediment discharge	[g/s]
r_u	profile function of the velocity profile	[-]
r_c	profile function of the concentration profile	[-]
x	coordinate in streamwise direction	[m]
S_s	transport rate of suspended sediment, per unit width	[g/m/s]
S_t	total transport rate, per unit width	[g/m/s]
T	water temperature	[^{0}C]
$\bar{u}$	overall averaged mean flow velocity: $\bar{u} = Q_w/(Wa_0)$	[m/s]
u_*	bed friction velocity, based on C : $u_* = (u\surd g)/C$	[m/s]
X	fraction suspended sediment transport	[-]
W	width of the flume	[m]
w_s	fall velocity of sediment	[m/s]
Z	the Z parameter: $Z = w_s/(\beta\kappa u_*)$	[-]
z_r	reference level	[m]

α_s	product velocity and concentration profile	[-]
β	ratio of exchange coefficients of sediment and momentum	[-]
κ	von Karman constant	[-]
ρ	density of water; ρ =1000 kg/m^3	[kg/m^3]
ρ_s	density of sediment; ρ_s=2650 kg/m^3	[kg/m^3]
σ_g	gradation of sediment; $\sigma_g = D_{84}/D_{16}$	[-]
ν_{tm}	turbulent diffusion coefficient of momentum	[m^2/s]
ν_{tc}	turbulent diffusion coefficient of mass	[m^2/s]
θ	Shields number, with $d=a_0$: $\theta = di/(\Delta D_{50})$	[-]
θ_{cr}	critical Shields number	[-]
Δ	relative density of the sediment; $\Delta = 1.65$	[-]

1. INTRODUCTION

The interaction between the flow and bed topography of alluvial rivers is complicated. The presence of suspended sediment transport is, in addition to bed load transport, expected to affect the bed topography.

An experiment in a straight flume, at Delft Hydraulics, displays a steady bed oscillation of which two periods are included in the flume. No damping of the wave is observed. This is caused by an obstruction in the flume entrance.

The bed topography was measured under quidance of Delft Hydraulics. The bed topography data has been reported by Ahmed (1990). Local suspended sediment concentrations were measured by J. de Graaff of the Delft University. In this report both the data on the bed topography (less extensive) and suspended sediment concentrations are reported.

In chapter 2 the experiment and the measuring procedures are described briefly. In chapter 3 the sediment characteristics and the flow conditions are given. In chapter 4 the results of the bed level and concentration measurements are reported. In chapter 5 the conclusions are given.

The experiment is part of a Netherlands Technical Assistance project "Hydraulic Studies on the Nile River and its Structures". The ministries involved are: Kingdom of the Netherlands, Ministry of Foreign Affairs, Directorate General for International Co-operation and the Arab Republic of Egypt, Ministry of Public Works and Water Resources, Water Research Center. Training on river morphology is provided by Delft Hydraulics to members of the Hydraulic & Sediment Research Institute of Egypt.

The research at Delft University is a part of a project: 'River Bend Morphology with Suspended Sediment', project no. DCT59.0842. The project is supported by the Netherlands Technology Foundation (STW).

2. THE EXPERIMENT

2.1 The flume

The layout of the flume is shown in figure 1. Water and sand are recirculated. The dimensions of the flume are:

length	24.00 m
width	W = 0.60 m
depth	H = 0.70 m

The bottom of the flume is made of steel, the side walls are made of glass.

2.2 The experiment

The flume is partly filled with sand. An obstruction in the entrance section causes the flow and bed topography to show a steady oscillation. The experiments runs 24 hours per day. The experiment has run about 2 weeks before the bed-level measurements, given in this report, started (bed soundings 9 to 30, Ahmed 1990). The concentration measurements are performed during the end phase of the experiment (corresponding with bed soundings 25 to 30).

The water surface and the bed level are measured twice per day (at 10 a.m. and 3 p.m.). The steady bed topography is calculated by ensemble averaging.

Sediment concentration profiles at the centre-line are taken at the locations 11 m, 13 m, 16 m and 19 m. At 13 m also measurements at 0.25W and 0.75W are performed. At 10.3 m the concentrations in one of the deepest parts are measured, at 0.75W.

In a vertical, depending on the local water depth, about 20 samples are taken (interval 5 mm). Near the bed it is difficult to measure because of the bed forms.

2.3 Measuring procedures

2.3.1 Discharge

The discharge is measured once per day (except weekends) by a volumetric method. For a short instance (~ 7 s) the retour pipeline is disconnected, water and sand are lead into a container. The water volume is measured and divided by the filling time. The sand is collected by opening a valve in the bottom of the container. The sand is then lead into a glass gauge (sometimes referred to as van Rijn's apparatus), and the sand volume is determined.

2.3.2 Water surface and bed level

The bed and water level are measured manually, twice per day, by point gauges. The tip of the gauge by which the bed is measured is equipped with a horizontal square steel plate (3x3 cm^2) to prevent gauge intrusion into the sand bed. An estimate of the sand bed intrusion of the steel pate is 3 mm (Struiksma, personal communication). From these measurements the longitudinal water level and local water depths are calculated. Bed levels are determined throughout the whole length of the flume at an interval of 25 cm. In transverse direction 3 locations are measured: 0.25W, 0.5W and 0.75W.

2.3.3 Concentrations

Concentration measurements, by siphoning, have been taken at four specific locations at the centre-line. These locations cover one wave period. Also measurements off centre-line are performed at a location where the bed is horizontal and in one of the deepest parts of the flow regions.
Sediment concentrations are determined from samples siphoned by tube-pipettes of stainless steel (outside diameter 5 mm, inside diameter 3 mm) shaped much like pitot tubes. The samples are collected in buckets. The tip of the samplers is flattened in order to minimize the vertical extended of the measuring volume.

Measuring periods of about 45 minutes are employed. Consequently about 9 liters are gathered. The samples are weighed to determine the volume. Then the water is separated from the sediment. The sediment is weighed under water using an electronic balance (Mettler PE 360). Weights are read with an accuracy of 10 mg. The results are converted to equivalent weights of dry sand.

3. FLOW AND SEDIMENT CONDITIONS

3.1 Sediment

3.1.1 Sieve curve

Sediment samples are collected from three different sources: the bed (Delft Hydraulics), the retour pipe line and suspended sediment (2 cm below water surface). Figure 2 shows the cumulative probability density distributions of the grain sizes (sieve curves) of these sediment samples. Characteristic grain diameters are:

	D_{10}[μm]	D_{16}[μm]	D_{50}[μm]	D_{84}[μm]	D_{90}[μm]	D_g[μm]	σ_g
bed layer :	76	80	99	128	133	101	1.60
retour pipe :	69	73	93	112	117	90	1.53
suspended sed.:	67	70	88	108	113	87	1.54

The quantity D_p is defined as the grain size for which p % of the total mixture volume is smaller then D_p.
The geometric mean diameter is defined by: $D_g = \sqrt{(D_{84}D_{16})}$
The gradation of the sediment is defined by: $\sigma_g = D_{84}/D_{16}$
The bed material is courser than both the suspended material and the mixture of recirculated (=supply) material. (The Delft Hydraulics and the Delft University sieve curve analysis methods are compatible.)

3.1.2 Fall velocity

The fall velocity of the suspended sediment is determined in a settling tube. This is a device to determine the fall velocity distribution of particles in a sample. At the lower end of the settling tube the sediment particles accumulate on a very sensitive weighing device. A cumulative weight distribution of the sample as a function of the measuring time is obtained. This distribution is converted into the fall velocity distribution of the sample using the height of the settling tube (Slot and Geldof, 1986).
Samples of suspended sediment are gathered from the retour pipe line. The samples are dried and split into amounts that can be used in the settling tube. Figure 3 shows the probability density distribution of

the fall velocity. The mean fall velocity, at 20^0C, of the sediment is: w_s= 0.0079 m/s. At higher temperatures the fall velocity increases; 2% per ^{0}C. The sedimentation diameter is: D_s= 100 μm. (Slot, 1983)

3.2 Flow conditions

The flow conditions are given in table 3.1. The bed consists of ripples. The values of parameters determined by measurement are given in table 3.1a. The parameter values obtained by subsequent calculation are given in table 3.1b. The total sediment transport is determined by using van Rijn's apparatus (sec. 2.3.1.). The apparatus is operated without measures to obtain an optimal packing of sediment (no aggitation), but a porosity coefficient of Γ=0.4 has been used by Ahmed (1990), table 34. In situ calibration of this method yielded a porosity coefficient of Γ=0.53 to convert volume water+sand to volume sand. An experiment at the Delft University in a glass gauge yielded the same value, without aggitation, and a value of 0.43 when strongly aggitated. The latter value has been confirmed by Delft Hydraulics (Wilkens, personal communication). The sediment transport value reported in Ahmed (1990) is wrong even though the text suggests Γ=0.53 has been used.

Table 3.1a Measured parameters

Q_w	= 0.0072	[m^3/s]	
W	= 0.60	[m]	
a_0	= 0.043	[m]	
i	= 3.3 10^{-3}	[-]	
D_{50}	= 90	[μm]	(susp+supply)
w_s	= 7.9 10^{-3}	[m/s]	(20^0C susp.)
Q_s	= 10.0	[g/s]	
T	= 20	[°C]	

Table 3.1b Calculated parameters

$\bar{u}$	$= Q_w/(Wa_0)$	= 0.28	[m/s]
$\bar{c}_{tr}$	$=(Q_s/Q_w)10^{-3}$	= 1.39	[g/l]
C	$= \bar{u}/\sqrt{(a_0 i)}$	= 23.4	[$m^{0.5}$/s]
Fr	$= \bar{u}/\sqrt{(g a_0)}$	= 0.43	[-]
θ	$= a_0 i/(\Delta D_{50})$	= 0.96	[-]
u_*	$= (\bar{u}\sqrt{g})/C$	= 0.038	[m/s]
D_s	= 100 [μm]	(susp.)	
Z	$= w_s/(\beta\kappa u_*)$	= 0.30	(sec. 4.2.2)

4. RESULTS

4.1 Depth measurements

4.1.1 Mean depth

The ensemble averaged water depth of 22 measurements is tabulated in appendix A. Figure 4 shows the ensemble averaged water depth at 0.25W, 0.5W and 0.75W, as a function of the longitudinal coordinate.
The bed topography displays an undamped oscillation of the transverse bed slope with a wavelength of 11 m. The oscillation is caused by the obstruction at the flume entrance.

At x=10.5, 12.0 and 13.2 m additional bed level measurements have been performed (following the period of longitudinal bed level measurements). The results are given in figure 5. These measurements indicate that the bed topography gradually changed during the final phase of the experiment, Ahmed (1990, fig 35...37). Consequently only the measurement on the first day (of three) is given, figure 5 (dates of measurements: appendix C). The results indicates that the bed topography is shifted about 1 m upstream in comparison with the ensemble averaged bed topography, figure 4.

4.1.2 Bed form statistics

The bed consists of bed forms moving downstream. The height of the bed forms is a significant fraction of the flow depth. These bed forms cause a significant form drag. This is reflected in the small Chézy value; C = 23.4 $m^{0.5}/s$. The large dimensions of the bed forms also affect the choice of reference level, i.e. the level above which the sediment is considered to be transported as suspended load and below which the sediment is considered to be transported as bed-load.
To guide the choice of reference level the probability density distribution of bed form height at the channel centre-line is calculated (here the average water depth is about the same as the

overall water depth). Soundings in which unsteady bars were noticed were discarded (soundings 17, 19, 23, 24)
The probability density distribution is shown in fig. 6. The 5% and 10% exceedance levels of bed form height are indicated. These are within the range: 0.2a to 0.25a.

4.2 Concentration measurements

4.2.1 Concentrations

The concentration measurements are tabulated in appendix B.
Figure 7 shows the concentration profiles at 11 m, 13 m, 16 m and 19 m.
In figure 8 the concentration measurements at and off centre-line at x=13 m are given. In fig. 9 the concentration profile in one of the deep flow regions, x=10.3 m, is given. Unfortunally no measurements have been taken at the deepest locations: z = 40 to 60 mm

Mean concentrations of each vertical are computed by:

$$\bar{c} = \frac{1}{j_{max}} \sum_{j=1}^{j_{max}} c_j \qquad (4.1)$$

with j_{max} the number of measurements in a vertical
The mean concentrations at each location are given in table 4.1

Table 4.1 Mean concentrations

x [m]	$\bar{c}$ (1/4 W) [g/l]	$\bar{c}$ (2/4 W) [g/l]	$\bar{c}$ (3/4 W) [g/l]
10.5	1.15	-	-
11	-	1.23	-
13	1.67	1.49	1.12
16	-	1.30	-
19	-	1.62	-

4.2.2. Curve fit of concentration profiles

It is assumed that the shape of the concentration vertical at the centre-line corresponds to a concentration vertical at equilibrium conditions.

The Rouse equilibrium concentration profile is fitted with these measurements. This profile is related to a parabolic distribution function for the turbulent exchange coefficient over the vertical.
The parameters describing the concentration vertical are: the reference height z_r/a, the concentration at reference height c_r, the profile shape parameter $Z=w_s/(\beta\kappa u_*)$

The concentration profile is given by: $$c = c_r\left(\frac{z_r}{a_0-z_r}\frac{a_0-z}{z}\right)^Z \qquad (4.2)$$

in which: $Z=w_s/(\beta\kappa u_*)$ = the Rouse parameter

β = efficiency factor turbulent sediment transport

Curve fitting has been performed with the aid of a computer program which, given z_r, estimates the Z and c_r parameters of eq.(4.1). A least squares method is employed. Results of curve fit of the measurements at 11 m, 13 m, 16 m, 19 m and a data set including all these locations are given in table 4.2. A reference level of 0.15a is used. The curve fit for the centre-line data is given in fig. 10.

Table 4.2 Results of concentration profile curve fitting

x [m]	z_r/a[-]	c_r[g/l]	Z [-]
11	0.15	2.1	0.29
13	0.15	2.2	0.23
16	0.15	2.5	0.31
19	0.15	2.7	0.26
11..19	0.15	2.4	0.27

Only small differences in the value of the Z parameter are noticed. The average Z parameter is estimated to be: Z=0.27. The reference concentration will vary with the choice of reference level.

The efficiency factor of turbulent sediment transport β, which is the inverse of the turbulent Prandtl number, is back calculated from the estimated Z value, the measured fall velocity and the bed shear velocity. Turbulent diffusion of sediment is modelled by: $\nu_{tc} = \beta\ \nu_{tm}$. (with: ν_{tm}= turbulent diffusion of momentum, ν_{tc}= turbulent diffusion of mass (sediment)). The back calculated coefficient of the experiment is: $\beta = 1.9$

The calculated Z and β values are in agreement with previous experiments by (one of) the writers with 90 μm sand at similar conditions:

run 1	(Talmon & Marsman 1988) :	Z = 0.25..0.30	β = 1.7
run 2	(Talmon 1988) :	Z = 0.33	β = 1.8
run 3	(Talmon & de Graaff 1989):	Z = 0.37	β = 1.5

4.2.3. Fraction suspended sediment transport

The fraction of suspended sediment transport is an important parameter in morphological models. The division between bed and suspended load transport is somewhat arbitrary and is effected by the choice of reference level. The most likely choice of reference level is near the top of the bed ripples. The suspended sediment transport rate per unit width is defined by:

$$S_s = \int_{z_r}^{a} u\ c\ dz \tag{4.3}$$

The suspended sediment transport rate per unit width can be expressed by similarity profiles of velocity and concentration:

$$S_s = \bar{u}\ \bar{c} \int_{z_r}^{a} r_u r_c dz = (a-z_r)\bar{u}\ \bar{c} \int_0^1 r_u r_c d\zeta = (a-z_r)\bar{u}\ \bar{c}\ \alpha_s \tag{4.4}$$

with: r_u, r_c = similarity profiles of velocity and concentration

$\alpha_s = f(C, Z, z_r/a)$ = integral of the product of r_u and r_c

The total sediment transport rate per unit width is by equal to:

$$S_t = a\ \bar{u}\ \bar{c}_{tr} \tag{4.5}$$

in which: $\bar{c}_{tr}$= the transport concentration defined by eq.(4.4)

The fraction (X) of suspended sediment transport for a given choice of reference level is given by (elimination of $a\bar{u}$ of eq.(4.3) and eq.(4.4)):

$$X = \bar{c}/\bar{c}_{tr}(1-z_r/a)\ \alpha_s \qquad (4.6)$$

For the calculation of this fraction data points greater than 2.5 g/l at a depth of 25 mm are removed, because these values have probably been affected by ripples.
The fraction suspended sediment transport for reference level values within the range $z_r/a=0.15..0.25$ is given in table 4.3 ($z_r/a=0.15$: $\alpha_s=1$, $z_r/a=0.25$: $\alpha_s=1.1$):

Table 4.3 Fraction of suspended sediment transport

x [m]	z_r/a[-]	c_r[g/l]	Z [-]	$\bar{c}$	X
11..19	0.15	2.38	0.27	1.26	0.77
11..19	0.20	2.16	0.27	1.27	0.73
11..19	0.25	2.00	0.27	1.29	0.70

The suspended sediment fraction is within the range X=0.7 to 0.8 ($z_r/a=0.15..0.25$).
A less accurate way to estimate the fraction of suspended sediment transport is by multiplying the mean concentration, eq.(4.1), and the depth of measurement. The mean concentration is $\bar{c}=1.33$ and the depth of measurement is 3 cm, consequently the fraction of suspended sediment is: X=0.77. This corresponds with the values in table 4.3

4.3 Velocities at the water surface

Velocity measurements at the water surface are taken x=15.2, 17.5 and 20.8 m. Near x=15.2 and 20.8 m the bed amplitudes are maximal. Near x=17.5 m the bed amplitude is circa half the maximal value and is located downstream of the location of maximal bed amplitude.
The velocity at the water surface is determined by measuring the time interval, that a floating ping-pong ball needs to travel a distance of 1 m. These measurements are repeated 10 times for calculation the average time interval and so the velocity. In the shallow flow regions

the path of the ping-pong ball indicates the flow to diverge towards the deeper parts. Consequently the velocities are overestimated at these locations.

The velocities are given in fig. 11. Seen from y=1/6W to 5/6W the velocity at x=15.2 m increases from 0.25 m/s in the shallow part to 0.38 m/s in the deep flow region. At x=17.5 m the same tendency is noticed. At x=20.8 m the velocity decreases from 0.40 m in the deep flow region to 0.20 m/s in the shallow part.

4.4 Total sediment transport

One sediment transport formula, Engelund & Hansen 1967, is evaluated. In previous experiments, run 1 to 5, which are characterized by nearly similar overall hydraulic conditions this transport formula overestimated sediment transport a factor 2 or 3. It is investigated whether this experiment follows this trend.

The Engelund Hansen formula reads:

$$\phi = \frac{0.05}{1-\Gamma} \frac{C^2}{g} \theta^{2.5}, \quad \text{with } \theta = \frac{di}{\Delta D_{50}}, \ \phi = \frac{S}{\sqrt{(\Delta g D^3)}}, \tag{4.7a}$$

$$\text{or:} \quad \bar{c}_{tr} = \rho_s \frac{1}{\bar{u}a_0} 0.05 \sqrt{(\Delta g D_{50}^3)} \frac{C^2}{g} \theta^{2.5} \tag{4.7b}$$

The predicted transport concentration is: $\bar{c}_{tr} = 1.72$ g/l
(for D_{50} the value of retour line sand is used)
The Engelund & Hansen formula predicts the total transport well. It is overestimated 25%, which is quite good for a sediment transport formula.

5 CONCLUSIONS

The bed topography and sediment concentrations are measured in straigth flume. The median diameter of the sediment is 90 μm.

The main features of the experiment are:

- The stationary bed topography is excitated by an disturbance at the entrance of the flume. The bed displays two periods of oscillation no damping is observed. The wavelength of oscillation is 11 m.

The following parameters characterize the experiment.

- The overall friction coefficient is: $C = 23.4\ m^{0.5}/s$
- The profile shape parameter of suspended sediment is estimated to be: $Z = 0.27$
- Due to ripple dimensions the reference height should be chosen within: $0.15 < z_r/a < 0.25$
- The fraction of suspended sediment transport is within the range: $X = 0.7.$ to 0.8
- Total sediment transport is well predicted by Engelund & Hansen's formula.

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Appendix A: Ensemble averaged water depths.

In this appendix the ensemble averaged relative water depths of the 22 measurements are tabulated.

Relative mean water depth a/a_0. (a_0 = 0.043 m.)

x (m)	1/4W	1/2W	3/4W
2.00	1.09	0.92	0.94
2.25	1.01	0.92	0.98
2.50	1.01	0.97	1.03
2.75	1.01	0.93	1.19
3.00	0.98	0.97	1.26
3.25	0.88	0.96	1.23
3.50	0.84	0.97	1.29
3.75	0.73	0.99	1.43
4.00	0.64	1.04	1.41
4.25	0.50	1.11	1.53
4.50	0.41	0.97	1.59
4.75	0.35	0.98	1.58
5.00	0.27	0.98	1.55
5.25	0.23	1.02	1.56
5.50	0.28	1.05	1.54
5.75	0.34	1.09	1.58
6.00	0.38	1.07	1.48
6.25	0.39	1.03	1.47
6.50	0.47	1.04	1.32
6.75	0.56	0.95	1.32
7.00	0.65	1.07	1.30
7.25	0.79	1.10	1.24
7.50	0.90	1.02	1.20
7.75	0.96	1.01	1.15
8.00	1.04	1.02	0.99
8.25	1.09	0.91	1.00
8.50	1.21	0.97	0.89
8.75	1.30	0.96	0.90
9.00	1.34	0.99	0.83
9.25	1.39	0.94	0.68
9.50	1.42	0.91	0.65
9.75	1.55	0.87	0.50
10.00	1.55	0.91	0.45
10.25	1.60	0.98	0.40
10.50	1.70	0.97	0.31
10.75	1.65	1.01	0.25
11.00	1.64	0.98	0.25
11.25	1.62	1.03	0.32
11.50	1.59	1.06	0.40
11.75	1.51	1.07	0.44
12.00	1.44	1.04	0.58
12.25	1.35	1.07	0.66
12.50	1.26	1.11	0.71
12.75	1.20	1.11	0.81
13.00	1.14	0.99	0.88
13.25	1.10	1.10	1.01
13.50	1.06	0.99	1.05
13.75	0.99	0.97	1.11
14.00	0.91	0.98	1.20
14.25	0.78	1.00	1.28
14.50	0.74	0.93	1.38
14.75	0.76	0.96	1.50
15.00	0.55	0.99	1.53
15.25	0.46	1.01	1.57
15.50	0.37	1.01	1.61
15.75	0.28	1.03	1.58
16.00	0.32	1.02	1.65
16.25	0.30	1.03	1.63
16.50	0.30	1.08	1.67
16.75	0.33	1.05	1.51
17.00	0.38	1.03	1.47
17.25	0.46	0.94	1.41
17.50	0.57	1.01	1.31
17.75	0.68	0.99	1.30
18.00	0.77	1.03	1.21
18.25	0.85	0.99	1.13
18.50	0.93	0.98	1.05
18.75	1.05	1.03	1.02
19.00	1.12	0.95	0.95
19.25	1.24	0.97	0.88
19.50	1.30	0.92	0.80
19.75	1.30	0.91	0.76
20.00	1.43	0.89	0.71
20.25	1.45	0.91	0.60
20.50	1.45	0.94	0.51
20.75	1.59	1.00	0.46
21.00	1.65	0.94	0.35
21.25	1.56	0.94	0.34
21.50	1.60	0.95	0.33
21.75	1.57	0.99	0.33
22.00	1.57	0.98	0.36
22.25	1.51	1.00	0.42
22.50	1.43	1.06	0.49
22.75	1.31	1.04	0.58
23.00	1.28	1.05	0.61
23.25	1.20	1.02	0.73
23.50	1.17	1.02	0.83
23.75	1.11	1.04	0.98

Appendix B: Concentration data

location in x-direction [m]	location in cross-direction [y/W]	Mean water depth [mm]	Distance beneath water surface [mm]	Concentration [g/l]		
0	1/8	250	105	0.979		
			115	0.877		
			125	0.858		
			135	1.267		
			145	1.158		
0	3/8	250	105	1.206		
			115	1.228		
			125	1.607		
			135	1.300		
			145	1.400		
10.3	1/4	73	5	0.720	0.637	
			10	0.866	0.683	
			15	1.048	0.875	
			20	1.038	1.089	
			25	1.382	1.057	
			30	1.451	1.342	
			35	1.627	1.158	
			40	1.540	1.808	
11.0	1/2	42	5	0.607	0.705	0.740
			10	1.028	0.825	1.007
			15	0.915	1.058	1.106
			20	1.086	1.410	1.301
			25	1.154	2.646	1.592
			30	1.449	1.883	1.597
13.0	1/4	52	5	0.942	0.952	
			10	1.227		
			15	1.435	1.258	
			20	1.584		
			25	1.608	2.241	
			30	1.948		
			35	3.472	1.743	
			40	1.888		
13.0	1/2	48	5	0.821	0.834	1.256
			10	0.968	1.102	1.259
			15	1.222	1.228	1.512
			20	1.274	1.488	1.456
			25	1.600	1.612	3.622
			30	1.641	1.726	2.179
13.0	3/4	35	5	0.516		
			10	0.978	0.793	
			15	0.812		
			20	1.212	1.052	
			25	0.980		
			30	1.407	1.215	
			35	2.243		
			40	1.656	3.434	

location in x-direction [m]	location in cross-direction [y/W]	Mean water depth surface [mm]	Distance beneath water [mm]	Concentration [g/l]		
16.0	1/2	44	5	0.795	0.846	0.769
			10	0.957	1.112	1.046
			15	1.157	0.844	1.114
			20	1.485	1.207	1.638
			25	1.409	1.369	2.133
			30	1.404	2.298	1.872
19.0	1/2	41	5	0.999	0.834	1.075
			10	1.299	1.055	1.168
			15	1.322	1.872	1.503
			20	1.647	1.576	1.534
			25	1.741	3.076	2.201
			30	2.148	1.705	2.317

Appendix C: Dates of measurements

date	bed measurements (3 x 50 grid)	bed measurements (transverse slope)	concentrations
17-09-90	sounding 1, 2		
18-09-90	sounding 3, 4		
19-09-90	sounding 5, 6		
20-09-90	sounding 7, 8		
21-09-90	sounding 9, 10		
weekend			
weekend			
24-09-90	sounding 11, 12		
25-09-90	sounding 13, 14		
26-09-90	sounding 15, 16		
27-09-90	sounding 17, 18		
28-09-90	sounding 19, 20		
weekend			
weekend			
01-10-90	sounding 21, 22		
02-10-90	sounding 23, 24		
03-10-90	sounding 25, 26		centre-line
04-10-90	sounding 27, 28		centre-line
05-10-90	sounding 29, 30		centre-line
weekend			
weekend			
08-10-90		sounding 1...8	off-centre-line
09-10-90		sounding 9...16	off-centre-line (½ day)
10-10-90		sounding 17...24	

sounding numbers refer to Ahmed (1990)

LAYOUT DELFT HYDRAULICS FLUME

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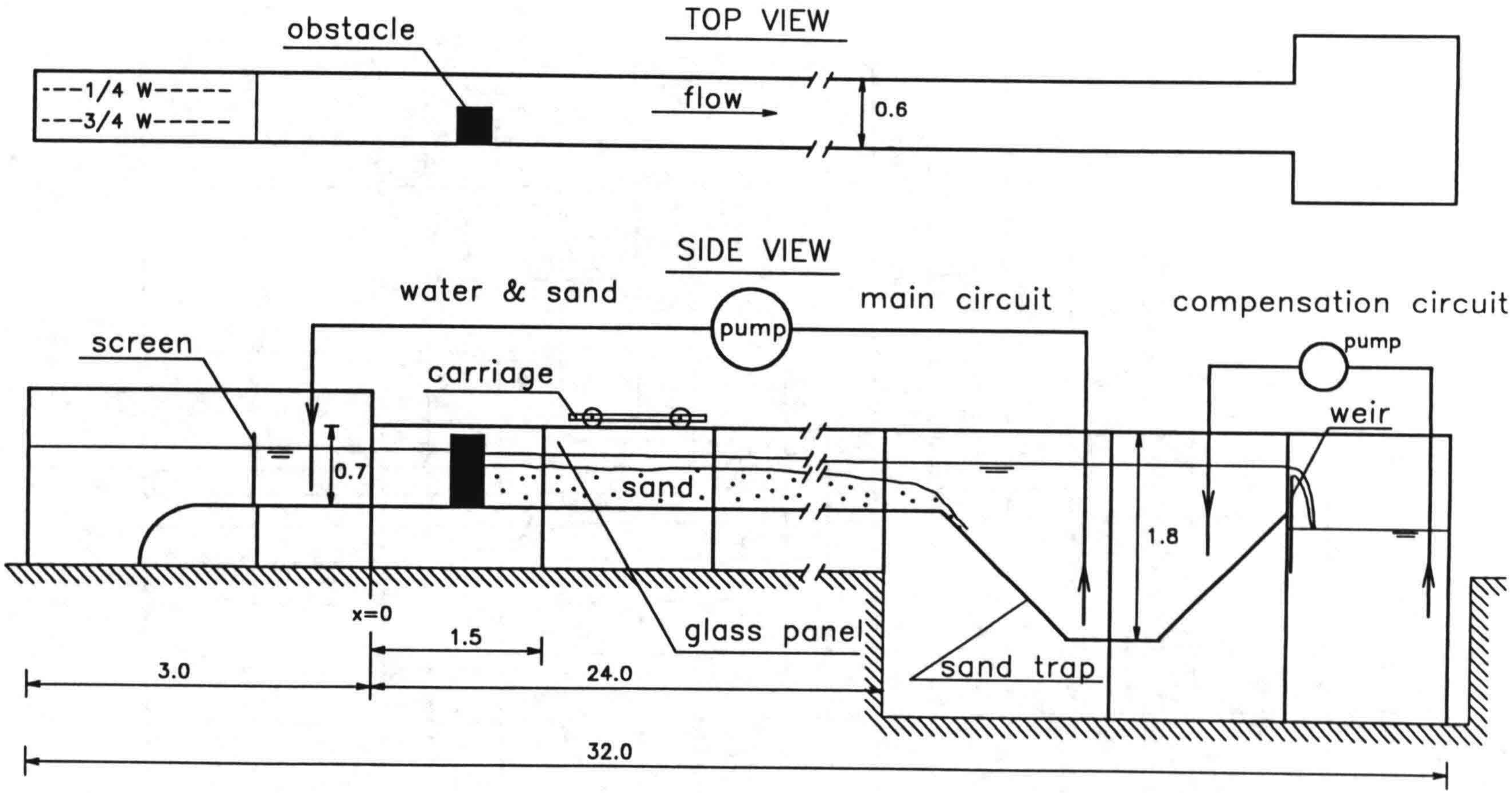
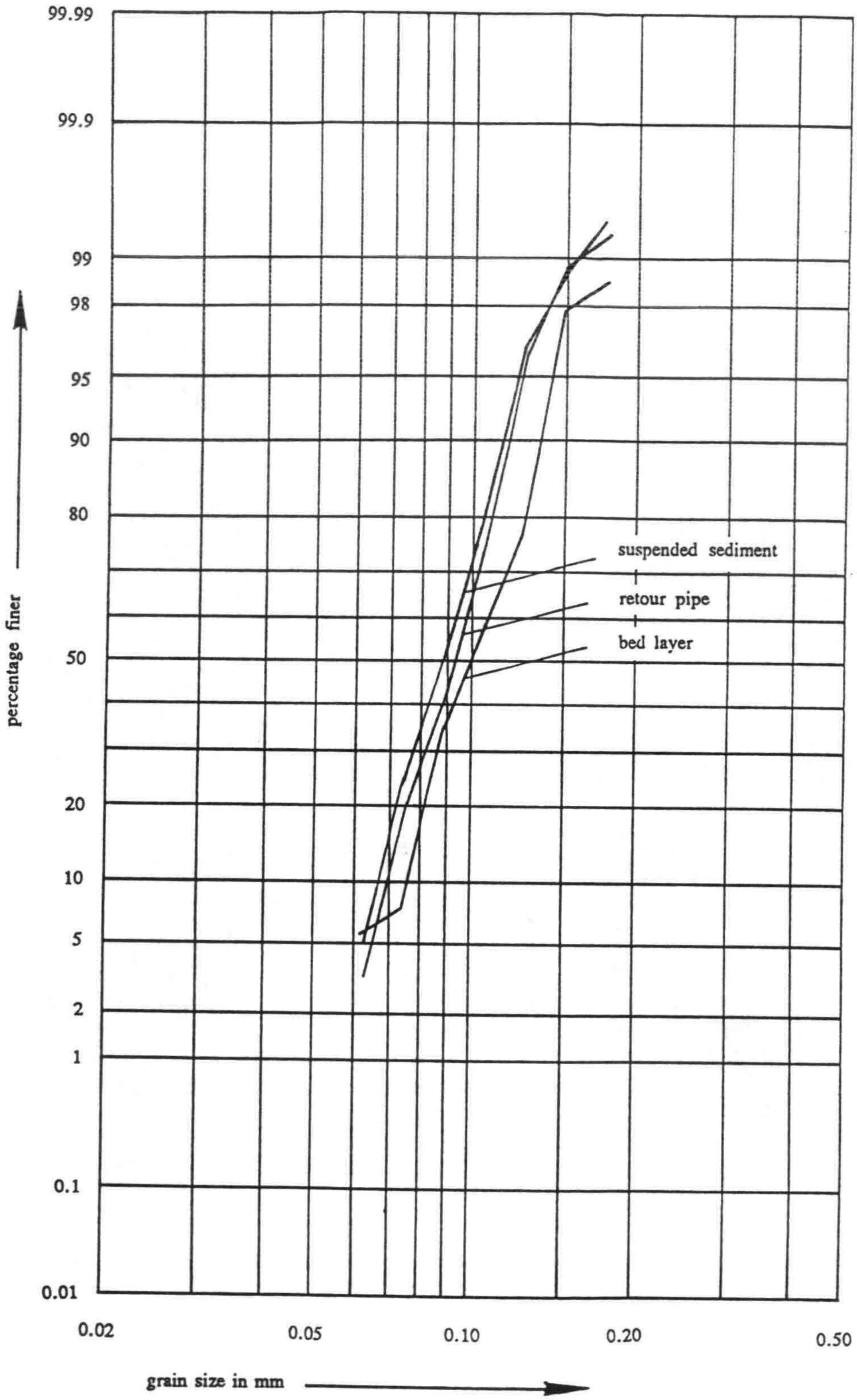


FIG. 1



SIEVE CURVES OF SEDIMENT

FIG. 2

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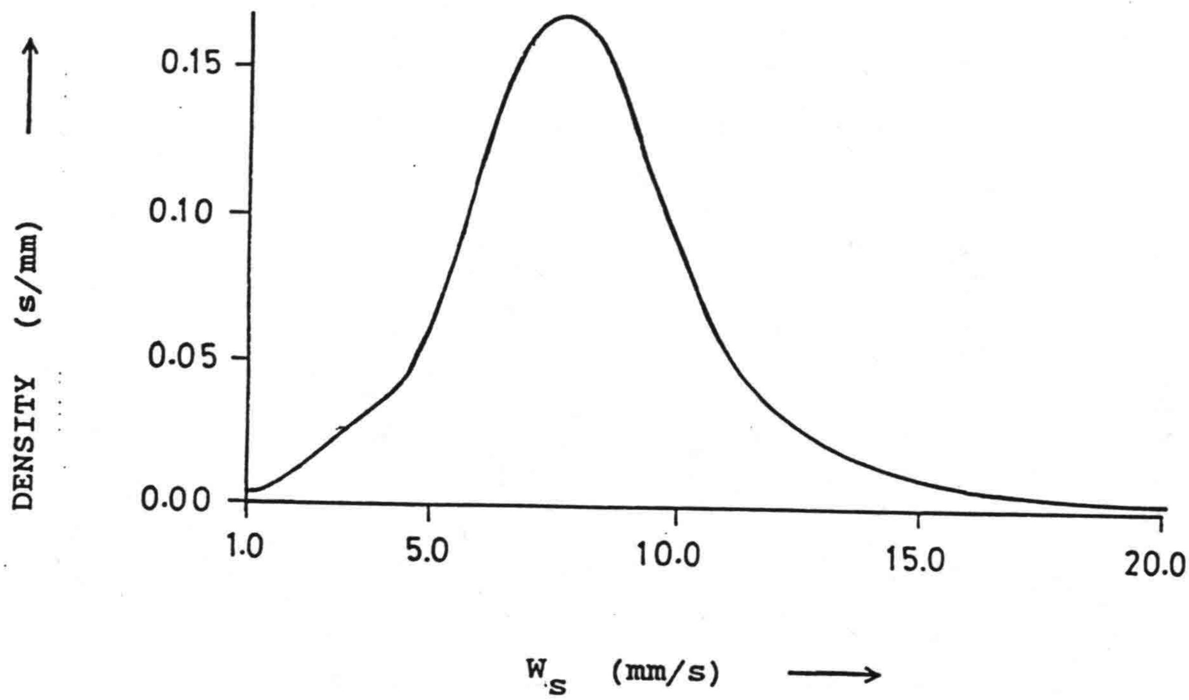
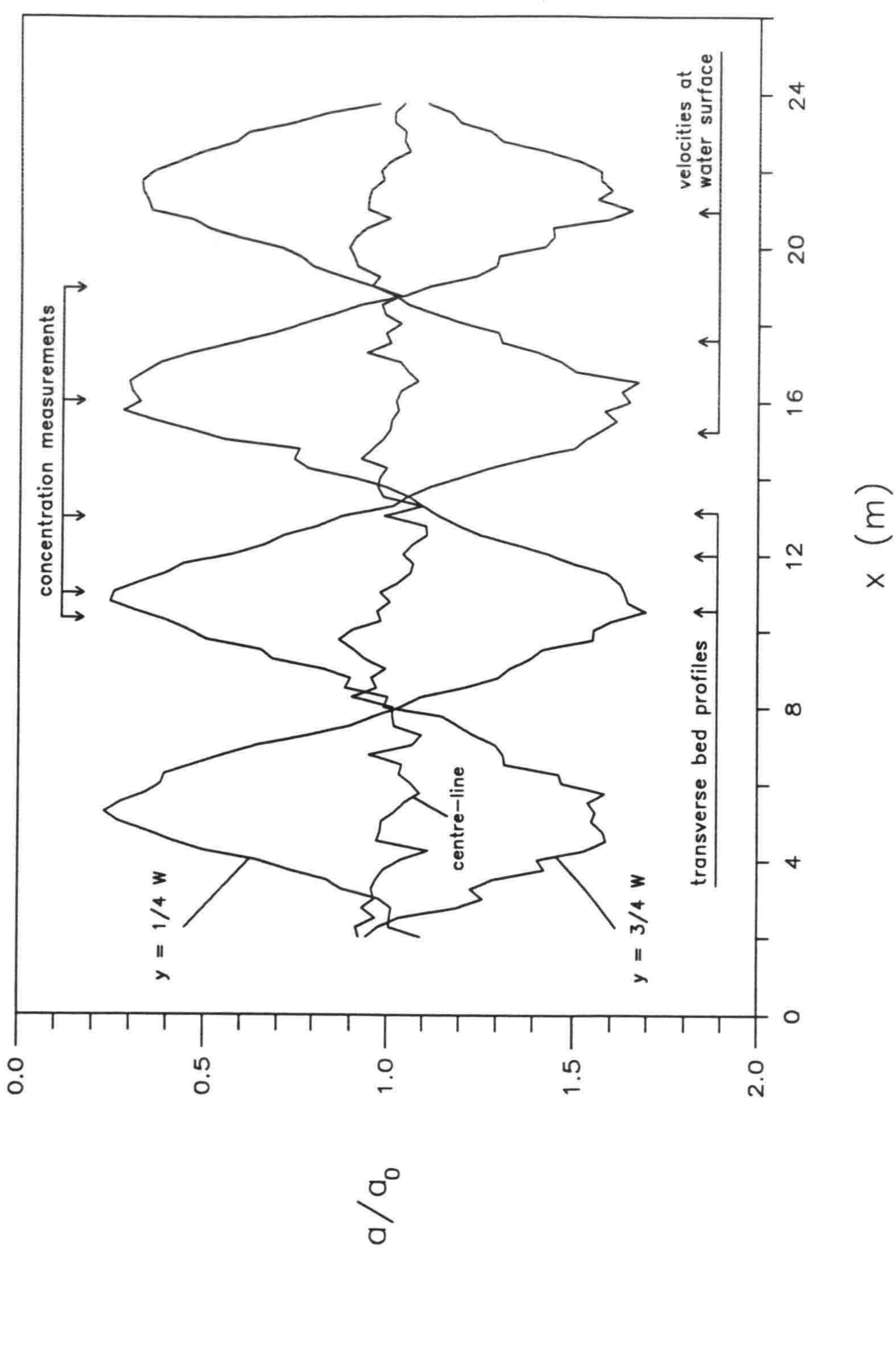


PROBABILITY DENSITY DISTRIBUTION OF FALL VELOCITY	FIG. 3
DELFT UNIVERSITY OF TECHNOLOGY	



W = 0.6 m a_0 = 0.043 m

ENSEMBLE AVERAGED WATER DEPTH

FIG. 4

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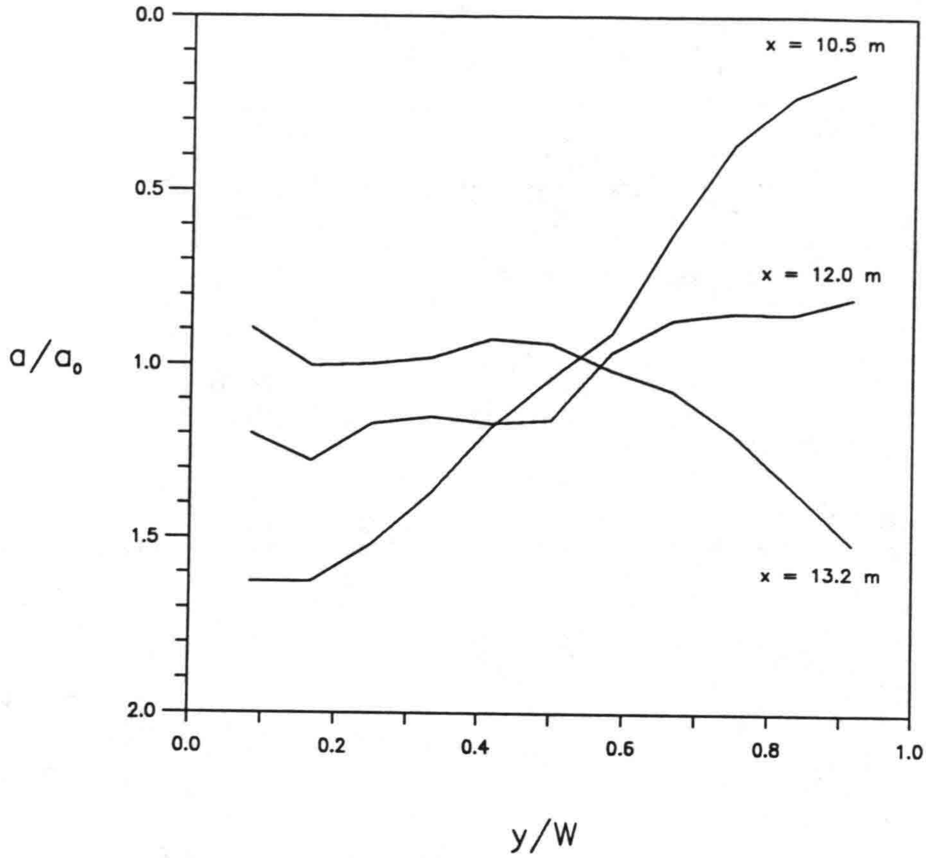

W = 0.6 m a_0 = 0.043 m

TRANSVERSE BED PROFILES

FIG. 5

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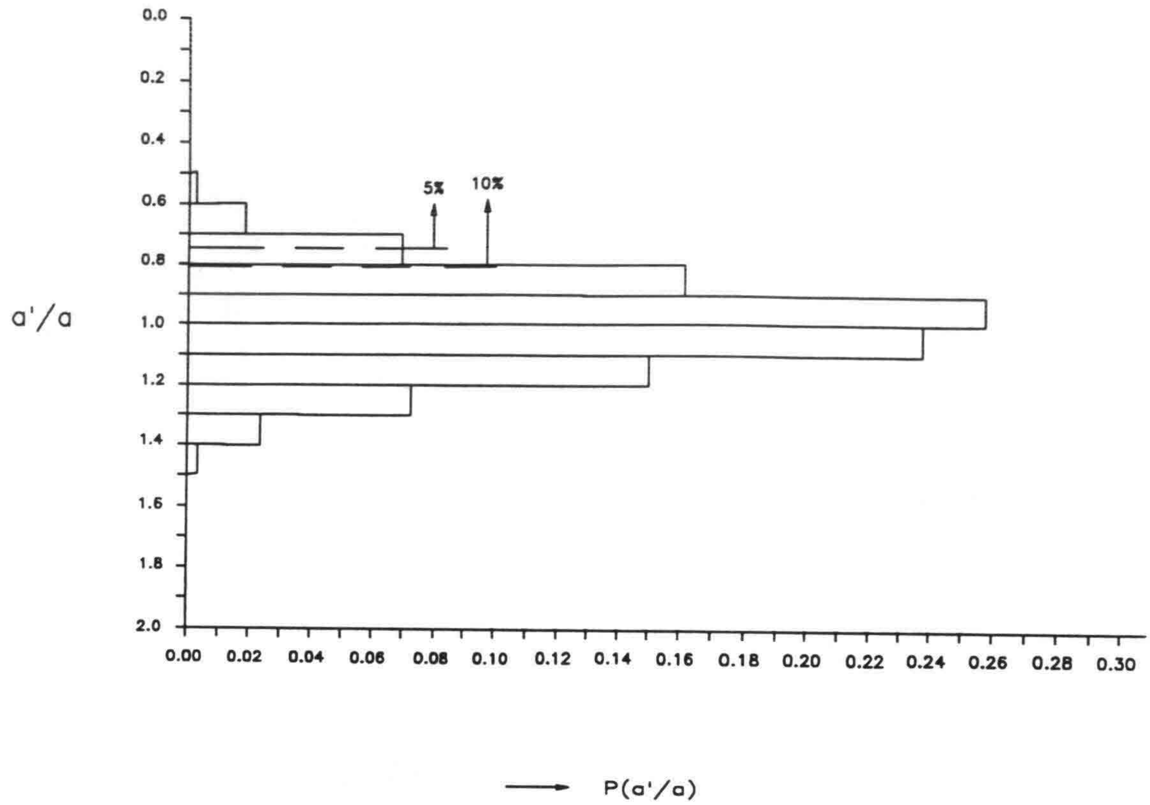

CENTRE–LINE

a' local water depth

a ensemble mean local water depth

PROBABILITY DISTRIBUTION OF BED LEVEL

FIG. 6

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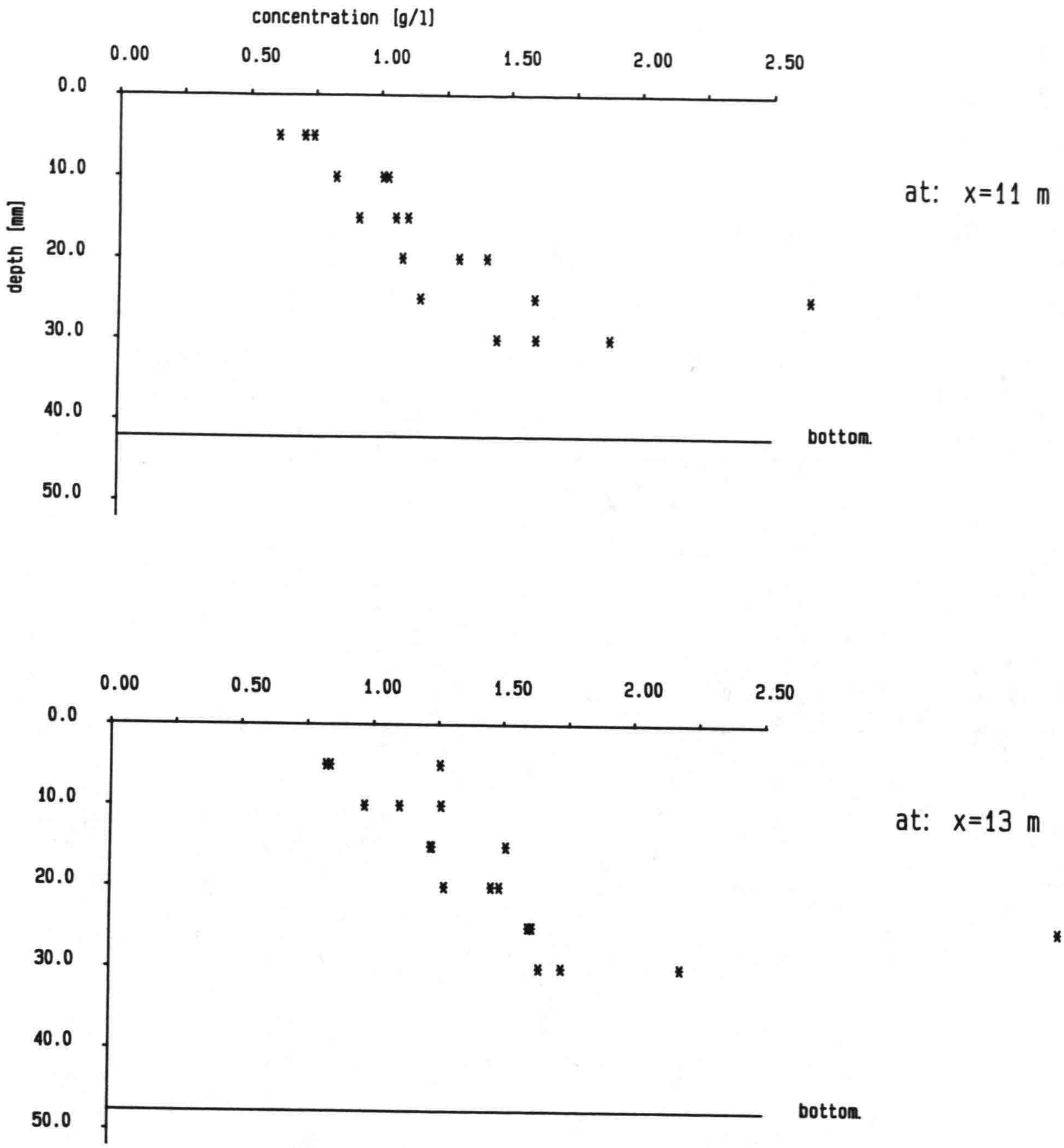

CONCENTRATIONS AT THE CENTRE-LINE

FIG. 7a

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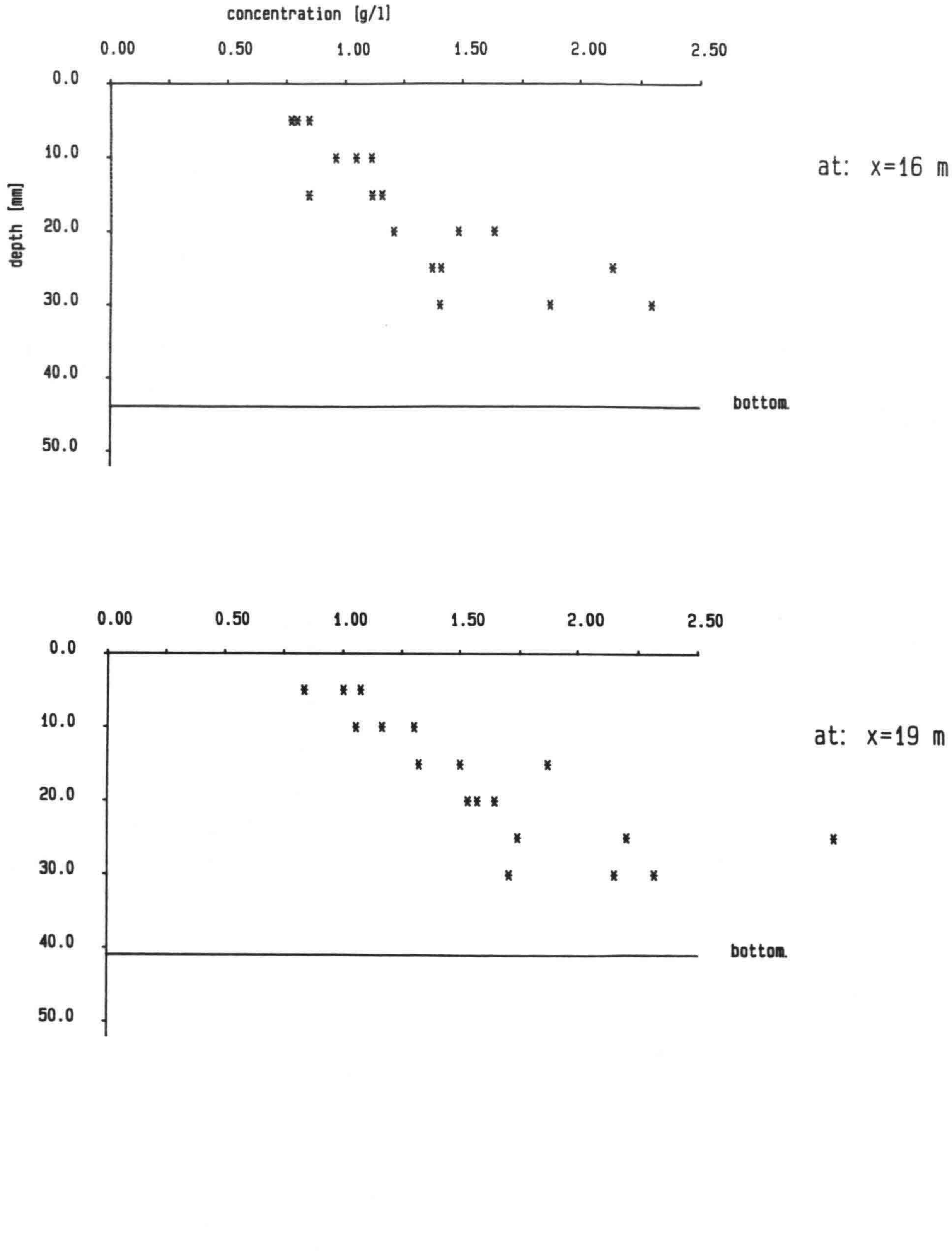

CONCENTRATIONS AT THE CENTRE-LINE

FIG. 7b

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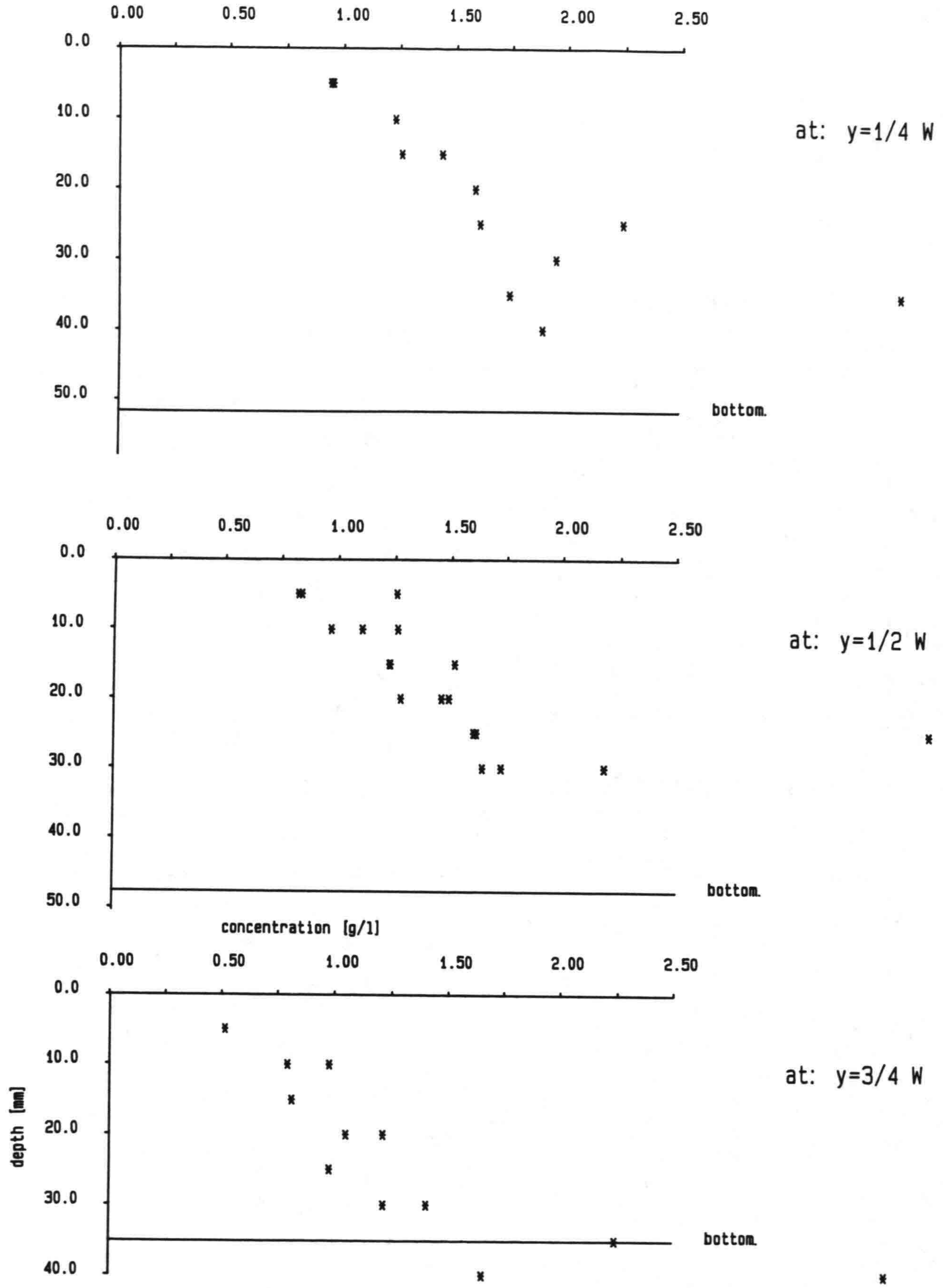

CONCENTRATIONS AT x = 13 m

FIG. 8

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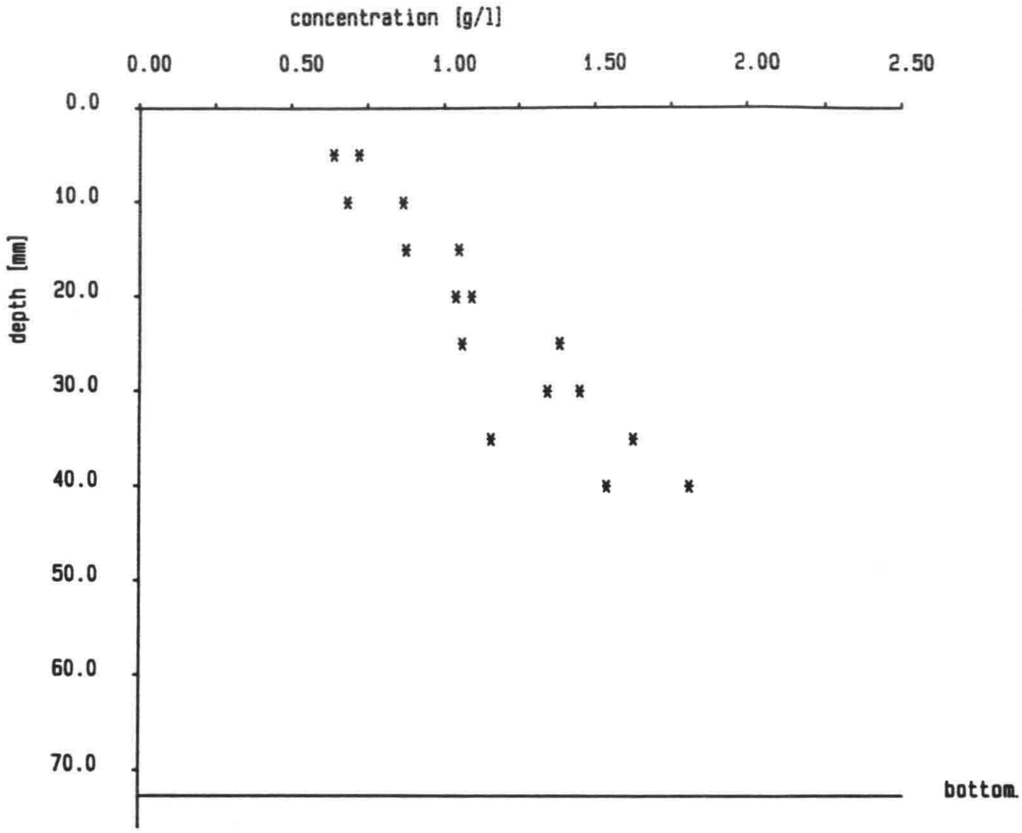

at: y=1/4 W

CONCENTRATIONS OFF-CENTRE AT x = 10.3 m

FIG. 9

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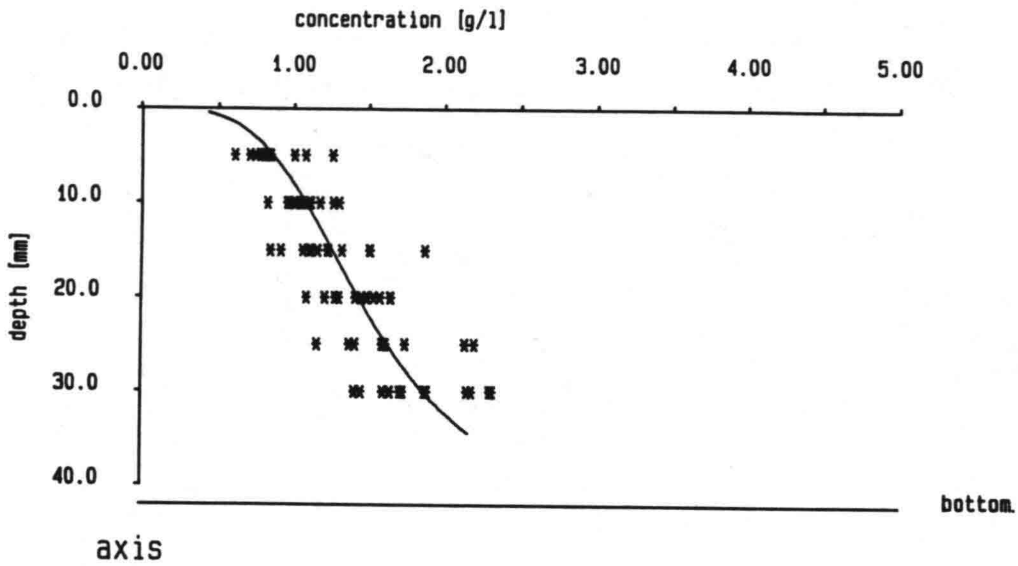

Rouse prof.: Z=0.27

CURVE FIT OF CENTRE-LINE CONCENTRATIONS

FIG. 10

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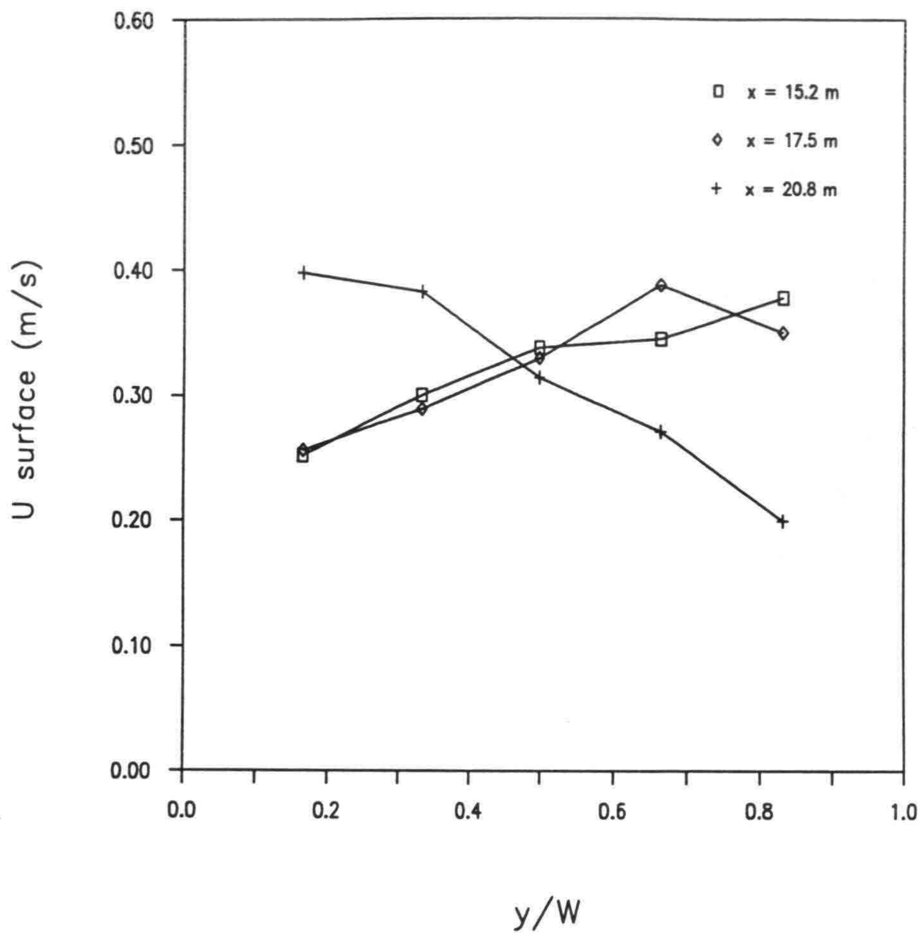

W = 0.6 m a_0 = 0.043 m

VELOCITIES AT THE WATER SURFACE

FIG. 11

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