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EXPERIMENTS ON ALLUVIAL FRICTION OF SAND-SILT MIXTURES

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ABSTRACT

Experiments are described in which the alluvial friction was measured for steady state flows over sediments consisting of sand and silt mixtures with varying proportions of silt. The results are analysed in terms of existing theories for alluvial friction of sand beds to determine if these theories need to be adjusted if silt concentrations up to 3000ppm are present. The results show that the presence of the silt has no discernable effect on the alluvial friction under steady state conditions. Comments are made on the predictions of the alluvial friction theories used.

CONTENTS

SYMBOLS

D	(m)	Grain diameter for uniform sediments
D_n	(m)	Grain diameter for which n% of the sample is finer
D_{gr}		Dimensionless sediment size
d	(m)	Average depth of flow
d'	(m)	$\tau_o'/(\rho g S)$
d''	(m)	$\tau_o''/(\rho g S)$
F_{gr}		Dimensionless sediment mobility
F_{fg}		Dimensionless sediment mobility (fine grains)
f		Friction factor (V/v_*)
g	(ms^{-2})	Acceleration due to gravity
k_s'	(m)	Equivalent sand roughness
S		Water surface slope
s		Specific gravity of sediments (ρ_s/ρ)
V	(ms^{-1})	Velocity of flow
v_*	(ms^{-1})	Shear velocity $(\sqrt{gdS})$
v_*'	(ms^{-1})	$\sqrt{gd'S}$
v_*''	(ms^{-1})	$\sqrt{gd''S}$
Y		sediment mobility
Y'		sediment mobility based on v_*'
ν	($m^2 s^{-1}$)	kinematic viscosity of water
ρ	($kgm\ m^{-3}$)	Density of water
ρ_s	($kgm\ m^{-3}$)	Density of sediment
τ_o	($kg\ m^{-2}$)	Bed shear stress
τ_o'	($kg\ m^{-2}$)	Bed shear stress due to surface roughness
τ_o''	($kg\ m^{-2}$)	Bed shear stress due to bed forms
Φ		Function
ψ'		$1/Y'$

1 INTRODUCTION

To calculate flow or sediment transport in an alluvial channel an engineer is faced with the problem of determining the frictional losses on the boundary of the channel.

For artificial, regular channels which are fixed in shape and carry little sediment there is data readily available which can be used as a basis for the estimation of appropriate friction factors. When natural channels are considered the problems of estimating the friction losses grow. In this case, not only must the frictional losses due to the composition of the banks and bed of the channel be estimated but also due allowance must be given for the effects of channel irregularities and other factors. If one considers channels with movable beds the problems are compounded. The frictional losses are dependent on the bed features present, but these are influenced by the transport of the sediment. The sediment transport, however, depends on the fluid motion and is hence inseparable from the determination of the frictional losses.

There are a number of theories for predicting the frictional losses in alluvial channels (Einstein and Barbarossa, 1952; Engelund, 1966; Raudkivi, 1967; White et al, 1980). Most of these theories are based on data, the vast majority of which is from laboratory experiments. Laboratory experiments are almost invariably characterised by the use of narrow-graded, clean sand, that is, sand with a small range of sizes from which both the larger sizes and any smaller silt or clay material has been removed. The finer silt and clay sizes frequently show very different properties to those of sand since these materials demonstrate cohesive properties whereas sands are non-cohesive. The silts and clays are sufficiently small that the physico-chemical properties associated with the surface of the particles become significant. In applications to practical problems, however, it is rare that the sediments which are encountered are similar to the narrowly graded sands used in laboratory experiments. Much more frequently sediments are widely graded and contain varying quantities of silts and clays.

This first report is an account of a simple, steady state laboratory investigation to discover if, under these circumstances, the presence of significant proportions of silt mixed with a sand bed have a discernible effect on the alluvial roughness in terms of the methods used to predict alluvial friction. The results were analysed to determine if the theories for predicting alluvial friction based on clean sand needed modification before they could be applied to channels where a proportion of silt is present. The work was confined to predominantly sand beds, as frequently found in rivers. It does not cover the case, which is more frequently found in estuaries than rivers, in which the predominant sediment is cohesive but contains some non-cohesive sand sizes.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were performed in a 2.44m wide, 24m long, recirculating, tilting flume. The sediment bed was 16m in length. At the downstream end of the flume a tailgate was used to control the depth of flow.

A flat-V Crump weir located 3m downstream of the tailgate was used to measure the discharge. The tapping point for measuring the head over the weir was 2m upstream from the weir crest. During some of the experiments a quantity of sediment was deposited immediately upstream of the weir but never enough to affect the stage-discharge relationship for the weir. The recirculating system consisted of two $0.113m^2s^{-1}$ and one $0.028m^3s^{-1}$ pumps. The entrances where the recirculating system returned the flow to the upstream end of the flume were proportioned according to the downstream of where the flow returned to the flume to ensure the uniformity of the velocity distribution across the flume.

Water surface slope was measured using five tapping points located at 2.5m intervals along the flume. 8mm diameter plastic tubing connected the tapping points to 60mm diameter stilling pots. The gauged heads in the stilling pots were measured using vernier point gauges reading to 0.02mm. A similar arrangement was used to measure the head above the crest of the Crump weir.

A 10m section of the flume had glass walls, this transparent section covering the central part of the sediment bed. The flow depth was measured at 6 points along this length on both sides of the flume. At each location the average bed level and water level were measured using a ruler attached to the wall.

A total of 29 experiments were performed; the first 6 runs, with a sand only bed, were used to test the equipment and the range of possible flows. Runs 7 to 14 were also carried out with a sand only bed. The grading curve of the sand is shown in Figure 1. The D_{50} size is 0.24mm and D_{85}/D_{15} = 2.33. For the remaining three series of experiments (Runs 15 to 20, 21 to 24 and 25 to 29) increasing quantities of silt were added to the sand bed. The discharges for the experiments varied from 0.13 to 0.21 cumecs.

The silt was obtained from the River Thames at Wallingford. It was first of all sieved to removed cobbles, shells, leaves and other foreign bodies. The grading curve of the resulting silt is shown in Figure 2; the specific gravity of the sediment was 2.65. To add the silt to the sand bed the water in the flume was drained down without draining the water from the bed and then the silt was poured onto the surface of the bed as a thick slurry.

The bed was sampled periodically during the experiments. The grading curves of the sediments changed very slightly. The D_{35} varied from 0.21mm to 0.19mm. No systematic change of D_{35} with the silt content of the flume was observed.

At the end of each sand only experiment the pumps were quickly stopped and the water was allowed to overflow from the stilling basin at the downstream end of the flume. The overflowing water did not carry any sediment in suspension. The sand bed was never drained between the experiments. At the end of each experiment with silt the water was retained in the flume to avoid the loss of the finer part of the suspended sediments.

At least once a day the average sediment concentration was measured from samples taken from the recirculating pipes via Pitot tubes. The sampling time was approximately 2 minutes and the sample volume was about 1.5 litres. The Pitot tubes were situated in vertical pipes to ensure that the distribution of sediments across the pipe cross-section was not affected by gravity.

During the experiments involving silt some velocity and concentration profiles were measured. All the measurements were taken along the axis of the channel and approximately half way along the sediment bed. The velocity profiles were determined by placing a miniature current meter, 10mm in diameter, at a given distance from the water surface and recording the pulse rate. The pulse rate was measured by a digital counter which averaged the pulses from the meter every 10 seconds. For each depth the average number of readings was 20, corresponding to a time interval of 200 seconds. Each profile consisted of 7 to 10 velocity measurements; the local depth of flow was also measured by lowering a probe with a flat base onto the bed of the channel. Sediment movement in suspension was obtained by taking simultaneous measurements of velocity and sediment concentration at 6 different depths. A small plastic tube of 0.6mm diameter was used to take samples of water and sediment at the same location as the propellor meter.

The sampling time was approximately 1 minute and the sample volume was approximately half a litre.

It was not possible to control the temperature of the water which varied from 14 ^{0}C at the beginning of an experiment to 23 ^{0}C at the end. The temperature was measured for every test with a thermometer reading to 0.1 ^{0}C.

3 DATA SUMMARY

The average water surface slope was calculated from the measured water levels by using a least-squares linear regression. Two values of the slope were determined, the first from the three central levels only, the second using all 5 points. The first value was used for all calculations because it was less affected by end effects. The second value of slope was used as a control.

The average flow depth was calculated by averaging the six depths measured in the central part of the flume. The standard deviation of the measurements was always less than 1cm, being greater when the sediment transport rate as higher and the bed less regular.

A summary of the measured data for the 146 tests is given in Table 1. For each test the following data is provided:

- time from the beginning of the experiment, in hours;
- water temperature, in degrees Celsius;
- average water surface slope, calculated using the 3 central water levels;
- average water surface slope, calculated using all 5 measured levels;
- average flow depth, in metres
- discharge, in litres per second
- average flow velocity, calculated from the measured discharge and mean cross section
- average concentration of sediments, if measured, in parts per million by weight, obtained from samples taken from the water and sediment return system. The concentration values refer to the mixture of sand and silt. It is also indicated if a velocity profile or a velocity and sediment concentration profiles were recorded during the test

The observed velocity profiles are given in Table 2. For each water depth (measured in metres from the free surface) there is:

- the average flow velocity, in metres per second;

- the standard deviation of the recorded data, in metres per second;
- the standard deviation of the recorded data, in percentage of the mean value

The last depth of each profile indicates the bed level.

The recorded concentration profiles are given in Table 3. In addition to the same values as for the velocity profiles, there is also the sediment concentration, in parts per million by weight.

4 DATA ANALYSIS

The experimental data was analysed by using four different theories on alluvial friction: Einstein and Barbarossa (1951), Engelund (1966), Raudkivi (1967) and White et al (1980). In the following sections the basic theory of these approaches is outlined together with the data analysis procedures. Figure 3 defines the symbols used in Figures 4 to 7 inclusive.

4.1 Einstein and Barbarossa (1951)

This method was the first working on the principle that all frictional characteristics of the flow could be related to the grain size of the bed material. The effect of viscosity is neglected. The basic assumption is that part of the total shear stress τ_o is due to the surface roughness (τ_o') and part is due to the bed forms (τ_o''):

$$\tau_o = \tau_o + \tau_o'' \qquad (1)$$

The splitting is attributed to the hydraulic radius; for a two dimensional flow, the depth is used instead:

$$\tau_o = \rho\ g\ S\ d \qquad (2)$$

$$\tau_o' = \rho\ g\ S\ d' \qquad (3)$$

$$\tau_o'' = \rho\ g\ S\ d'' \qquad (4)$$

and therefore

$$d = d' + d'' \qquad (5)$$

The effect of grain roughness is considered through one of the following formulae:

$$\frac{V}{v_*'} = 7.66 \left(\frac{d'}{k'_s}\right)^{1/6} \qquad (6)$$

$$\frac{V}{v_*'} = 5.75 \log_{10} \left(12.2 \frac{d'}{k_s'}\right) \tag{7}$$

where

$$v_*' = \sqrt{g\, S_f\, d'} \tag{8}$$

The analysis by Einstein and Barbarossa of field data from the Missouri River Basin suggested a functional relationship between ψ' and V/v_*'' where

$$\psi^1 = \frac{1}{Y'} = \frac{g\,(s-1)\,D_{35}}{(V_*')^2} \tag{9}$$

and

$$V_*'' = \sqrt{g\, s\, d''} \tag{10}$$

This theory, particularly the proposed relationship between ψ' and V/v_*', has been criticised (Garde and Ranga Raju, 1966, and Yalin, 1977) and in extensive comparisons with both field and laboratory data White et al (1980) found the theory to provide poor predictions of friction factor.

The present experimental data was analysed assuming

$$k_s' = D_{65} = 0.27\text{mm} \tag{11}$$

$$D_{35} = 0.21\text{mm} \tag{12}$$

and

$$s = 2.65 \tag{13}$$

Using the values of V and S, d' was first determined using equation (7). Then d^{11} was calculated from equation (5), using the average flow depth d. The values of ψ' and V/v_*'' were then calculated and the results plotted in Figure 4. The curve representing the relationship proposed by Einstein and Barbarossa is also shown in the Figure. It can readily be seen that the experimental points appear to be unrelated to the Einstein and Barbarossa relationship. This is similar to the behaviour found by Garde and Ranga Raju (1966) for experiments with dune covered beds. Further it can be seen that there is no discernible difference between the results with a sand only bed and those with varying silt concentrations.

The friction factor was then calculated using the Einstein and Barbarossa method using an iterative procedure and the calculated value compared with the observed value. A first value of d^1 was guessed and Y' was calculated. The corresponding value of V/v_*^{11} was determined from Figure 4 and using equation (7) d'' was determined. The value of d^1 was adjusted and the procedure was repeated until equation (5) was satisfied. The comparison of observed and calculated friction factors is shown in Figure 5. Less than 2% of the predictions are within 20% of the observed value. Not all the experimental points are plotted because many of the data yielded values of ψ' outside the range given by Einstein and Barbarossa. There is no discernable difference between the results with sand and silt mixtures and those with sand alone.

4.2 Engelund

The method is based on the similarity principle of the hydraulic model theory, and disregards the effect of viscosity. The energy loss per unit weight and per unit length of the uniform flow, S, can be separated in two terms:

$$S = S' + S'' \tag{14}$$

S' accounts for the losses due to skin roughness. S^{11} represents the losses due to the drag caused by bed forms, calculated as a sudden expansion of the flow in passing the forms. It is then possible to define two different forms of mobility number (here expressed for a two dimensional flow):

$$Y = \frac{v_*^2}{g\ (s-1)\ D} \tag{15}$$

$$Y' = \frac{v_*'^2}{g\ (s-1)\ D} \tag{16}$$

D_{35} is an appropriate value for D. Provided that the Froude number is the same, the similarity principle adopted by Engelund ensures that there is a unique relationship between Y and Y' and therefore:

$$\frac{v_*}{v_*'} = \frac{Y}{Y'} \tag{17}$$

Some flume data yielded a relationship expressed as an experimental curve (Engelund, 1966).

Furthermore, an analytical relationship for the calculation of the skin roughness friction only was provided by:

$$\frac{V}{V_*'} = 2.5 \ln \frac{d}{k_s'} + 6.0 \qquad (18)$$

where k_s' is the skin roughness, for which a value of $2\ D_{65}$ is recommended.

The present experimental data was analysed assuming the following values:

$$D_{35} = 0.21\text{mm} \qquad (19)$$

$$D_{65} = 0.27\text{mm} \qquad (20)$$

$$s = 2.65 \qquad (21)$$

First of all, the value of V_*' was determined using the relation. Then the values of Y and Y' were calculated, and the points were plotted on a Y - Y' diagram (Fig 5). On the same diagram are plotted the experimental curve suggested by Engelund and the relationship expressed by the equation:

$$Y' = 0.06 + 0.4\ Y^2 \qquad (22)$$

The present experimental data follows the same trend as the equations proposed by Engelund, particularly for low values of Y'. The bulk of the data, however, plotted below the curve. Again there seemed to be no discernible difference between the experimental results with sand and silt mixtures and those for sand alone.

The friction factor was then calculated using the present method using the equation:

$$\frac{V}{V_*} = \frac{Y'}{Y} \left(2.50 \ln \frac{d}{k_s'} + 6.0\right) \qquad (23)$$

which is derived from equations (17) and (18). The value of Y'/Y was determined from the curve in Figure 6 using the value of particle mobility Y. The calculated and observed friction factors are shown in Figure 7. The predictions provided by the Engelund method were very good; 65% of the predictions were within 20% of the observed value and all were within a factor of 2. This is a better performance than that reported by White et al (1980). Again there seemed to be no discernible difference between the experimental results with sand and silt and those for sand alone.

4.3 Raudkivi (1967)

Raudkivi suggested plotting $V/\sqrt{v_*^2 - v_{*cr}^2}$ against particle mobility Y, where v_{*cr} is the shear velocity at threshold conditions for the movement of the sediments. Plotting various data in this form he obtained relationships for gravels, sands and fine sands.

In the present calculations the critical shear velocity was determined using the Shield's curve (Yalin 1977). A plot of $V/\sqrt{v_*^2 - v_{*cr}^2}$ against Y is shown in Figure 8 together with Raudkivi's curve for fine sand. The results follow the same trend as Raudkivi's curve but consistently plot above it. There is no discernible difference between the results for sand and silt and those for sand alone.

To obtain the predicted friction factor the calculated average velocity was directly calculated from the mobility number Y and the Raudkivi curve. Figure 9 shows the calculated friction factor plotted against the observed. Though 50% of the predictions lie within 20% of the observed values it can be seen that the predicted values show a lot less variation than the observed values. The agreement between observed and predicted, however, is better than that reported by White et al (1980). Again, within the results there is no discernible difference between the results for sand and silt mixtures and those for sand alone.

4.4 White, Paris and Bettess (1980)

This method concerns two dimensional free surface flow, which is completely determined by the parameters ρ, ρ_s, ν, g, V_*, s, D and d. Four non dimensional numbers can be associated with these parameters. The dimensionless grain size is defined by:

$$D_{gr} = D \left[\frac{g\ (s-1)}{\nu^2}\right]^{1/3} \qquad (24)$$

This method uses the mobility number F_{gr} introduced by Ackers and White in their theory on sediment transport. Its general form is:

$$F_{gr} = \frac{v_*^n}{\sqrt{g D (s-1)}} \left[\frac{V}{\sqrt{32} \log_{10} \left(\frac{10d}{D}\right)}\right]^{1-n} \qquad (25)$$

The exponent n varies from 1.0 for fine sediments ($D_{gr} = 1$) to 0.0 for coarse sediments ($D_{gr} = 60$). The mobility number for fine sediments F_{fg} is, therefore,

$$F_{fg} = \frac{V_*}{\sqrt{g D (s-1)}} \qquad (26)$$

A selection of flume data suggested a relationship between F_{gr} and F_{fg} in the form:

$$\frac{F_{gr} - A}{F_{fg} - A} = \Phi \left[D_{gr}\right] \qquad (27)$$

A is the value of F_{gr} at the threshold of movement of the sediments. It is a parameter also used by Ackers-White theory on sediment transport and it depends only on D_{gr}.

The form of the function Φ was determined by fitting a curve to experimental points:

$$\Phi \left[D_{gr}\right] = 1 - 0.76 \left[1 - \frac{1}{\exp \left[(\log_{10} D_{gr})^{1.7}\right]}\right] \qquad (28)$$

With these relationships, if ρ, ρ_s, ν, v_*, D and d are given it is possible to calculate the average velocity of the flow V and the friction factor $f = V/v_*$.

The application of the theory is limited to Froude numbers less than 0.8; the minimum D_{gr} is 1.

The experimental data were analysed using:

$$D_{35} = 0.21\text{mm} \qquad (29)$$

$$s = 2.65 \qquad (30)$$

The dimensionless grain size was first determined; the value of kinematic viscosity was calculated on the basis of water temperature. The exponent n was then calculated according to Ackers and White theory:

$$n = 1.0 - 0.56 \log (D_{gr})$$

The values of the parameters F_{fg} and F_{gr} were determined according to equations (25) and (26). The results obtained from the present experiments are plotted in Figure 10. The theoretical relationship from the present experiments are plotted in Figure 10 for values of Dgr of 4.7 and 5.2. These are the extreme values calculated with the experimental data: the variation is due to changes in temperature. It can be seen that the experimental values follow the same general trend as that postulated by the theory but that they are displaced from the theoretical curve. This supports the general form of equation (27) but does not agree with the value of Φ derived from numerous other experimental results. The purpose of carrying out the sand only experiments was to provide a baseline for judging the sand-silt results and it is disappointing that the behaviour of the sand only results should be at such variance with the trend displayed by the large amount of data analysed by White et al. There is no discernible difference between the results with sand and silt mixtures and those with sand alone.

To calculate the friction factor the value of n and A were first determined from D_{gr}. Then the values of Φ and F_{gr} were calculated using equations (28) and (27), respectively. The average velocity V was determined from F_{gr} using the relationship (25). Predicted and observed friction factors are shown in Figure 11. The comparison is disappointing. The theory consistently overpredicts and none of the predictions are within 20% of the observations. This behaviour is considerably worse than that reported by White et al (1980). Again there is no discernible difference between the results with sand and silt mixtures and those with sand alone.

The van Rijn method for friction factor calculation (van Rijn, 1984) was briefly examined. It was found that the determination of the equivalent skin roughness was based on assumptions that were not suitable for the present experiments. A few calculations with this method, that was originally conceived for rivers, yielded values of friction factor overestimated by more than 80%.

To investigate the scatter found with each method of analysis results from just two of the experiments were plotted on the appropriate graphs and are shown in Figure 12. The results were from experiments 12 and 20. In the context of the available data, experiment 12 had a low average velocity of 0.25m/s and experiment 20 had a high average velocity of 0.32m/s. An apparent dependence upon velocity can be observed which is confirmed by the other data. This suggests that in each case there is some relevant variable which is being omitted from the analysis. There is theoretical support for this in that Yalin (1977) suggests that the friction factor is a function of three non-dimensional variables but none of the theories considered include this many degrees of freedom. This suggests that in the various theories presented the single curves might possible by more correctly replaced by a family of curves.

5 CONCLUSIONS AND RECOMMENDATIONS

The analysis of the experimental data indicates that the presence of silt fractions in concentrations of up to 3000ppm has no effect on the determination of alluvial friction using accepted theories for predicting alluvial friction of sand beds for steady state, well mixed structures. It is, therefore, recommended that in situations where silt is present in a sand bed but the sediment concentration in the flow does not exceed 3000ppm theories for predicting alluvial friction of sand beds are used without modification. The results further show that the theory of Einstein and Barbarossa provides poor predictions of alluvial roughness as has been reported elsewhere and that of the theories tested that by Engelund provided the best predictions.

5.1 Suggestions for further work

1. Perform experiments to determine effect of finer clay material on alluvial friction developed by sand beds formed of sand of this size range.

2. Perform similar experiments with sand beds composed of sand of different sizes. The size and form of bed features that develop depend upon the size of the sediment present and so experiments with different sizes may lead to different results.

3. Consider variations in flow. In the present restricted range of experiments it was not possible to look at effects generated by variations in the flow. In a natural river the flow varies significantly and this results in variations in the shear stress applied to the bed. This can produce a cycle of erosion and deposition which may influence the interaction of the sands and silts. In extreme cases, parts of the bed may dry out leading to changes in the properties of the silt.

4. Sediment transport of sand and silt mixtures. This work has not considered the related problem of the sediment transport of sand and silt mixtures and whether the presence of both sands and silts influences the individual behaviour of each.

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Tables

TABLE 1

EXPERIMENT	TEST	TIME FROM BEGINNING [h]	TEMPERATURE [°C]	SLOPE 3 POINTS 10^{-3}	SLOPE 5 POINTS 10^{-3}	AVERAGE DEPTH [m]	DISCHARGE [l/s]	AVERAGE VELOCITY [m/s]	AVERAGE CONCENTRATION [ppm]	VELOCITY PROFILE	CONCENTRATION PROFILE
6	1	1.5	15.0	0.080	0.056	0.260	150.2	0.237			
	2	20.5	22.9	0.140	0.124	0.262	149.8	0.235			
	3	27.2	23.2	0.200	0.160	0.260	150.4	0.237	25.6		
7	1	2.0	14.7	0.080	0.080	0.256	164.9	0.264			
	2	5.5	17.8	0.220	0.196	0.257	174.6	0.278			
	3	22.5	23.0	0.320	0.312	0.261	174.6	0.275			
	4	28.5	23.4	0.320	0.312	0.258	173.1	0.275	67.3		
8	1	1.2	15.3	0.120	0.104	0.200	134.0	0.274			
	2	4.2	17.4	0.200	0.152	0.200	123.9	0.253	7.64		
	3	7.2	19.0	0.440	0.344	0.199	125.3	0.258			
	4	25.2	23.0	0.500	0.428	0.202	124.5	0.253			
	5	28.2	23.3	0.500	0.476	0.207	124.3	0.247			
	6	31.2	23.7	0.480	0.448	0.204	125.1	0.251	39.0		
	7	48.2	24.2	0.340	0.428	0.203	124.5	0.252			
	8	53.2	24.3	0.380	0.420	0.202	124.1	0.252	37.0		
9	1	1.0	14.9	0.460	0.364	0.208	143.7	0.283			
	2	4.0	17.4	0.620	0.588	0.212	143.9	0.278			
	3	7.0	19.3	0.680	0.672	0.209	144.1	0.282	79.3		
	4	25.0	23.4	0.480	0.576	0.210	144.5	0.282			
	5	29.0	23.0	0.520	0.584	0.212	145.1	0.281			
	6	31.0	23.7	0.500	0.572	0.212	142.0	0.275	72.9		
10	1	1.2	15.9	0.440	0.408	0.279	207.6	0.305			
	2	5.0	18.7	0.480	0.448	0.278	208.1	0.307	95.0		
	3	22.2	22.3	0.440	0.328	0.276	207.6	0.308			
	4	25.2	22.5	0.460	0.404	0.275	206.5	0.308			
	5	28.5	22.3	0.360	0.376	0.275	207.0	0.308	75.0		
	6	46.2	21.9	0.340	0.452	0.275	208.4	0.311	64.0		

TABLE 1 (Cont/d)

EXPERIMENT	TEST	TIME FROM BEGINNING [h]	TEMPERATURE [°C]	SLOPE 3 POINTS 10^{-3}	SLOPE 5 POINTS 10^{-3}	AVERAGE DEPTH [m]	DISCHARGE [l/s]	AVERAGE VELOCITY [m/s]	AVERAGE CONCENTRATION [ppm]	VELOCITY PROFILE	CONCENTRATION PROFILE
11	1	1.0	14.0	0.800	0.792	0.204	166.4	0.334			
	2	4.0	16.7	0.800	0.880	0.204	167.4	0.337			
	3	7.0	18.7	1.020	0.924	0.203	166.4	0.336	136.0		
	4	25.0	23.2	0.740	0.852	0.215	171.7	0.328			
	5	28.0	23.5	0.760	0.736	0.217	173.8	0.328	77		
12	1	1.2	17.4	0.900	0.932	0.165	103.8	0.258			
	2	3.2	18.7	0.820	0.924	0.172	104.6	0.250			
	3	20.2	23.6	0.740	0.748	0.172	106.0	0.253			
	4	23.5	24.1	0.720	0.784	0.171	106.4	0.255			
	5	26.8	24.5	0.680	0.768	0.169	106.4	0.258	29.3		
13	1	2.0	15.0	0.780	0.948	0.216	179.4	0.340			
	2	5.6	17.4	0.860	0.924	0.219	176.6	0.331	179		
	3	22.5	21.7	0.860	0.860	0.229	185.5	0.332			
	4	26.3	21.9	0.780	0.780	0.232	184.4	0.326			
	5	28.6	22.1	0.680	0.720	0.233	184.6	0.324	166		
	6	46.7	22.4	0.860	0.756	0.226	184.8	0.335			
	7	49.7	22.4	0.780	0.788	0.227	185.7	0.335			
	8	53.5	22.5	0.740	0.820	0.229	184.6	0.330	179		
14	1	2.8	14.8	1.280	1.296	0.210	194.3	0.379			
	2	5.8	16.7	1.168	1.099	0.218	192.7	0.362	197		
	3	23.6	21.4	0.646	0.680	0.216	192.7	0.366			
	4	26.5	21.9	0.854	0.797	0.216	190.0	0.361			
	5	29.3	22.2	0.706	0.763	0.210	192.7	0.376	218		
	6	46.2	21.7	0.700	0.711	0.220	191.1	0.355			
	7	49.3	21.7	0.723	0.751	0.216	191.8	0.364			
	8	51.7	22.1	0.789	0.775	0.216	191.6	0.364	229		

TABLE 1 (Cont/d)

EXPERIMENT	TEST	TIME FROM BEGINNING [h]	TEMPERATURE [°C]	SLOPE 3 POINTS 10^{-3}	SLOPE 5 POINTS 10^{-3}	AVERAGE DEPTH [m]	DISCHARGE [1/s]	AVERAGE VELOCITY [m/s]	AVERAGE CONCENTRATION [ppm]	VELOCITY PROFILE	CONCENTRATION PROFILE
15	1	2.0	13.6	0.100	0.068	0.212	126.6	0.245			
	2	5.0	15.5	0.100	0.060	0.215	125.6	0.239		Y	
	3	22.0	20.0	0.300	0.236	0.216	125.6	0.239			
	4	26.0	20.8	0.320	0.232	0.219	126.2	0.237	629.6		Y
	5	29.3	21.1	0.340	0.271	0.215	125.8	0.240			
	6	46.0	20.7	0.320	0.344	0.214	125.8	0.241			
	7	49.5	20.9	0.240	0.304	0.213	126.4	0.244	751.6	Y	
16	1	2.3	20.8	0.392	0.474	0.214	161.7	0.309			
	2	19.0	21.0	0.687	0.583	0.218	157.0	0.295			
	3	23.0	21.2	0.593	0.569	0.220	158.5	0.295		Y	
	4	26.3	21.5	0.436	0.492	0.215	158.5	0.302	1132.6		
	5	44.5	21.1	0.615	0.623	0.225	157.6	0.288	1134.4	Y	Y
17	1	5.3	16.9	0.588	0.580	0.252	181.9	0.296			
	2	22.0	19.8	0.484	0.530	0.243	180.7	0.305			
	3	26.0	20.0	0.600	0.578	0.244	180.1	0.303	897.0	Y	Y
	4	29.0	20.1	0.565	0.519	0.240	180.1	0.308		Y	
	5	46.0	20.8	0.576	0.588	0.241	179.4	0.306			
	6	50.0	21.0	0.680	0.566	0.246	178.3	0.297	884		
18	1	2.8	20.7	0.645	0.749	0.240	189.3	0.324			
	2	19.5	20.7	0.750	0.746	0.247	187.2	0.310			
	3	24.0	20.3	0.624	0.640	0.251	193.2	0.315	1040		Y
	4	26.8	20.4	0.596	0.601	0.248	193.4	0.319		Y	
	5	43.5	20.4	0.504	0.683	0.240	188.6	0.322		Y	
	6	48.0	20.4	0.580	0.721	0.241	191.4	0.325	1024	Y	

TABLE 1 (Cont/d)

EXPERIMENT	TEST	TIME FROM BEGINNING [h]	TEMPERATURE [°C]	SLOPE 3 POINTS 10^{-3}	SLOPE 5 POINTS 10^{-3}	AVERAGE DEPTH [m]	DISCHARGE [l/s]	AVERAGE VELOCITY [m/s]	AVERAGE CONCENTRATION [ppm]	VELOCITY PROFILE	CONCENTRATION PROFILE
19	1	2.5	13.6	0.300	0.250	0.268	156.4	0.239			
	2	4.5	14.1	0.293	0.259	0.267	154.1	0.236			
	3	22.3	17.9	0.267	0.264	0.270	154.7	0.235			
	4	25.5	18.6	0.290	0.286	0.265	154.3	0.239	688	Y	Y
	5	29.0	19.0	0.353	0.297	0.265	153.9	0.238			
	6	47.5	18.7	0.135	0.261	0.263	154.5	0.241	693		
20	1	2.5	18.8	0.556	0.406	0.267	207.2	0.319			
	2	5.0	18.8	0.560	0.424	0.267	206.7	0.318			
	3	22.0	18.9	0.357	0.417	0.256	204.6	0.328			
	4	25.0	19.2	0.288	0.486	0.257	203.7	0.325	972	Y	Y
	5	29.0	18.8	0.404	0.562	0.261	208.1	0.327		Y	
	6	46.0	19.6	0.620	0.573	0.260	209.1	0.329			
	7	50.0	19.0	0.573	0.549	0.264	210.0	0.326	954	Y	
21	1	4.3	14.7	0.612	0.566	0.214	153.1	0.293			
	2	6.8	16.1	0.648	0.640	0.214	153.7	0.295	2410		
	3	23.8	19.8	0.867	0.715	0.221	152.9	0.283		Y	
	4	26.8	20.2	0.830	0.687	0.222	153.3	0.283	2795	Y	Y
	5	30.8	21.0	0.764	0.666	0.226	153.0	0.278			
	6	47.8	21.5	0.560	0.616	0.226	153.3	0.278		Y	
	7	50.5	21.8	0.572	0.630	0.228	152.9	0.275	2206		
22	1	3.0	21.8	0.928	0.912	0.223	202.1	0.371		Y	
	2	20.5	20.7	0.800	0.787	0.235	207.1	0.361		Y	
	3	23.5	20.7	0.712	0.814	0.242	211.0	0.357	2927	Y	Y
	4	27.5	21.0	0.700	0.828	0.237	211.0	0.366			
	5	44.5	20.6	0.740	0.756	0.237	209.3	0.363		Y	
	6	48.5	20.9	0.743	0.707	0.236	207.1	0.360	3317		

TABLE 1 (Cont/d)

EXPERIMENT	TEST	TIME FROM BEGINNING [h]	TEMPERATURE [°C]	SLOPE 3 POINTS 10^{-3}	SLOPE 5 POINTS 10^{-3}	AVERAGE DEPTH [m]	DISCHARGE [l/s]	AVERAGE VELOCITY [m/s]	AVERAGE CONCENTRATION [ppm]	VELOCITY PROFILE	CONCENTRATION PROFILE
23	1	3.3	14.4	0.268	0.207	0.242	154.5	0.262			
	2	7.0	16.5	0.184	0.208	0.242	155.1	0.263	1464		
	3	23.8	20.0	0.355	0.253	0.244	154.7	0.260		Y	
	4	26.5	20.3	0.360	0.236	0.241	154.7	0.263	1864.2	Y	Y
	5	31.0	21.1	0.348	0.279	0.243	155.0	0.261		Y	
	6	47.8	20.9	0.284	0.357	0.235	155.0	0.271			
	7	50.3	21.0	0.176	0.296	0.236	154.4	0.261	1867.2	Y	
24	1	4.0	20.8	0.328	0.392	0.261	212.3	0.334			
	2	21.2	20.2	0.488	0.534	0.257	209.6	0.335		Y	
	3	24.3	20.5	0.704	0.562	0.258	213.6	0.339	2228.2	Y	Y
	4	28.0	20.8	0.704	0.662	0.265	213.4	0.331			
	5	45.0	21.0	0.640	0.650	0.262	211.2	0.330		Y	
	6	49.0	21.2	0.516	0.662	0.267	212.6	0.327	2227.9		
25	1	19.7	19.6	0.696	0.746	0.219	155.1	0.290		Y	
	2	22.5	19.6	0.824	0.718	0.219	155.1	0.290		Y	
	3	26.5	19.8	0.684	0.722	0.221	155.1	0.288	3239.5		
	4	43.7	20.4	0.600	0.658	0.221	155.3	0.288		Y	
	5	46.5	20.3	0.572	0.668	0.223	154.8	0.284	3520.1		Y
26	1	3.0	15.2	0.204	0.215	0.238	139.3	0.239			
	2	7.0	15.6	0.188	0.198	0.239	139.2	0.239	1108.8		
	3	24.5	19.6	0.196	0.198	0.237	139.2	0.240		Y	
	4	26.3	20.1	0.196	0.193	0.236	138.9	0.241	1182.1	Y	Y
	5	30.8	20.7	0.180	0.193	0.237	139.4	0.241			
	6	47.8	20.4	0.208	0.210	0.235	138.6	0.242			
	7	50.5	20.6	0.184	0.198	0.234	138.5	0.243	1170.0	Y	

TABLE 1 (Cont/d)

EXPERIMENT	TEST	TIME FROM BEGINNING [h]	TEMPERATURE [°C]	SLOPE 3 POINTS 10^{-3}	SLOPE 5 POINTS 10^{-3}	AVERAGE DEPTH [m]	DISCHARGE [l/s]	AVERAGE VELOCITY [m/s]	AVERAGE CONCENTRATION [ppm]	VELOCITY PROFILE	CONCENTRATION PROFILE
27	1	3.5	20.5	0.700	0.642	0.231	184.2	0.328			
	2	20.3	19.8	0.600	0.672	0.230	182.9	0.327		Y	
	3	23.3	20.0	0.540	0.697	0.232	182.8	0.323	3600	Y	Y
	4	27.3	20.2	0.460	0.711	0.235	181.4	0.317			
	5	44.3	20.4	0.680	0.668	0.233	182.0	0.320		Y	
	6	48.0	20.8	0.548	0.665	0.236	181.4	0.315	3610		
28	1	3.3	14.8	0.112	0.170	0.264	138.7	0.215			
	2	6.5	16.1	0.148	0.166	0.264	138.5	0.215			
	3	23.5	20.8	0.132	0.154	0.263	138.6	0.216		Y	
	4	26.8	21.2	0.128	0.154	0.263	138.6	0.216	774	Y	Y
	5	30.5	21.5	0.136	0.154	0.265	138.6	0.215			
	6	47.5	21.7	0.145	0.151	0.263	138.7	0.216		Y	
	7	50.8	21.9	0.140	0.151	0.263	138.6	0.216	744		
29	1	3.5	21.8	0.168	0.210	0.265	186.3	0.288			
	2	20.3	20.7	0.280	0.302	0.265	185.0	0.287		Y	
	3	23.5	21.0	0.267	0.372	0.264	185.0	0.287	2170	Y	Y
	4	27.3	21.2	0.280	0.325	0.267	186.3	0.286			
	5	44.3	20.8	0.388	0.388	0.259	185.0	0.293		Y	
	6	48.0	20.8	0.237	0.366	0.260	185.4	0.292	2604		

TABLE 2

VELOCITY PROFILE
EXPERIMENT 28 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.317	0.0048	1.5
0.050	0.320	0.0074	2.3
0.085	0.311	0.0093	3.0
0.120	0.303	0.0123	4.1
0.155	0.291	0.0094	3.2
0.190	0.261	0.0117	4.5
0.225	0.241	0.0108	4.5
0.245	0.153	0.0193	12.7
0.270			

VELOCITY PROFILE
EXPERIMENT 28 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.315	0.0033	1.0
0.050	0.319	0.0047	1.5
0.085	0.311	0.0113	3.6
0.120	0.303	0.0100	3.3
0.155	0.279	0.0130	4.6
0.190	0.241	0.0119	5.0
0.225	0.220	0.0079	3.6
0.250	0.182	0.0117	6.4
0.265			

VELOCITY PROFILE
EXPERIMENT 28 TEST 6

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.313	0.0052	1.7
0.050	0.316	0.0083	2.6
0.085	0.314	0.0082	2.6
0.120	0.310	0.0084	2.7
0.155	0.291	0.0091	3.1
0.190	0.265	0.0109	4.1
0.225	0.221	0.0083	3.4
0.250	0.173	0.0081	4.7
0.265			

VELOCITY PROFILE
EXPERIMENT 28 TEST 2

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	.407	.0087	2.1
0.050	.412	.0104	2.5
0.085	.402	.0132	3.3
0.120	.394	.0113	2.9
0.155	.375	.0144	3.8
0.190	.329	.0116	3.6
0.225	.286	.0178	6.2
0.240	.272	.0191	7.0
0.260			

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 29 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	.416	.0103	2.5
0.050	.416	.0142	3.4
0.085	.399	.0204	5.1
0.120	.373	.0205	5.5
0.155	.323	.0167	5.2
0.190	.305	.0142	4.7
0.225	.239	.0163	6.8
0.240	.190	.0201	10.6
0.260			

VELOCITY PROFILE
EXPERIMENT 29 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	.402	.0133	3.3
0.050	.410	.0227	5.5
0.085	.390	.0230	5.9
0.120	.353	.0180	5.1
0.155	.315	.0161	5.1
0.190	.278	.0207	7.5
0.225	.244	.0176	7.2
0.255	.209	.0155	7.4
0.275			

TABLE 2

VELOCITY PROFILE
EXPERIMENT 15 TEST 7

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.01	0.343	0.0091	2.6
0.03	0.350	0.0103	3.0
0.05	0.328	0.0102	3.1
0.07	0.307	0.0139	4.5
0.09	0.292	0.0137	4.7
0.11	0.288	0.0213	7.4
0.13	0.280	0.0213	7.6
0.15	0.255	0.0135	5.3
0.17	0.235	0.0157	6.7
0.185	0.207	0.0168	8.1
0.195	0.177	0.0122	6.9
0.205			

VELOCITY PROFILE
EXPERIMENT 29 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 15 TEST 2

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.347	0.0022	0.6
0.050	0.357	0.0017	0.4
0.080	0.347	0.0043	1.2
0.110	0.336	0.0059	1.7
0.140	0.305	0.0160	5.3
0.175	0.226	0.0095	4.2
0.185	0.177	0.0087	4.9
0.205			
0.205			

VELOCITY PROFILE
EXPERIMENT 16 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.459	0.0098	2.1
0.050	0.447	0.0225	5.0
0.080	0.437	0.0171	3.9
0.110	0.400	0.0124	3.1
0.140	0.354	0.0204	5.8
0.170	0.291	0.0153	5.3
0.180	0.273	0.0147	5.4
0.190	0.241	0.0164	6.8
0.200	0.217	0.0194	9.0
0.220			

VELOCITY PROFILE
EXPERIMENT 16 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.470	0.0065	1.4
0.040	0.472	0.0135	2.9
0.065	0.452	0.0164	3.6
0.090	0.433	0.0199	4.6
0.115	0.381	0.0240	6.3
0.140	0.350	0.0197	5.6
0.165	0.255	0.0194	7.6
0.190	0.178	0.0126	7.1
0.200	0.155	0.0125	8.0
0.210	0.128	0.0299	23.4
0.220			

VELOCITY PROFILE
EXPERIMENT 17 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.455	0.0121	2.7
0.045	0.452	0.0128	2.8
0.075	0.424	0.0138	3.2
0.105	0.388	0.0301	7.8
0.135	0.374	0.0194	5.2
0.165	0.354	0.0185	5.2
0.195	0.312	0.0205	6.6
0.225	0.261	0.0288	11.0
0.235	0.246	0.0222	9.1
0.245	0.169	0.0192	11.3
0.255			

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 17 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.480	0.0063	1.3
0.055	0.482	0.0099	2.1
0.090	0.441	0.0176	4.0
0.125	0.415	0.0134	3.2
0.160	0.366	0.0196	5.4
0.195	0.287	0.0240	8.4
0.215	0.224	0.0207	9.2
0.235			

VELOCITY PROFILE
EXPERIMENT 18 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.504	0.0142	2.8
0.055	0.486	0.0131	2.7
0.090	0.460	0.0257	5.6
0.125	0.419	0.0208	5.0
0.160	0.358	0.0192	5.4
0.195	0.312	0.0196	6.3
0.215	0.263	0.0145	5.5
0.235	0.168	0.0180	10.7
0.250			

VELOCITY PROFILE
EXPERIMENT 18 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.492	0.0187	3.8
0.050	0.491	0.0178	3.6
0.085	0.482	0.0156	3.2
0.120	0.449	0.0247	5.5
0.155	0.388	0.0297	7.7
0.190	0.321	0.0181	5.6
0.215	0.247	0.0304	12.3
0.225	0.214	0.0282	13.2
0.245			

VELOCITY PROFILE
EXPERIMENT 18 TEST 6

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.510	0.0075	1.5
0.060	0.510	0.0125	2.4
0.100	0.450	0.0172	3.8
0.140	0.402	0.0158	3.9
0.180	0.351	0.0179	5.1
0.220	0.260	0.0137	5.3
0.230	0.180	0.0164	9.1
0.245			

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 19 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.354	0.0088	2.5
0.060	0.342	0.0142	4.1
0.100	0.328	0.0129	3.9
0.140	0.294	0.0188	6.4
0.180	0.266	0.0176	6.6
0.220	0.184	0.0152	8.3
0.240	0.131	0.0059	4.5
0.260			

VELOCITY PROFILE
EXPERIMENT 20 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.440	0.0130	3.0
0.060	0.437	0.0168	3.8
0.100	0.405	0.0256	6.3
0.140	0.373	0.0253	6.8
0.180	0.369	0.0252	6.8
0.220	0.320	0.0217	6.8
0.240	0.275	0.0150	5.4
0.260	0.210	0.0245	11.7
0.275			

VELOCITY PROFILE
EXPERIMENT 20 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.476	0.0106	2.2
0.060	0.477	0.0096	2.0
0.100	0.449	0.0183	4.1
0.140	0.403	0.0159	3.9
0.180	0.334	0.0134	4.0
0.220	0.276	0.0158	5.7
0.240	0.111	0.0154	13.9
0.260			

VELOCITY PROFILE
EXPERIMENT 20 TEST 7

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.477	0.0115	2.4
0.060	0.492	0.0166	3.4
0.100	0.459	0.0200	4.4
0.140	0.413	0.0187	4.5
0.180	0.338	0.0204	6.1
0.210	0.263	0.0196	7.5
0.240	0.162	0.0084	5.2
0.250	0.161	0.0197	12.3
0.265			

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 21 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.020	0.419	0.0158	3.8
0.055	0.414	0.0151	3.6
0.090	0.395	0.0198	4.5
0.125	0.354	0.0247	7.0
0.160	0.317	0.0186	5.9
0.180	0.300	0.0203	6.8
0.195	0.279	0.0160	5.7
0.205	0.211	0.0167	7.9
0.230			

VELOCITY PROFILE
EXPERIMENT 21 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.433	0.0079	1.8
0.050	0.437	0.0127	2.9
0.085	0.423	0.0136	3.2
0.120	0.384	0.0156	4.1
0.155	0.324	0.0195	6.0
0.190	0.237	0.0121	5.1
0.205	0.194	0.0088	4.6
0.220			

VELOCITY PROFILE
EXPERIMENT 21 TEST 6

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.419	0.0118	2.8
0.050	0.410	0.0130	3.2
0.085	0.390	0.0165	4.2
0.120	0.341	0.0152	4.5
0.155	0.246	0.0118	4.8
0.190	0.211	0.0123	5.8
0.205	0.204	0.0142	6.9
0.210	0.160	0.0156	9.8
0.225			

VELOCITY PROFILE
EXPERIMENT 21 TEST 2

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.519	0.0157	3.0
0.050	0.546	0.0122	2.2
0.085	0.527	0.0195	3.7
0.120	0.467	0.0224	4.8
0.155	0.385	0.0257	6.7
0.190	0.330	0.0211	6.4
0.205	0.332	0.0166	5.0
0.215	0.099	0.0242	24.5
0.235			

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 22 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.527	0.0214	4.1
0.050	0.503	0.0174	3.5
0.085	0.480	0.0179	3.7
0.120	0.473	0.0230	4.9
0.155	0.410	0.0271	6.6
0.190	0.326	0.0154	4.7
0.205	0.293	0.0138	4.7
0.215	0.243	0.0184	7.6
0.230			

VELOCITY PROFILE
EXPERIMENT 22 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.532	0.0138	2.6
0.050	0.537	0.0199	3.6
0.085	0.496	0.0177	3.6
0.120	0.460	0.0364	7.9
0.155	0.394	0.0267	6.8
0.190	0.329	0.0166	5.0
0.205	0.269	0.0161	6.0
0.215	0.233	0.0120	5.1
0.235			

VELOCITY PROFILE
EXPERIMENT 22 TEST 1

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.545	0.0118	2.2
0.050	0.560	0.0069	1.2
0.085	0.525	0.0113	2.1
0.120	0.473	0.0313	6.6
0.155	0.424	0.0316	7.5
0.190	0.283	0.0255	9.0
0.205	0.238	0.0220	9.3
0.210	0.251	0.0285	11.4
0.225			

VELOCITY PROFILE
EXPERIMENT 23 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.358	0.0110	3.1
0.050	0.370	0.0105	2.8
0.085	0.342	0.0144	4.2
0.120	0.328	0.0119	3.6
0.155	0.307	0.0146	4.7
0.190	0.273	0.0134	4.9
0.210	0.240	0.0155	6.5
0.225	0.178	0.0119	6.7
0.250			

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 23 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.351	0.0097	2.7
0.050	0.356	0.0116	3.2
0.085	0.348	0.0124	3.6
0.120	0.338	0.0149	4.4
0.155	0.309	0.0135	4.4
0.190	0.260	0.0192	7.4
0.215	0.211	0.0118	5.6
0.230	0.170	0.0128	7.6
0.240			

VELOCITY PROFILE
EXPERIMENT 23 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.365	0.0100	2.7
0.050	0.373	0.0129	3.5
0.085	0.352	0.0136	3.9
0.120	0.328	0.0148	4.5
0.155	0.304	0.0170	5.6
0.190	0.230	0.0112	4.9
0.215	0.196	0.0103	5.2
0.235			

VELOCITY PROFILE
EXPERIMENT 23 TEST 7

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.374	0.0114	3.0
0.050	0.368	0.0120	3.3
0.085	0.354	0.0115	3.3
0.120	0.326	0.0100	3.1
0.155	0.312	0.0092	2.9
0.190	0.262	0.0205	7.8
0.225	0.157	0.0091	5.8
0.240			

VELOCITY PROFILE
EXPERIMENT 23 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 24 TEST 2

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.475	0.0089	1.9
0.050	0.480	0.0158	3.3
0.085	0.449	0.0219	4.9
0.120	0.424	0.0240	5.7
0.155	0.386	0.0193	5.0
0.190	0.302	0.0191	6.3
0.225	0.252	0.0130	5.2
0.240	0.239	0.0157	6.6
0.255			

VELOCITY PROFILE
EXPERIMENT 24 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.486	0.0067	1.4
0.050	0.501	0.0066	1.3
0.085	0.476	0.0110	2.3
0.120	0.421	0.0108	2.6
0.155	0.372	0.0218	5.9
0.190	0.329	0.0117	3.6
0.225	0.238	0.0184	7.7
0.235	0.089	0.0351	39.4
0.250			

VELOCITY PROFILE
EXPERIMENT 24 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.474	0.0163	3.4
0.050	0.483	0.0184	3.8
0.085	0.459	0.0200	4.4
0.120	0.433	0.0204	4.7
0.155	0.388	0.0271	7.0
0.190	0.327	0.0118	3.6
0.225	0.215	0.0164	7.6
0.245			

VELOCITY PROFILE
EXPERIMENT 25 TEST 1

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.446	0.0107	2.4
0.050	0.442	0.0118	2.7
0.085	0.414	0.0166	4.0
0.120	0.383	0.0178	4.7
0.155	0.339	0.0133	3.9
0.190	0.260	0.0177	6.8
0.200	0.094	0.0095	10.2
0.210			

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 25 TEST 2

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.457	0.0100	2.2
0.050	0.467	0.0103	2.2
0.085	0.437	0.0121	2.8
0.120	0.393	0.0139	3.5
0.155	0.350	0.0153	4.4
0.190	0.280	0.0158	5.7
0.205	0.233	0.0244	10.5
0.215	0.141	0.0146	10.4
0.225			

VELOCITY PROFILE
EXPERIMENT 25 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.434	0.0113	2.6
0.050	0.458	0.0071	1.5
0.085	0.446	0.0140	3.1
0.120	0.421	0.0122	2.9
0.155	0.348	0.0164	4.7
0.190	0.251	0.0122	4.8
0.195	0.199	0.0150	7.5
0.215			

VELOCITY PROFILE
EXPERIMENT 26 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.331	0.0058	1.7
0.050	0.325	0.0077	2.4
0.085	0.320	0.0072	2.3
0.120	0.307	0.0101	3.3
0.155	0.271	0.0187	6.9
0.190	0.228	0.0144	6.3
0.215	0.192	0.0119	6.2
0.225	0.178	0.0082	4.6
0.245			

VELOCITY PROFILE
EXPERIMENT 26 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.325	0.0068	2.1
0.050	0.327	0.0068	2.1
0.085	0.323	0.0106	3.3
0.120	0.306	0.0081	2.6
0.155	0.295	0.0113	3.8
0.190	0.264	0.0145	5.5
0.215	0.238	0.0126	5.3
0.230	0.209	0.0112	5.3
0.240	0.166	0.0116	7.0
0.250			

TABLE 2 (Cont/d)

VELOCITY PROFILE
EXPERIMENT 26 TEST 7

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.335	0.0068	2.0
0.050	0.335	0.0070	2.1
0.085	0.319	0.0111	3.5
0.120	0.286	0.0150	5.2
0.155	0.270	0.0182	6.7
0.190	0.223	0.0174	7.8
0.220	0.144	0.0101	7.0
0.230			

VELOCITY PROFILE
EXPERIMENT 27 TEST 2

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.511	0.0089	1.7
0.050	0.523	0.0100	1.9
0.085	0.491	0.0151	3.1
0.120	0.442	0.0201	4.5
0.155	0.362	0.0132	3.7
0.190	0.324	0.0135	4.2
0.210	0.275	0.0180	6.5
0.220	0.254	0.0180	7.1
0.230	0.202	0.0101	5.0
0.240			

VELOCITY PROFILE
EXPERIMENT 27 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.496	0.0056	1.1
0.050	0.514	0.0085	1.6
0.085	0.495	0.0104	2.1
0.120	0.429	0.0227	5.3
0.155	0.322	0.0240	7.4
0.190	0.247	0.0293	11.9
0.200	0.230	0.0116	5.1
0.210	0.220	0.0124	5.6
0.220	0.229	0.0114	5.0
0.230	0.125	0.0114	9.1
0.240			

VELOCITY PROFILE
EXPERIMENT 27 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]
0.015	0.482	0.0179	3.7
0.050	0.480	0.0122	2.5
0.085	0.449	0.0200	4.5
0.120	0.398	0.0149	3.8
0.155	0.343	0.0136	4.0
0.190	0.312	0.0174	5.6
0.215	0.276	0.0150	5.4
0.225	0.193	0.0544	28.1
0.245			

TABLE 3

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 29 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.405	0.0146	3.6	2080
0.070	0.388	0.0221	5.7	2163
0.120	0.352	0.0223	6.3	2240
0.170	0.318	0.0180	5.7	2268
0.220	0.281	0.0143	5.1	2242
0.250	0.236	0.0123	5.2	2253
0.265				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT TEST

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 17 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.454	0.0119	2.6	899
0.060	0.449	0.0177	3.9	919
0.105	0.427	0.0187	4.4	934
0.145	0.378	0.0198	5.2	929
0.185	0.325	0.0124	3.8	959
0.230	0.209	0.0220	10.5	1068
0.250				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 18 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.496	0.0140	2.8	1006
0.065	0.490	0.0188	3.9	1046
0.115	0.433	0.0258	6.0	1068
0.165	0.358	0.0261	7.3	1116
0.205	0.307	0.0174	5.6	1217
0.230	0.207	0.0181	8.7	2044
0.245				

TABLE 3

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 29 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.405	0.0146	3.6	2080
0.070	0.388	0.0221	5.7	2163
0.120	0.352	0.0223	6.3	2240
0.170	0.318	0.0180	5.7	2268
0.220	0.281	0.0143	5.1	2242
0.250	0.236	0.0123	5.2	2253
0.265				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT TEST

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 17 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.454	0.0119	2.6	899
0.060	0.449	0.0177	3.9	919
0.105	0.427	0.0187	4.4	934
0.145	0.378	0.0198	5.2	929
0.185	0.325	0.0124	3.8	959
0.230	0.209	0.0220	10.5	1068
0.250				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 18 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.496	0.0140	2.8	1006
0.065	0.490	0.0188	3.9	1046
0.115	0.433	0.0258	6.0	1068
0.165	0.358	0.0261	7.3	1116
0.205	0.307	0.0174	5.6	1217
0.230	0.207	0.0181	8.7	2044
0.245				

TABLE 3 (Cont/d)

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 27 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.505	0.0110	2.2	3551
0.060	0.497	0.0177	3.6	3661
0.100	0.457	0.0184	4.0	3754
0.140	0.424	0.0210	5.0	3809
0.180	0.349	0.0166	4.8	3993
0.220	0.263	0.0210	8.0	3984
0.245				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 28 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.319	0.0040	1.3	697
0.065	0.318	0.0057	1.8	708
0.110	0.307	0.0108	3.5	707
0.160	0.280	0.0120	4.3	710
0.205	0.242	0.0143	5.9	718
0.245	0.165	0.0072	4.4	1279
0.265				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 25 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.446	0.0097	2.2	3247
0.060	0.450	0.0180	4.0	3368
0.100	0.423	0.0163	3.9	3411
0.140	0.381	0.0199	5.2	3433
0.180	0.319	0.0086	2.7	3529
0.205	0.279	0.0134	4.8	3617
0.220				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 26 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.327	0.0062	1.9	1178
0.060	0.328	0.0076	2.3	1175
0.100	0.321	0.0105	3.3	1168
0.140	0.304	0.0100	3.3	1188
0.180	0.278	0.0157	5.7	1196
0.225	0.195	0.0116	6.0	1543
0.235				

TABLE 3 (Cont/d)

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 23 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.362	0.0087	2.4	1730
0.065	0.346	0.0122	3.5	1748
0.110	0.332	0.0160	4.8	1765
0.155	0.285	0.0167	5.9	1757
0.200	0.223	0.0153	6.8	1797
0.225	0.141	0.0094	6.6	1768
0.245				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 24 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.483	0.0097	2.0	2195
0.065	0.477	0.0153	3.2	2283
0.110	0.430	0.0166	3.9	2289
0.155	0.388	0.0224	5.8	2279
0.200	0.332	0.0177	5.3	2343
0.230	0.303	0.0139	4.6	2505
0.255				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 15 TEST

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.015	0.360	0.0067	1.8	639.4
0.045	0.361	0.0130	3.6	648.8
0.075	0.330	0.0102	3.1	655.8
0.115	0.295	0.0218	7.4	658.3
0.155	0.222	0.0222	10.0	660.4
0.185	0.153	0.0181	11.8	676.2
0.210				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 16 TEST 5

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.440	0.0090	2.0	1107.2
0.055	0.436	0.0171	3.9	1137.3
0.090	0.411	0.0164	4.0	1144.0
0.125	0.365	0.0125	3.4	1139.0
0.170	0.311	0.0201	6.5	1163.0
0.195	0.281	0.0172	6.1	1274.8
0.225				

TABLE 3 (Cont/d)

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 19 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.353	0.0088	2.5	684
0.075	0.343	0.0100	2.9	693
0.130	0.325	0.0123	3.8	691
0.185	0.284	0.0114	4.0	696
0.230	0.217	0.0152	17.0	702
0.250	0.146	0.0169	11.6	701
0.265				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 20 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.455	0.0128	2.8	969
0.075	0.446	0.0162	3.6	992
0.130	0.395	0.0204	5.2	1019
0.185	0.333	0.0170	5.1	1045
0.230	0.280	0.0157	6.9	1080
0.250	0.092	0.0191	20.8	1129
0.265				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 21 TEST 4

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.450	0.0115	2.6	2636
0.060	0.444	0.0112	2.5	2682
0.100	0.387	0.0200	5.2	2678
0.140	0.339	0.0190	5.6	2745
0.180	0.277	0.0180	6.5	2907
0.190	0.168	0.0349	20.8	2789
0.210				

VELOCITY AND CONCENTRATION PROFILE
EXPERIMENT 22 TEST 3

DEPTH [m]	AVERAGE VELOCITY [m/s]	STANDARD DEVIATION [m/s]	STANDARD DEVIATION [%]	CONCENTRATION [ppm]
0.020	0.522	0.0130	2.5	2206
0.060	0.514	0.0203	4.0	2820
0.100	0.500	0.0287	5.7	3006
0.140	0.469	0.0259	5.5	3034
0.180	0.379	0.0282	7.5	3071
0.210	0.250	0.0174	7.0	3731
0.245				

Figures

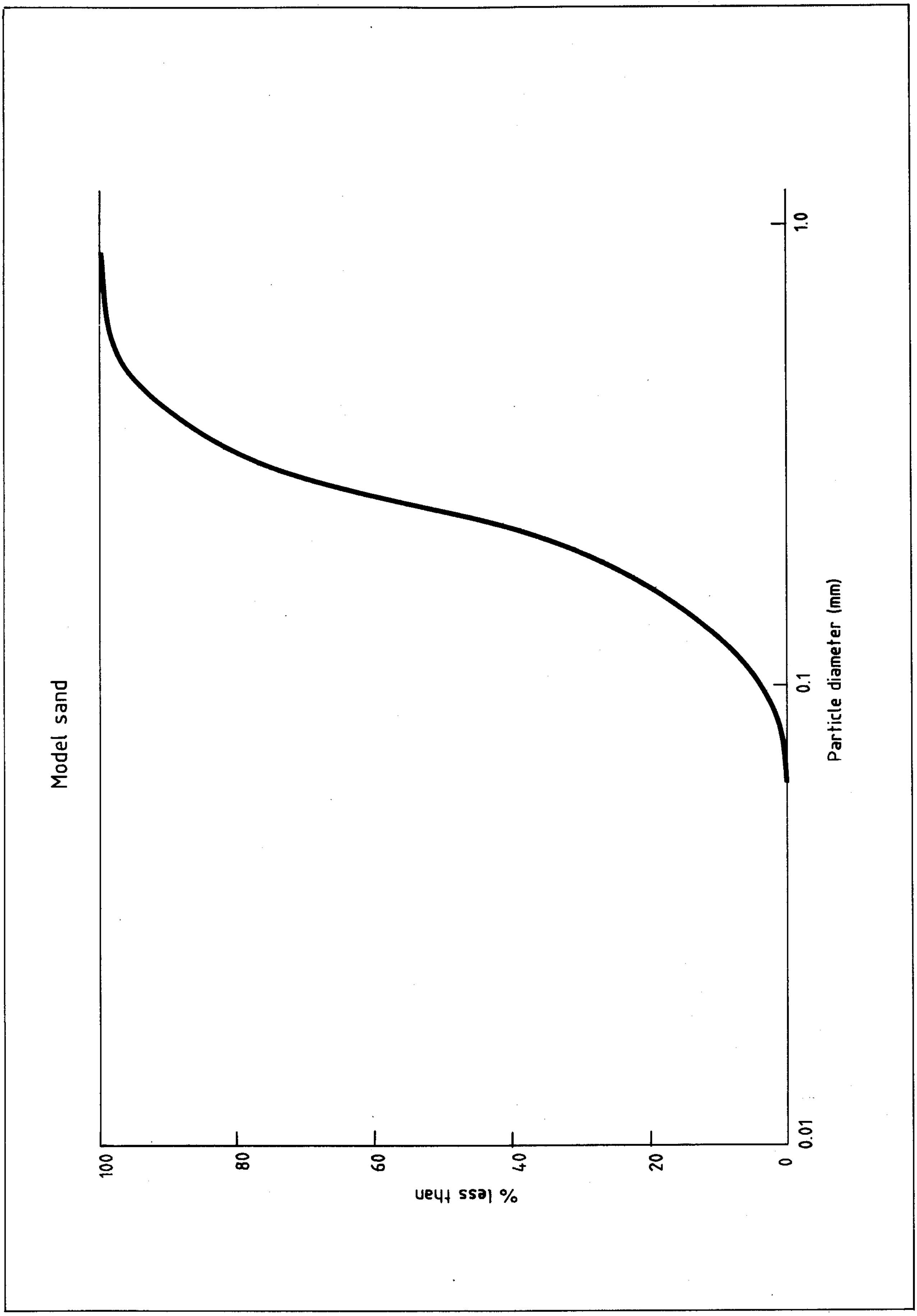

Fig 1 Grading curve of sand

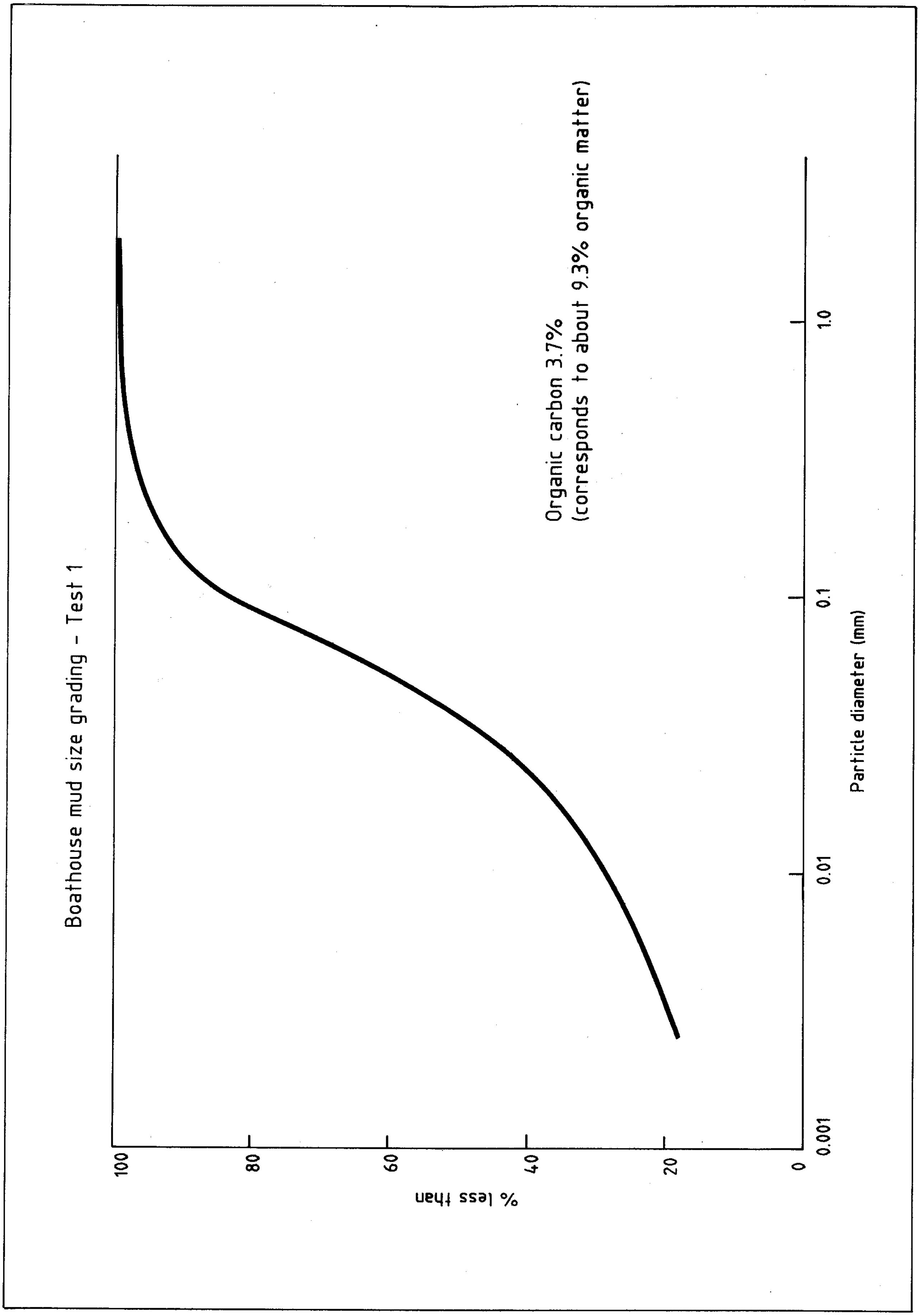

Fig 2 Grading curve of silt

Symbol	Run number
△	6
○	7
□	8
⊘	9
▽	10
×	11
+	12
●	13
◇	14
○	15
□	16
△	17
▽	18
◇	19
×	20
△	21
□	22
○	23
▽	24
△	25
□	26
▽	27
○	28
×	29

Fig 3 List of symbols.

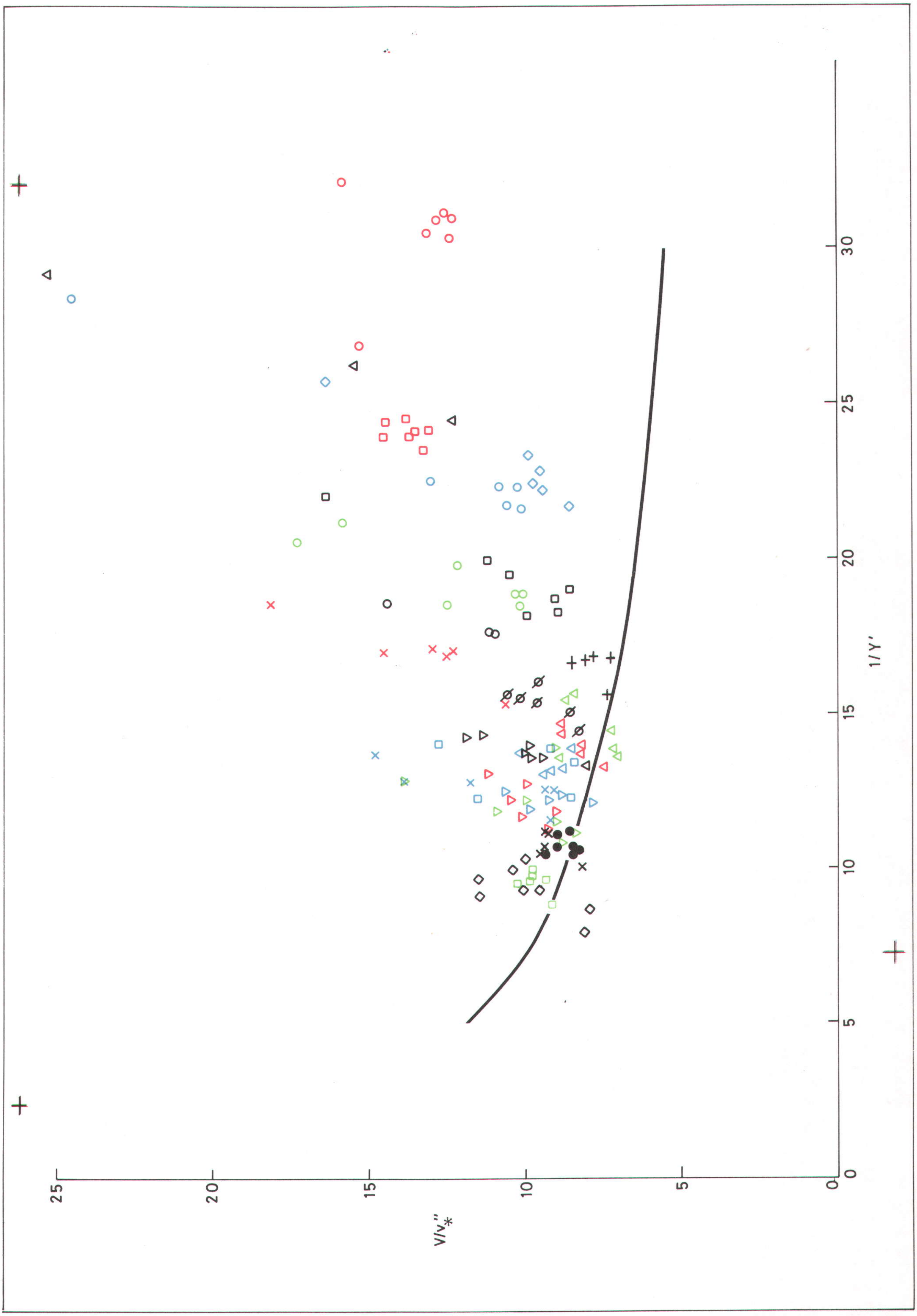

Fig 4 Data analysis according to Einstein and Barbarossa

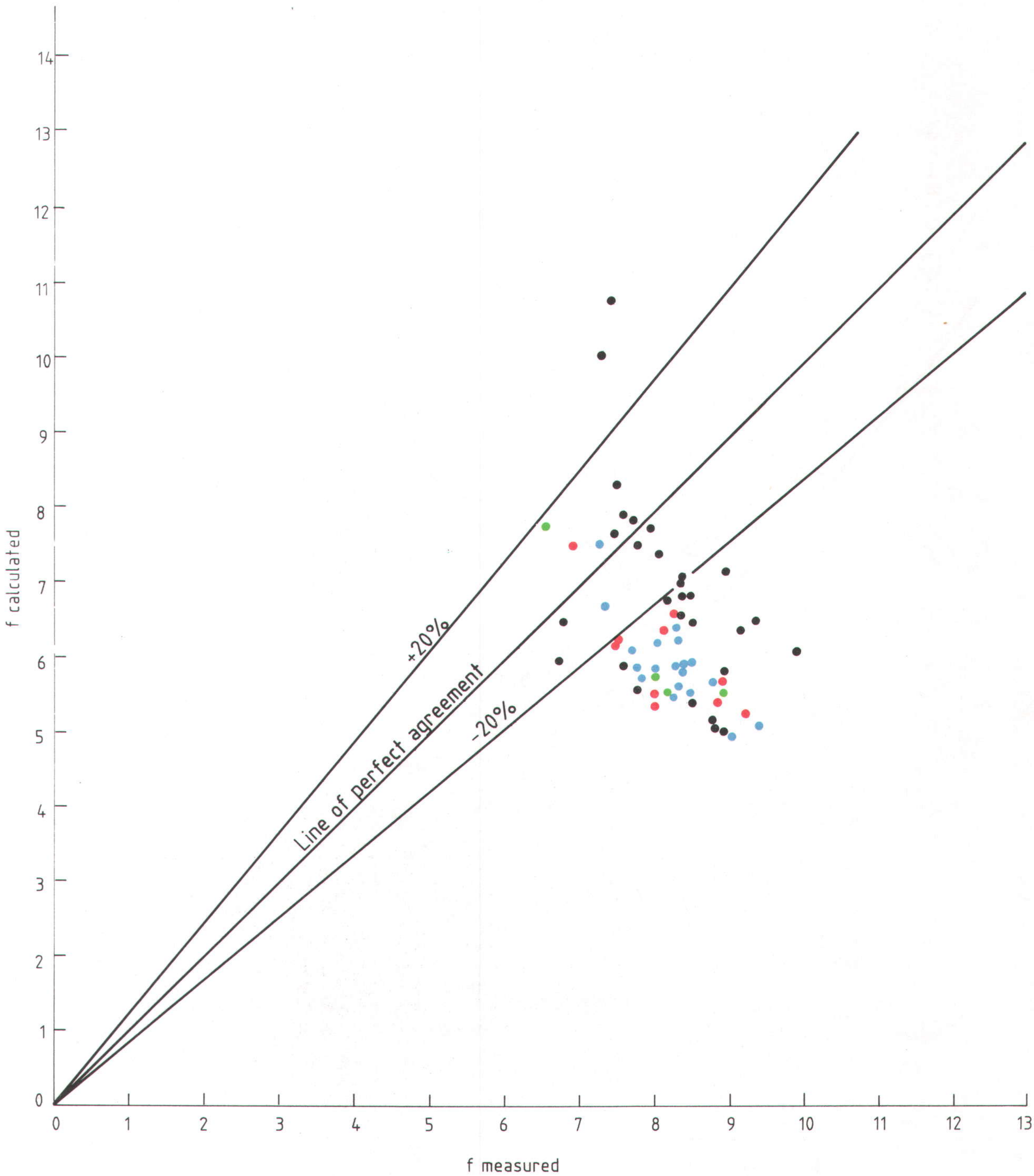

Fig 5 Comparison with measured friction factor, Einstein and Barbarossa method

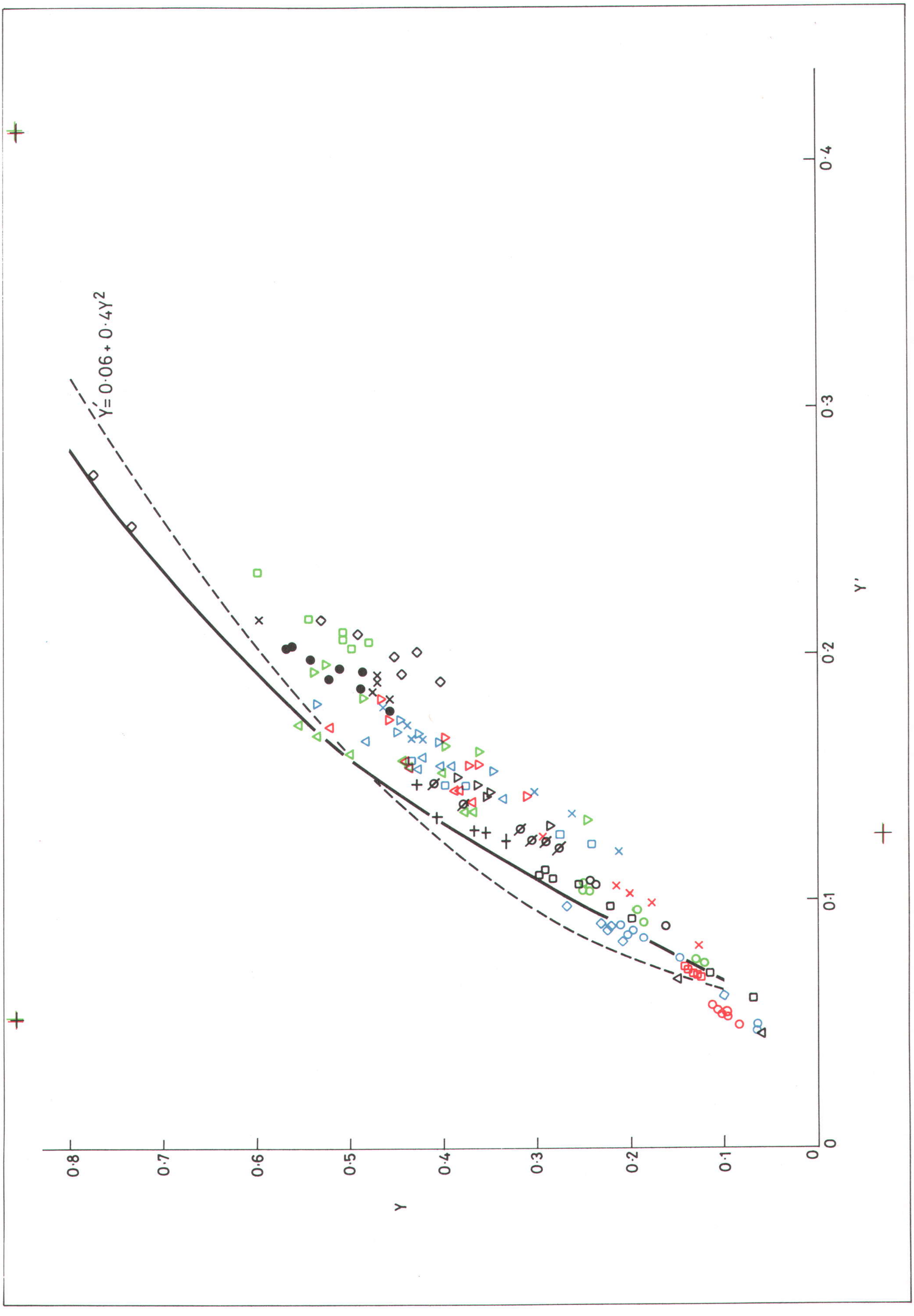

Fig 6 Data analysis according to Engelund

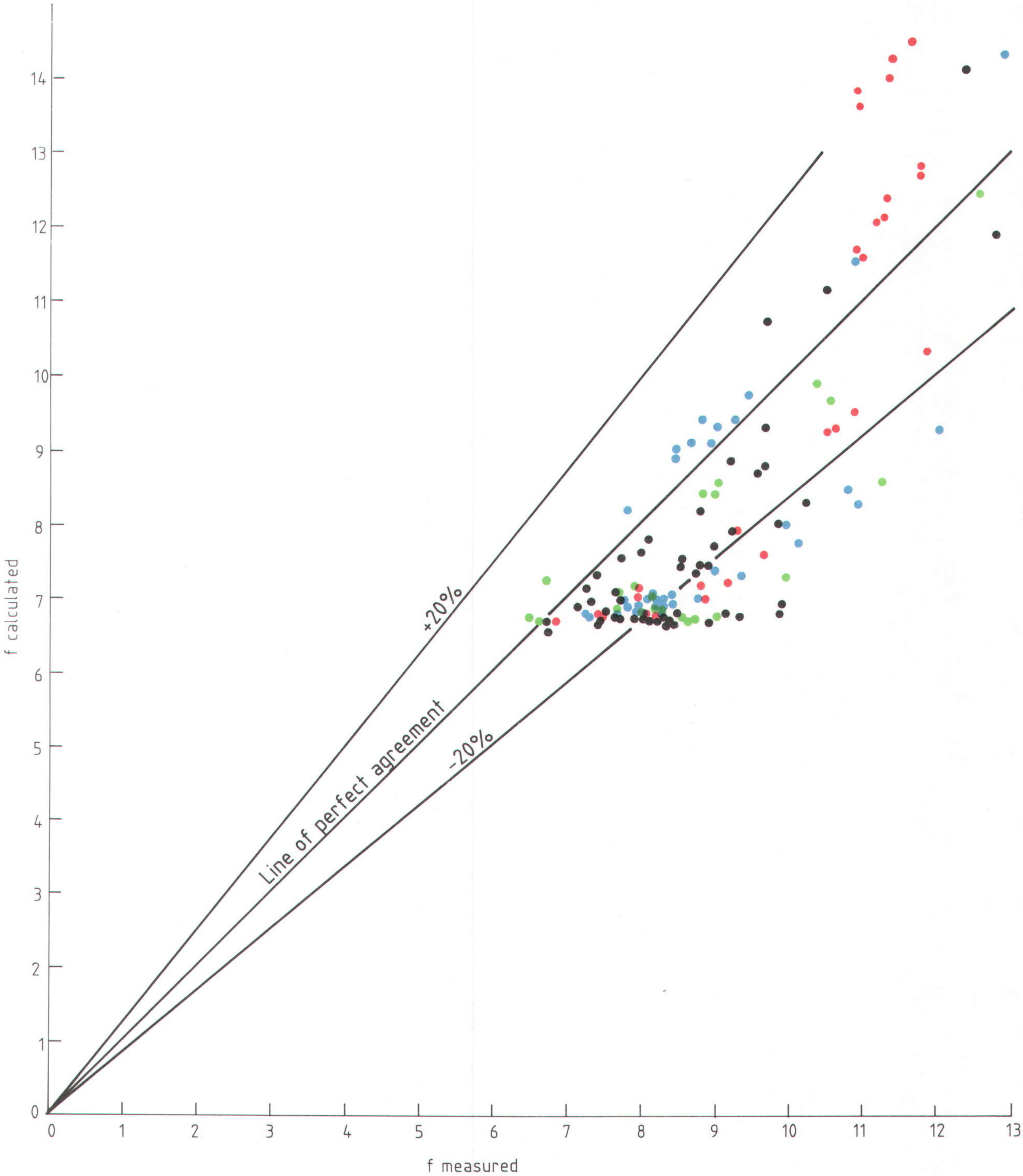

Fig 7 Comparison with measured friction factor, Engelund method

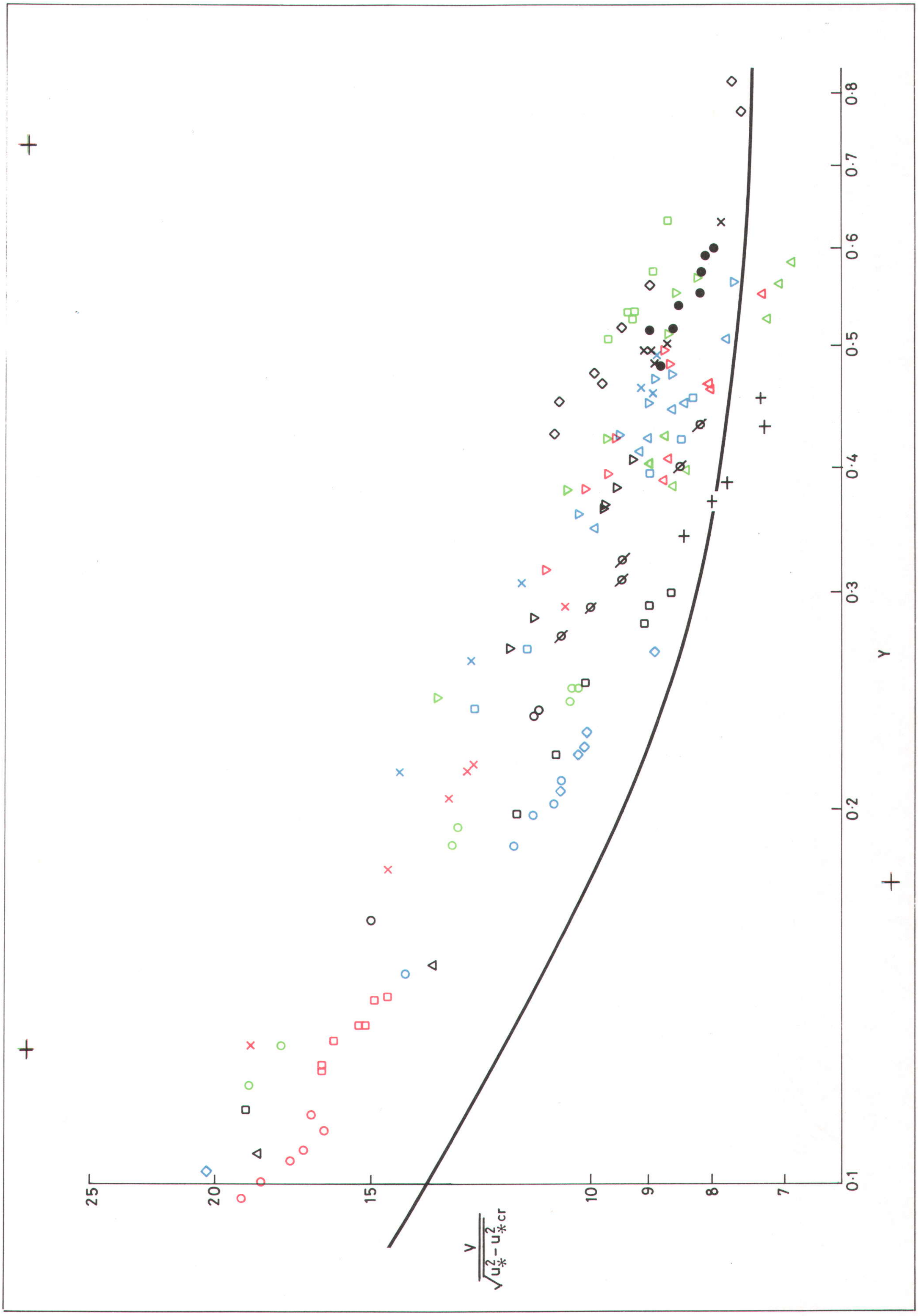

Fig 8 Data analysis according to Raudkivi

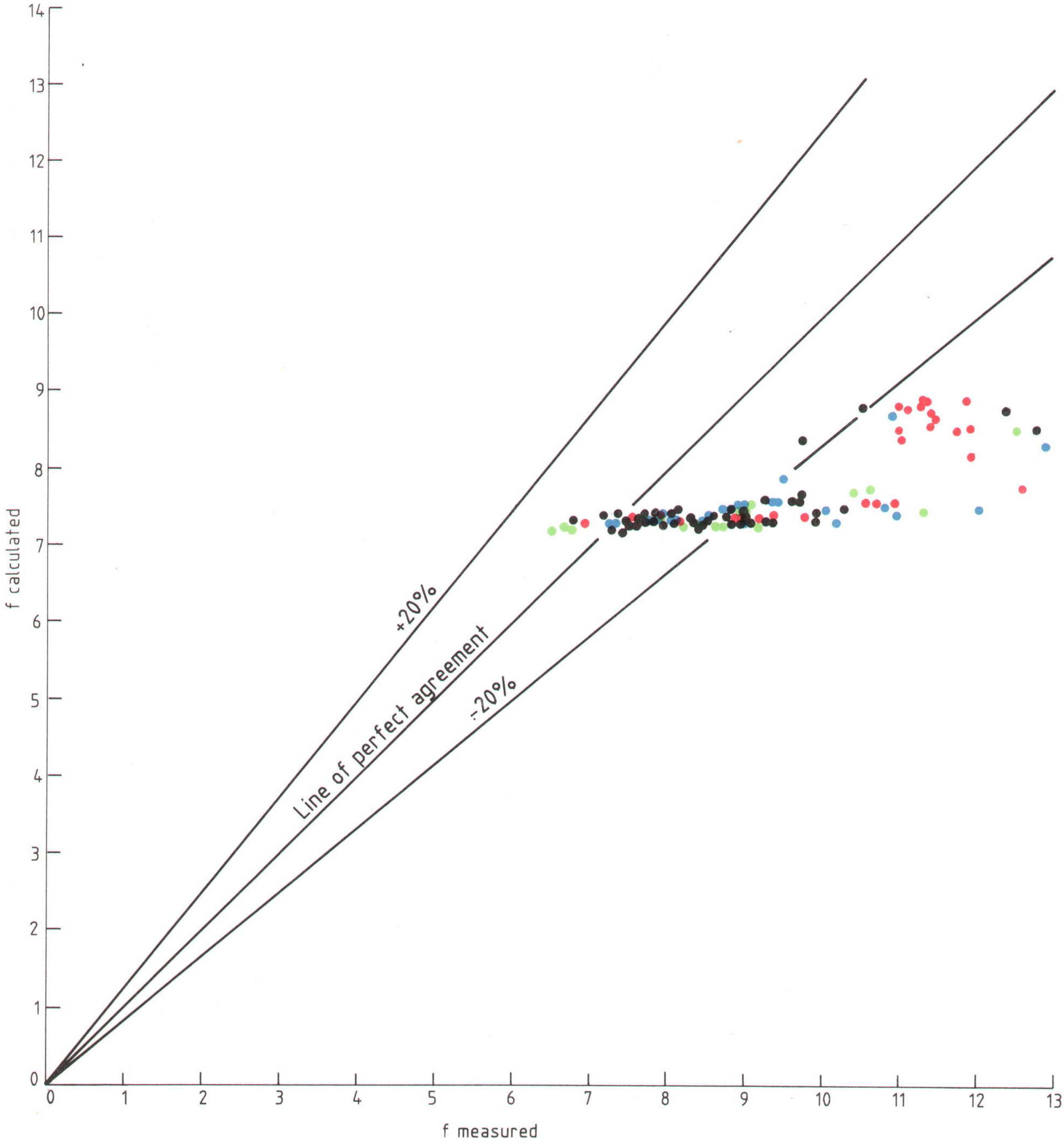

Fig 9 Comparison with measured friction factor, Raudkivi method

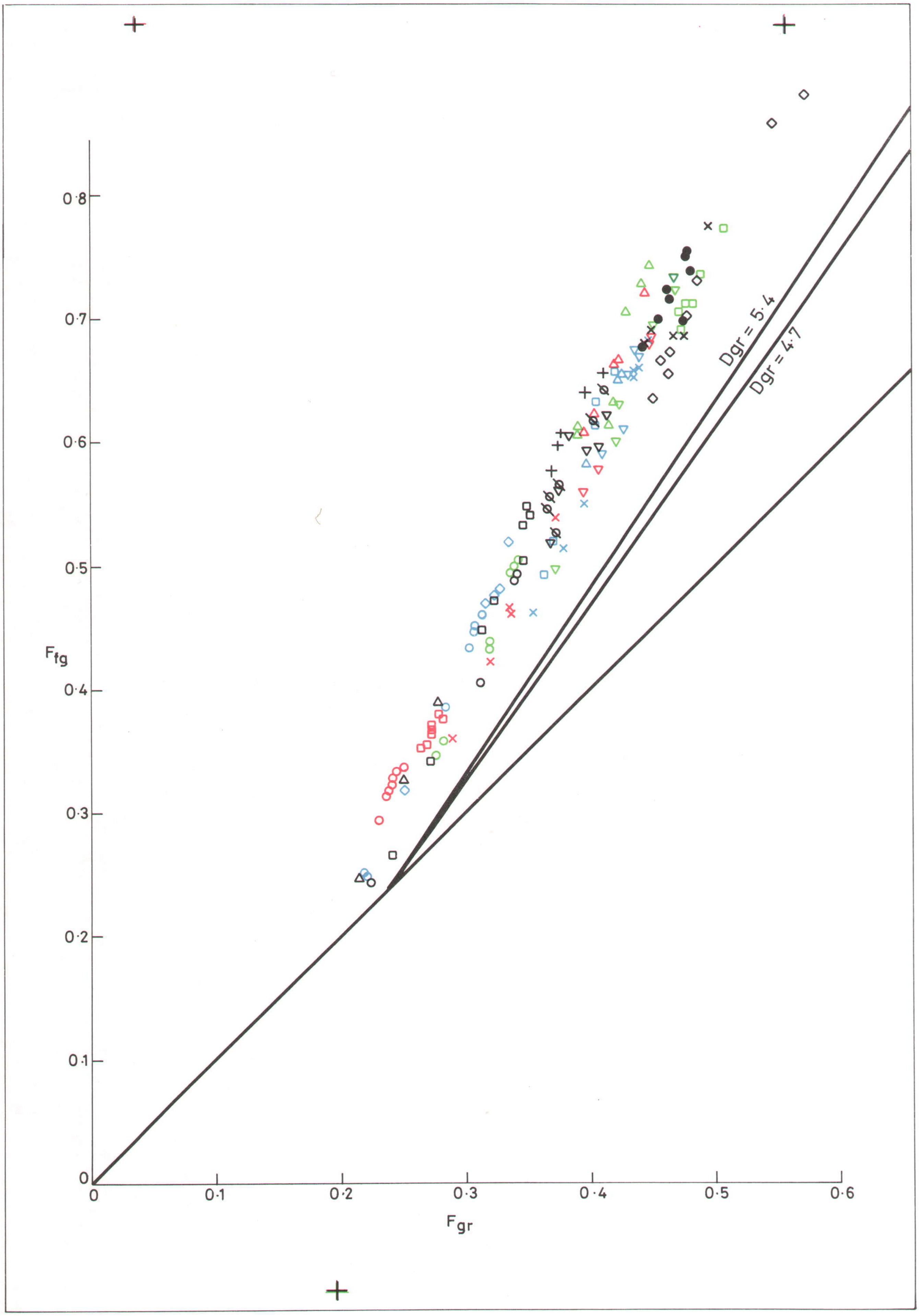

Fig 10 Data analysis according to White, Paris and Bettess

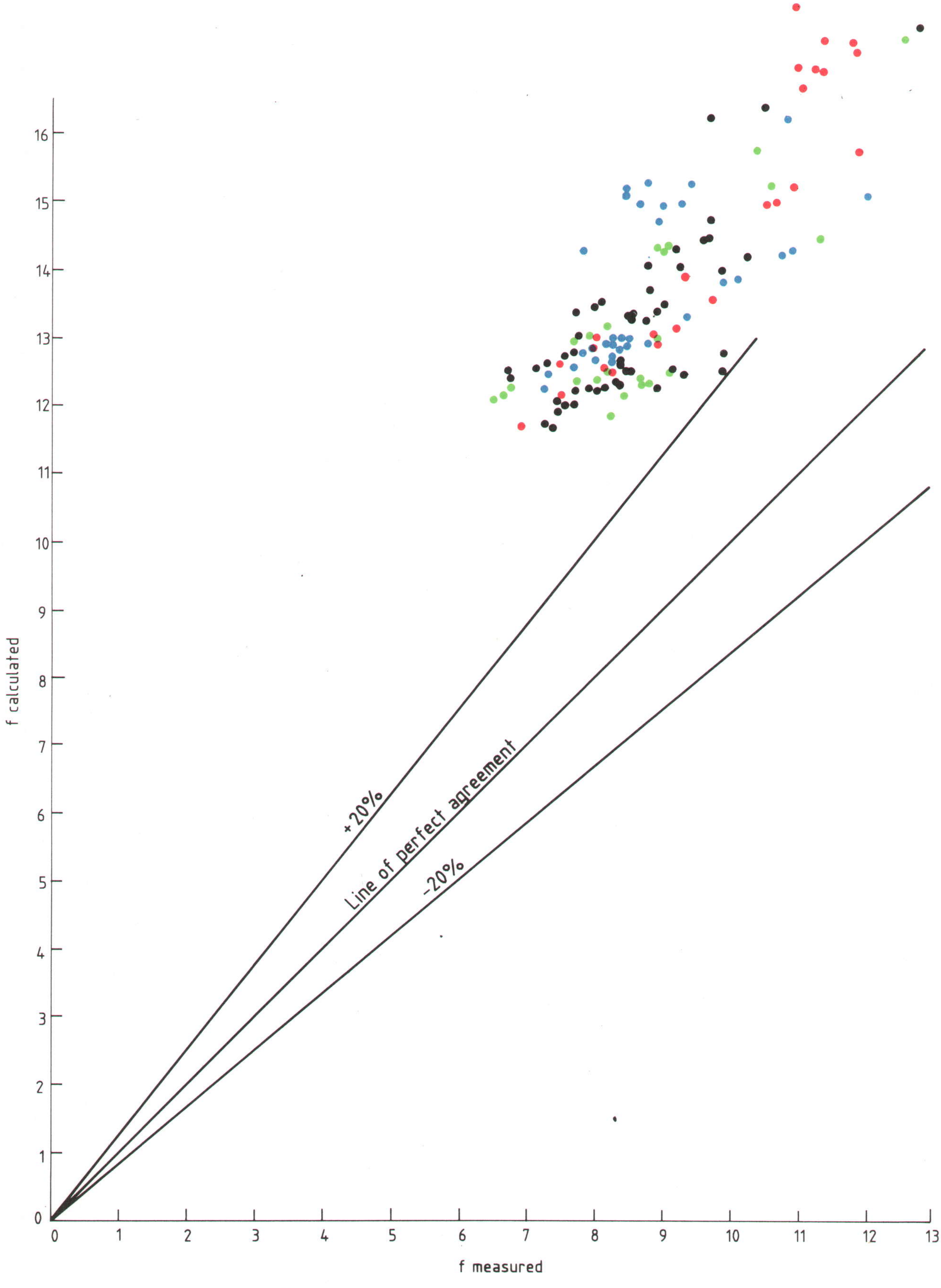

Fig 11 Comparison with measured friction factor, White, Paris and Bettess method

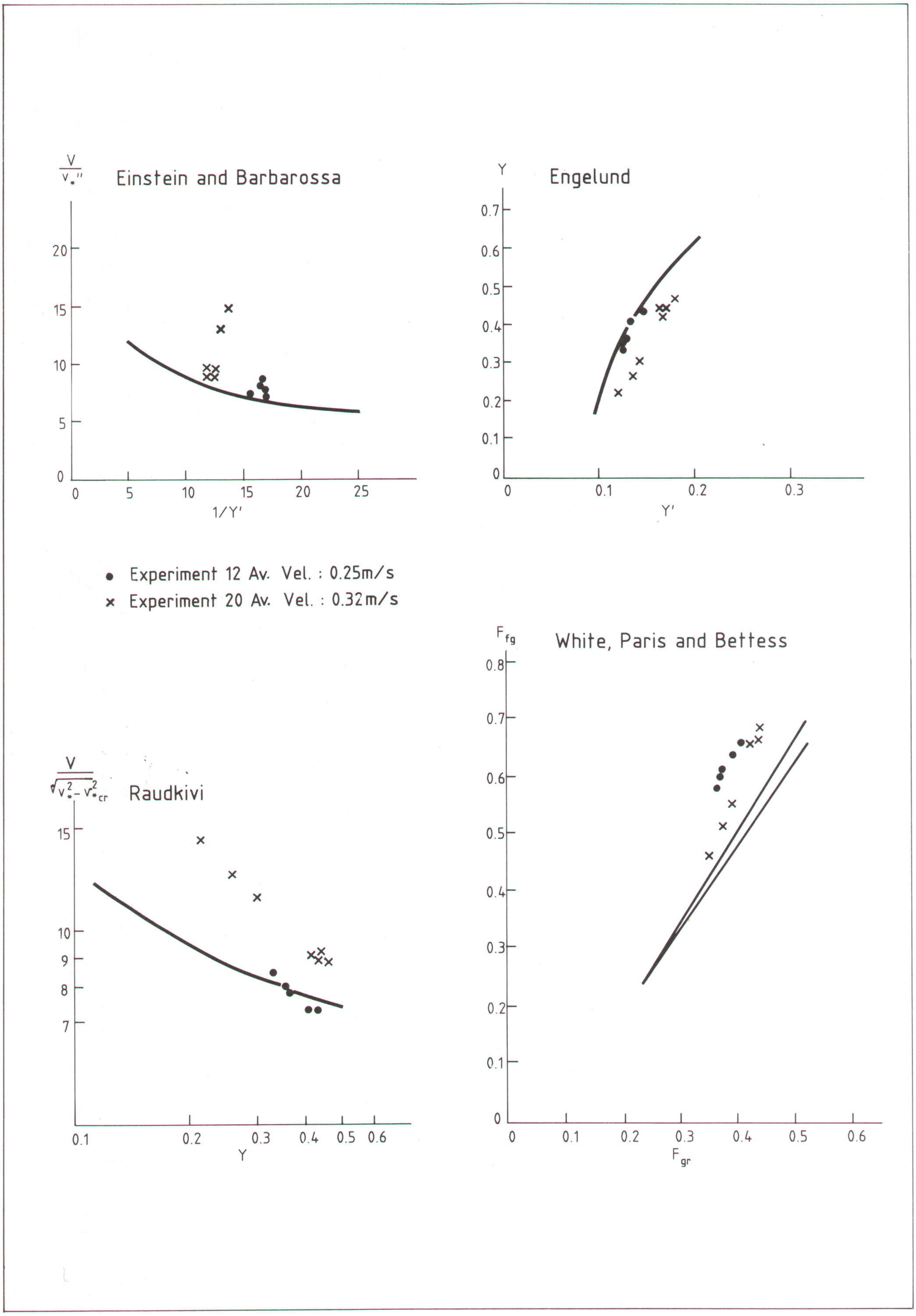

Fig 12 Grouping ofexperiments according to the velocity