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TEESDALE UNIT

PROJECT 73

Report to: Department of the Environment,
Northumbrian Water Authority,
Natural Environment Research Council

Date 19[illegible]

Infiltration of fine and coarse sand into an open-work gravel bed.

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CONTENTS

SUMMARY

The siltation of an experimental gravel bed, with three grades of sand moving in suspension and as bedload, was examined. The rate of infiltration of sand into the void space of the gravel was determined under differing conditions of discharge, water depth, and velocity (jointly expressed as variation in the Froude Number) and suspended sediment concentration. The downstream reduction in siltation from the point source was also examined. The main conclusions were as follows:

(1) For low suspended sediment concentrations (< 300 mg l^{-1} ~ typical of small Teesdale streams) a mean deposition rate of 6.7% of the initial gravel volume filled per hour is comparable to the rate reported by Beschta & Jackson (1979), 5.7% hr^{-1}.

(2) Deposition rates for sands 0.15 mm to 1.4 mm diameter with suspended sediment concentrations of 42-263 mg l^{-1} and Froude Numbers in the range 0.05 to 1.00 were found to be constant, with respect to Froude Number, deposition being controlled by an unquantified mass-exchange mechanism at the sediment-water interface.

(3) For high concentrations (>300 mg l^{-1}) deposition rate was strongly linearly correlated with the suspended sediment concentration.

(4) A re-examination of data presented by Beschta & Jackson (1979) indicates that high concentrations of sediment in suspension close to the bed (~ 7000 mg l^{-1}) may damp turbulence and increase sediment deposition.

(5) The downstream decrease in siltation rate from a point source is a negative exponential function of distance from that source. Sundborg's deterministic equation described the observed data well.

(6) Mean flow data, especially where derived from velocity profile data measured in the outer boundary-layer, are inappropriate for siltation investigations concerned with processes occurring very close to the bed.

Notation		Units
C_o	Suspended sediment concentration at source	$mg\ l^{-1}$
D	Depth	m
d_{50}	Grain-size at 50% percentile	m
F	Froude Number	–
g	Acceleration due to gravity	$m\ sec^{-2}$
K_s	Bed roughness	m
K	Deposition coefficient	–
L	Distance from source	m
Q	Discharge	$m^3 sec^{-1}$
R	Hydraulic radius	–
S_e	Energy slope	radians
U	Velocity	$m\ sec^{-1}$
u_*	Shear velocity	$m\ sec^{-1}$
v_s	Settling velocity	$m\ sec^{-1}$
Z	Height above bed	m
z_o	Roughness length	m
γ	Specific weight of water	$kg\ m^{-3}$
ρ	Density of water	$kg\ m^{-3}$
∂	Thickness of viscous sublayer	m
τ_o	Shear stress	$kg\ m^{-2}$
Δ'	Raw deposition rate	$g\ m^{-2}\ hr^{-1}$
Δ	Adjusted deposition rate	$\%\ hr^{-1}$, $g\ m^{-2}\ hr^{-1}$
p	Deposition coefficient	–
ϵ	Depth mean diffusion coefficient $= 0.0667\ D\bar{U}\sqrt{f/8}$ where f is the D'Arcy-Weisbach coefficient	$cm^2\ sec^{-1}$
χ	von Karman's constant	–

Subscripts

b	bed
c	critical
l	limiting
p	pots
w	water surface

Numerical subscript is height above bed in centimetres.

INTRODUCTION

The silting of gravel beds has been of significant concern to North American fisheries biologists. Various investigations have shown that accumulation of fine inorganic fractions (< 1mm) in the interstices of gravel beds has a largely detrimental effect on upland stream biota. Sediments occlude the surface of fish eggs, and also reduce gravel permeability, thereby reducing oxygen supply rate and the removal of toxic metabolic wastes. The emergence of newly hatched alevins also may be prevented. The result can be increased mortality. In addition, in silted gravel the invertebrate population is commonly reduced in variety and absolute numbers, restricting the food supply of fishes. Beschta & Jackson (1979) give a useful summary of recent key references in relation to the biological impacts of siltation.

The emphasis on fisheries impacts belies the value of siltation investigations for other disciplines. The sealing of riverbed gravels by fine sediments reduces transmission losses in arid and semi-arid water-supply canals and rivers (Renard & Keppel, 1966; Quashu & Buol, 1967; Woudt & Nicolle, 1978) whilst the mechanisms of erosion, transportation and in-channel storage of fine sediments is of interest to the agriculturist and geomorphologist (Rendon-Herroro, 1974; Mucher & De Ploey, 1977). Sedimentologists are interested in siltation processes, as an aid to interpreting the depositional history of sedimentary sequences (Pettijohn, 1975 - p. 49; Fraser, 1935 - p. 919; Smith, 1974; Blacknell, 1981), as are sanitary engineers (Camp, 1943; Dobbins, 1944) concerned with the performance of settling tanks (Cordoba-Molina et al., 1978).

The bulk of siltation literature refers to the effect of forest management in North America, especially clear-felling of large areas of catchments by methods which are not conducive to soil conservation (see refs. in Beschta & Jackson, 1979). At best, investigations have sought to ameliorate problems of sedimentation in streams after identifying the multivariate processes involved in fine sediment production (e.g. Adams & Beschta, 1980).

The emphasis on problems of immediate consequence in North America does not negate the potential problem in the United Kingdom. Large areas of upland Britain afforested in the first half of the this century will be cleared and replanted by the turn of the century. Present forest management has already been shown to result in sediment problems in mid-Wales (Newson, 1980) whilst the extensive practice of deep-ploughing for drainage increases sediment production, at least in the short term (Robinson, 1979).

Industrial pollution of natural upland water courses by fine quartz sands, mica, coal and clay is an example of a problem which was probably more widespread in the past, when disposal of fine mine and quarry waste into natural streams was more prevalent than today. However, examples of the effect of inert-sediment pollution on river biota (Herbert _et al._, 1961; Nuttall, 1972; Turnpenny & Williams, 1980) and upland channel morphology (Richards, 1979) emphasise that local serious problems of siltation occur in British rivers.

Preliminary investigations of natural siltation in upland water courses have shown a seasonal pattern in the amount and spatial distribution of deposition (Smith, 1980), whilst the grain-size of material settling onto the gravel surface, from low concentration suspensions during base flow periods, has been found to be similar in size distribution to the matrix material infilling gravel void space (Carling & Reader, in press). However, little is presently known of the mechanisms of interchange of silt from suspension to the interstitial environment (Einstein, 1968; Beschta & Jackson, 1979).

Beschta & Jackson (1979) measured the amount of deposition of medium and coarse sand (d_{50} = 0.2 mm and 0.5 mm) in pots (150 mm deep) buried at the bed surface in an experimental gravel bed, 300 mm thick. They attempted to correlate the degree of siltation to average hydraulic parameters including shear stress, but were only successful in the case of the Froude Number, $F = \bar{U} / gD$. The percentage of gravel volume silted by 0.5 mm sand increased as a positive linear function of the Froude Number, for values of F in the range 0.5 - 1.5, when sediment concentrations in the flow approximated an average of 2400 mg l^{-1}. In contrast, for the same range of Froude Numbers it was argued that percentage siltation followed a parabolic function with the minimum close to a Froude Number of 1.0, when concentrations were relatively low $\sim$ 600 mg l^{-1}. The lack of correlation with bed shear stress is surprising as observation of particle and tracer motion close to the sediment-water interface indicates that fluid exchange close to the bed is related to the bed shear stress (McCave & Swift, 1976). Nevertheless, Einstein (1968) found experimentally, and Lee _et al._ (1981) concluded from theory, that the deposition rate is proportional primarily to the local concentration close to the sediment-water interface and that hydraulic controls are of secondary importance.

In this report data for coarse and fine sands at low concentrations are given. In the light of these results additional and in some cases alternative interpretations are given for Beschta & Jackson's data. Conclusions are drawn in respect of the utility of gross flow parameters for predicting siltation.

METHODS

The first 16 experimental runs were conducted in an experimental fibre-glass flume of rectangular section with smooth side-walls. A range of discharges up to 117 litres sec^{-1} may be passed through the flume. The width is 0.98 m and although the overall length is 12 m only a 6 m section was used to avoid unsteady flow at the entrance and exit. Neither water nor sediment were recirculated. Unfortunately the flume is of fixed gradient (0.014). Strictly uniform flow through the test section was difficult to achieve, however non-uniformity was minimised by keeping the test section short, by retamping the gravel to a required gradient and by adjusting the water surface slope using a tail-gate.

15 cm depth of clean rounded quartz-density (2.65 g cm^{-3}) gravel was used in each test run. The surface was tamped to provide a uniform bed-surface. Average grain-size statistics are mean grain size ($\bar{x}$) = 15.57 mm, sorting (σ) = 8.10 mm, skewness (γ_1) = 0.54 and kurtosis (γ_2) = 2.22. The grain-size distribution is given in Fig. 1. The void ratio of the deposit was typically 0.67.

Three grades of fine quartz-density sediment were fed into the upstream end of the test section using a commercially available sediment feed hopper. Maximum feed rate increased with increasing grain-size and consequently the hopper was calibrated for each sediment size used. Deposition rates are expressed in Table 1 as raw deposition rates (Column 12) and also as values adjusted to a common feed rate, 300 g min^{-1} (Columns 13-15). Sediment transport concentrations at the delivery location were 42 to 263 mg l^{-1} depending on the discharge. Each grade of sand is commercially available and has a narrow size range (Fig. 1). Summary statistics are: - Sand (1) $\bar{x}$ = 0.19 mm, σ = 0.039, γ_1 = 2.84, γ_2 = 18.34, sand (2) $\bar{x}$ = 0.15 mm, σ = 0.046, γ_1 = -0.72, γ_2 = 1.68, sand (3) $\bar{x}$ = 1.40 mm, σ = 0.33, γ_1 = 1.44, γ_2 = 9.72.

Viewing siltation through a perspex window set in the side wall, initial exploratory runs indicated that, for sands (1) and (2), sand grains moved down through the gravel and deposition occurred from the base of the gravel initially and continued at a steady rate until the void space was filled. Consequently there was no need to run the experiments until the gravel was completely silted (although this was done in some cases) in order to calculate siltation rates. Generally runs were made over durations of 60 min and 120 min and siltation rates were corrected to a 60 min duration.

Experiments were scaled to give a range of Froude Number from 0.005 to 1.2. The result of using Froude Numbers in this range was such that the downstream change in concentration of suspended sediment, as settling occurs, may be expected to be a function of V_s/U_* (Camp, 1943). All runs were within Owen's (1969) transitional range $0.005 < V_s/U_* > 5.0$ (Fig.10), so that the settling rate might be expected to be dependent both on the level of turbulence and the grain-size of the suspended sediment.

For each run water surface slope was measured using a manometer with 13 pressure tappings in one side of the channel at 0.5 m intervals. Current speed was measured at 0.6 of the depth at 9 cm intervals across the width at the upstream end of the test section using an Ott current meter. Depth was measured at 9 cm intervals using a point gauge at the entrance and exit sections. At midstream 2 m down the section a velocity profile was measured at 0.5 or 1.0 cm increments above the bed with the lowest measure 2.5 cm above the bed. Depth-integrated suspended sediment samples were also taken at representative sections.

The distribution of sedimentation through the length of the section was measured using a row of gravel-filled pots, volume 355 cm^3, buried with the tops flush with the gravel surface at 0.5 m intervals down the centre of the flume. In addition a row of pots across the flume recorded lateral variation in siltation. It was difficult to ensure completely uniform dispersion of the sediment fed into the channel so that suspended sediment concentrations tended to be highest in the centre of the channel. To avoid this problem and the influence of the channel wall drag on deposition only the results from the centre of the channel, where flow was two dimensional, are reported here.

All fine sediment transported out of the flume was entrapped in a fine mesh bag (0.063 mm aperture). Although this might allow 0.10 to 2.0 % of the finest sand grade to pass, in practice the mesh became rapidly clogged and trapping efficiencies were close to 100%. Siltation rates could be calculated from the difference between the input and output of sand, as well as from the quantity of sand deposited in the siltation pots.

The shear velocity was calculated from logarithmic velocity profiles assuming von Karman's constant of 0.40 is valid for low concentration suspensions (Vanoni, 1977).

$$\ln Z = \frac{0.40}{U*} \bar{U} + \ln z_o \qquad (1)$$

The local energy slope was calculated from DuBoy's equation

$$S_e = \rho U_*^2 / \gamma R \qquad (2)$$

To check the flow was quasi-uniform the energy slope for the complete test section was estimated using the relationship

$$Se = Sw - \frac{U^2}{gD} (Sw - Sb) \qquad (3)$$

corrected for side wall influence using the method of Williams (1970) and compared to the bed gradient. These data are not reported here.

Bed roughness was initially estimated using Nikuradse's equivalent sand grain roughness (Schlichting, 1968);

$$K_s = 30\ z_o \tag{4}$$

but these data could not be related satisfactorily to the grain-size of the bed material. Meland & Norrman's (1966) equation for flow over rhombohedrally-packed glass beads,

$$\log z_o = 1.951 \log K_s - 0.939 \tag{5}$$

was found to give equivalent roughness values close to the mean grain size of the bed material (Table 1).

The initial 16 runs were conducted to seek hydraulic controls for deposition, consequently suspended sediment concentrations were kept low and inversely proportional to discharge. An additional 9 runs were conducted in a variable gradient recirculating flume to examine the influence of concentration on deposition rates. High sediment feed rates were possible in the latter runs with uniform distribution of sediment across the flume width. The high concentrations chosen did not correlate with discharge.

The gravel used, packed in a bed 100 mm deep had the summary statistics; $\bar{x}$ = 21.60 mm, σ = 5.31 mm, skewness = -0.37, kurtosis = 3.00 and void ratio = 0.55.

The sand used was sand (2) (p.4). The overall flume length was 12.8 m with a central working section of 6 m. The width was 0.81 m. 6 pots of individual surface area 266 cm^2 and depth 100 mm, were spaced 1 m apart in a downstream row with the first pot 1 m downstream of the sediment hopper. In addition two lateral pots were placed either side of the third and fifth pots giving ten pots in all. Not only were pots made larger than in runs 1-16, but they were also permeable, nine 1 cm diameter holes having been drilled in each side and the base. Deposited sand was prevented from escaping by 0.063 mm mesh glued over the holes.

Current speed and depth were measured similar to runs 1-16. Water surface slope was measured using a point gauge. No velocity profiles were taken, consequently the shear velocity was calculated from equation (2). All sediment moving out of the flume was caught in a 0.063 mm mesh bag. Because sediment feed rates were very high experiments were concluded rapidly; run times varying between 1.5 and 18 minutes.

RESULTS

General Observations

Up to Froude Numbers of about 0.70 the two fine grades of sand were transported in suspension and in traction. The transport of material as bedload was distinctly pulsatory, possibly associated with "bursting" phenomena close to the bed (Kline et al., 1967; Grass, 1971). During Run 1, which was typical of runs in the approximate Froude range 0.10 to 0.70, suspended sediment was observed to be introuduced into the gravel void space by turbulent pulses; thereafter grains were advected down into the fabric by turbulent intragravel flow. The turbulent nature of the intragravel flow was assessed by observing the irregular motion of solitary sand grains.

For Froude Numbers less than 0.10 fine sand was transported largely as bed-load. For example, during Run 2 as soon as the gravel was fully silted, the bed-load formed a carapace of rippled sand with ripple heights of 260 mm and wavelengths in the range 48-90 mm.

For flows characterised by suspension load transport and Froude Numbers greater than 0.10, fine sand introduced into the framework of the bed generally was deposited at the base of the gravel and filled the void space leaving only a surface gravel layer, approximately 15 mm thick (i.e. one pebble diameter), free of sand. Turbulence resuspended material from this layer and effectively prevented siltation at the surface. Occasional hanging lenses of sand developed in the gravel where local clogging of smaller than average voids occurred, but eventually these were surrounded by accreting sand.

At Froude Numbers greater than 0.70 no bedload transport occurred, grains moved in suspension but were continually entrapped in the surface void space and deposited in the bed.

Only three runs used the coarse sand. This material moved solely as bedload and infiltrated the gravel bed. Local clogs in the gravel void space were more widespread than was the case for the fine sand grades. However, there was a tendency for the gravel to fill from the base upwards with isolated areas of open void space residual in a largely silted bed. Only locally did a surface sand-seal develop.

Deposition rate

The siltation rate in the pots, expressed as a percentage by volume hr^{-1} (Table 1 Column 15), initially was calculated similarly to Beschta & Jackson (1979; i.e. volume of sand deposited divided by volume of gravel in pot) so that the results of the two investigations could be compared (Fig. 2). However it is preferable to express deposition as weight per unit area for a given time interval ($g\ min^{-1}\ m^{-2}$, Table 1, Column 14). The mean rate of deposition for the first 16 runs based on the siltation pots is 4.1% hr^{-1} (σ = 2.7%). As will be explained below the efficiency of the pots in trapping sediment is low. Consequently the true rate of deposition is 6.7% hr^{-1} for the two fine grades of sand. Both these values are comparable to Beschta & Jackson's (1979) mean pot deposition rate of 5.7% hr^{-1} for 0.5 mm sand with relatively low suspended sediment concentrations. It is evident that even at low sediment transport concentrations natural gravel beds of a similar thickness would rapidly become fully silted, regardless of Froude Number or grain-size of fine sand.

The deposition rate expressed as $g\ min^{-1}\ m^{-2}$ could be calculated accurately by subtracting the weight of sand caught at the end of the test section from the weight introduced to the test section (Table 1, Column 13). Deposition for runs 1-16 varied insignificantly between runs and may be regarded as constant ($\bar{x}$ = 29.2 $g\ min^{-1}\ m^{-2}$, σ = 1.8). This contrasts to the deposition rate measured in buried pots where rates not only were lower but also showed a tendency to decrease at high Froude Numbers ($\bar{x}$ = 17.9 $g\ min^{-1}\ m^{-2}$, σ = 8.9). The average efficiency of the pots in runs 1-16 could be calculated as the ratio between columns 13 and 14 (61.9% efficient, σ = 31.6%). The reduction in efficiency was most marked for Froude Numbers greater than 0.10 (Fig. 3) and may be explained by the absence of intragravel flow in the solid-walled pots advecting grains down though the void space. The use of permeable pots in runs 17 to 25 solved this problem (96.3% efficient, $\sigma = 14.2\%$).

In runs 17 to 25 very high suspended sediment concentrations were independent of velocity. The deposition rate was highly correlated with concentration (Fig. 4). Considering the data for all the 25 runs an equation describing the increase in deposition rate (in the unconfined bed) with concentration is;

$$\Delta'_b = 0.5570\,\bar{C} - 56.4929 \qquad r^2 = 0.95 \tag{6}$$

The pot data gave a similar curve (see inset Fig. 6).

Downstream siltation rate

The downstream sorting of sediment in rivers is commonly described by an exponential function relating the reduction in particle weight or diameter with distance from the source (e.g. Church & Kellerhals, 1978; Deigaard, 1980). Sternberg (1875) and Lokhtin (1897) originally derived the exponential form of the relationship and gave different heuristic physical explanations (Scheidegger, 1970). Sundborg (1957) introduced a sounder mechanical basis by explaining gradation as a differential transport process based on a sedimentation formula. Recently Stow & Bowen (1980) have advocated an equation similar to Sundborg's. Sundborg's equation is:

$$\Delta' = \frac{v_s p}{D}\, C_o\, e^{-v_s p\, L/\bar{U}D} \tag{7}$$

p is one minus the ratio between the number of particles entrained and the number deposited at any one location (Scheidegger, 1970) and, expressed as the overall probability of deposition, may be written $p = (1 - {}^{\tau_0}/_{\tau_1})k$ for silt and clay (McCave & Swift, 1978). p needs to be defined experimentally or introduced arbitrarily. Values cannot be greater than one and usually are in the range 0.4 to 1.0 (McCave & Swift, 1976). Stow & Bowen (1980) used a value of 0.5 in an investigation of sorting in turbidity currents, whilst Einstein (1968) found that $p \simeq 1.0$ in an experimental investigation of deposition from suspension into a gravel bed.

The experimental data obtained from siltation pots for the present investigation are shown in Figs. 5 & 6. Sand was fed into the channel at the water surface. Consequently settling grains were transported through a finite distance downstream over the bed before deposition; the distance, depending on settling velocity, water depth, stream velocity and turbulence was up to 1 m. Deposition rates for the first metre of experimental section were low and variable and were not included in the following analysis. Despite considerable scatter the data for runs 1-16 fit the exponential function;

$$\Delta = 0.2998\, e^{-0.2211L} \qquad (8)$$

Data for individual runs indicate a tendency for the exponent to decrease at high Froude Numbers (runs 1-16, Fig. 7) or as current speed increased (runs 17-25), but data were not conclusive. The reduction in the exponent reflects a more even distribution of siltation from suspension at high discharge compared to local deposition close to the source at low discharges: a similar result to Einstein's (1968).

Equation 7 was fitted to the data assuming in the first instance that $p = 1.0$. A consistent over-fit was obtained for the runs characterised by suspended sediment transport. The function is not intended to describe sorting by bedload transport and a fit could not be obtained for Runs 3, 14, 15 and 16 which were runs dominated by bedload transport. Values calculated from equation 7 for $L = 1$ m for runs 1-16 were on average 1.5 times the values obtained using equation 8. Similarly the ratio $\bar{\Delta}_b/\bar{\Delta}_p = 1.64$ suggests that equation 7 with $p = 1.0$ should describe deposition in an unconfined gravel bed. This indicates that p_p is 0.61. In fact p_p was found to decline exponentially downstream in 9 of the 12 suspended sediment runs (Table 3). In the remaining three runs p_p increased downstream, reflecting increased scour downstream, an unsatisfactory result for a deposition model. Equation 7 is plotted in Fig. 5 using a mean value of p_p at $L = 1$ m, derived from the 9 acceptable runs, and a settling velocity based on the mean grain size of sands 1 & 2 (from Table 2, Graf & Acaroglu, 1966). The observed data deviate progressively from the theoretical curve in the downstream direction. Similar results were obtained for runs 17-25 with the theoretical curve over-estimating observed values by a factor of 1.72 and yielding a value of p_p of 0.58 (Fig. 6).

Velocity profiles

Siltation rate is dependent, at least in part, on the turbulent exchange rate at the sediment-water interface (Einstein, 1968; McCave, 1970). The relative roughness may be expected to influence significantly the degree of turbulence over a rough boundary, turbulence intensity decreasing at low Reynold's numbers and at large values of the relative depth (Nowell, 1978).

Equation 1 can be expressed in a non-dimensional form so that all data from each run can conveniently be compared graphically (Fig. 8).

$$\frac{\bar{U}}{U_*} = \frac{1}{\chi} \ln \frac{z}{k_s} + C \tag{9}$$

A typical value for the constant C for a rough-turbulent planar sand-bed is 8.5 (Schlichting, 1968). However, C has been found to be a smaller value, 2.3 to 4.6, and to increase as a function of D/k_s over an experimental bed of 23 mm diameter hemispheres (Bayazit, 1976). Data from the present experiments confirm a lower value of C may be frequently appropriate for boundaries of large elements. An average value for the data is 4.92. Similarly to Bayazit's results with artificial roughness, C also was found to increase with D/k_s (Fig. 9).

The log-normal profile, equation 9, would seem to be inappropriate at values of D/k_s less than about 7 when data scatter becomes excessive (Fig. 8). Profile data can no longer be considered logarithmic but there is no consistent pattern to the data points which would allow the mathematical expression of $\bar{u}/u_* = f\ (z/k_s)$ to be derived.

DISCUSSION

Deposition rate

Although the data from the solid-walled pots may be used to show the downstream pattern of deposition (p. 12) they cannot give an accurate representation of deposition rates in an unconfined gravel bed. The vigorous introduction of suspended sand into the gravel void space at high Froude Numbers was enhanced by strong intragravel flow carrying particles down into the bed. Consequently, although at high Froude Numbers sediment was carried totally in suspension a mass-exchange mechanism at the sediment-water interface controlled deposition, maintaining a constant rate. Deposition, for low concentrations of fine and coarse sand over a wide range of hydraulic conditions, was therefore independent of the Froude Number or for that matter any of the average flow parameters in Table 1, the "decision" to deposit being made at or in the gravel surface (Einstein, 1968).

The concentration of suspended sediment at low concentrations < 300 mg l^{-1} is not related to the deposition rate. Although as discharge increased, the weight of suspended sediment lost from each litre of fluid to each m^2 of the bed decreased; this was owing to dilution of the load. The increase in the total volume of water passing over the bed sustained the transport rate and hence maintained the constant rate of deposition.

The conclusion expressed immediately above may not apply for very high concentrations of suspended sediment as used in some experiments by Beschta & Jackson (1979, Fig. 3), where, with concentrations 1 cm above the bed of the order of 12000 mg l^{-1}, deposition increased with Froude Number. A possible explanation for this phenomenon is given below.

The concentration of suspended particles at which particle interaction influences flow dynamics has not been determined precisely. Lumley (1978) suggests a value of 3000 mg l^{-1}. Beschta & Jackson's flows therefore were probably of a two phase non-Newtonian character, with the stress on the bed a function of both the flow field and the sediment concentration. High suspended sediment concentrations, especially near the bed, decrease turbulence and reduce the vertical eddy diffusivity coefficient as has been documented from laboratory experiments with sediments denser than water (Vanoni, 1977; p. 83-87). This process increases the likelihood of deposition of particles and may conceivably result in a thickened viscous sub-layer on the downstream side of gravel particles in which grains may be trapped (Einstein, 1968; McCave, 1970). The modification of boundary-layer properties has been suggested as a mechanism enhancing the deposition of particles from flows containing high concentrations of washload (Mucher & De Ploey, 1977).

It is not possible to test this idea rigorously from the data given by Beschta & Jackson (1979). Nevertheless, it is possible to obtain insight to the problem by reference to the velocity profiles they present in their Fig. 5. Increased values of concentration decrease the slope of the logarithmic velocity profile and the value of von Karman's coefficient (e.g. Vanoni, 1977; Fig. 2.38, p. 86). Inspection of Fig. 5 and Table 1 in Beschta & Jackson (1979) leads to the conclusion that the slope of the velocity profiles was reduced at high suspended sediment concentrations. The data for the seven runs used to construct Beschta & Jackson's Fig. 3 have been abstracted (Table 2). Although the increase in concentration with decrease in velocity profile slope is not highly significant, the general trend is evident. Suspended sediment concentration also increased at high Froude Numbers. The conclusion is that sediment damped turbulence at high Froude Numbers and promoted the increase in siltation rates noted by Beschta & Jackson (1979).

Beschta & Jackson's polynomial function for 0.5 mm sand at relatively low concentrations rests largely on only two points at about $F = 0.50$. Although scattered the data could be reinterpreted similarly to the data in column 12, Table 1 of this report which show a constant infiltration rate across a wide range of Froude Numbers.

Downstream siltation rate

No field data for siltation within gravels to support equation 7 are known to the author. If equation 7 is rewritten and expressed as the reduction in suspended sediment concentration as an exponential function of distance from the source, supporting data are available (Cordoba-Molina et al., 1978). For example, Miner (1968) reported a downstream reduction in concentration of total suspended solids from an experimental point release in a natural stream which would appear to fit a negative exponential function. Einstein (1968), in a flume study, found the concentration of particles (3.5 μ - 30 μ in size) decreased exponentially downstream as sediment was deposited in an open-work gravel. It should be noted however that Krone (1959; 1962) who also found an exponential function for silty-clay at low concentrations, < 300 mg l^{-1}, observed a logarithmic function for high concentrations. However, neither Miner nor Einstein give sufficient data concerned specifically with gravel beds, to enable one to recalculate their findings as siltation rates to compare with the present data and equation 7.

Measured p_p changed downstream (Table 3). In uniform flow one can expect the probability of deposition (and presumably resuspension) to remain constant in a downstream direction (Einstein, 1968). The observed change in p_p could be interpreted as reflecting non-uniform flow conditions through the test section. However this is unlikely because the flow was at least quasi-uniform throughout the test reach in all 25 runs. The change in p_p might therefore subsume changes in the settling velocity of the suspended sediment in a downstream direction. Einstein observed that coarser grains were deposited in the upstream test section and fines were transported further downstream. In effect the settling velocity in equation 7 should be recalculated for each increment in L to allow for differential sorting downstream. Beschta & Jackson for example found that the mean grain-size of deposited material was 60% of that of the suspended load. Unfortunately, the grain size of the deposited sediment in this study was not measured following individual runs 1-16 but was measured in runs 17-24 and was found to decrease downstream. Incorporation of a reduced grain size with distance downstream did not suffice to correct the theoretical curve to fit the observed data (Fig. 6). Choice of $p = 1.0$ gives a constant over-estimate of deposition rate. A smaller value e.g. $p = 0.58$ would yield a better fit at $L = 1.0$ m but would increasingly over-estimate deposition in the downstream direction.

Solution of the equation $p = (1 - \tau_o/\tau_1)k$ for $p_p = 0.60$, $k = 1$ and for individual values of τ_o in each experiment (Column 9, Table 1) yields a substantial value for τ_1 in each instance e.g., $\bar{\tau}_1 = 2.48$ kg m^{-2} (Runs 1-16). McCave & Swift (1978) indicated that τ_1 should be equivalent to τ_c for silt and clay and that other factors, subsumed in the value k, tend to decrease or increase deposition rates. Values of τ_c obtained, for the fine and coarse sands used in this investigation, from threshold curves presented by Miller et al. (1977) are in the range 0.01 to 0.07 kg m^{-2}. Arguing from the ratio τ_o/τ_c alone would indicate that little deposition should have occurred. The need to identify factors other than turbulence is further confirmed by plotting the present data as a function of v_s/u_* and $v_sD/2\epsilon$ (Fig. 10). Camp (1943) argued that the deposition of silt in a natural stream is a function both of v_s/u_*, which is analogous to $(1 - \tau_o/\tau_1)$ and to a turbulence parameter, $v_sD/2\epsilon$. When turbulence is great, the value of $v_sD/2\epsilon$ is low and the deposition rate is reduced.

As an example, if particles were expected to be 100% settled in a non-turbulent flow ($v_s/u_* = 1.0$) then deposition would be reduced to 64% if $v_s D/2\epsilon = 0.1$. At low deposition rates, $v_s/u_* < 0.40$, the effect of turbulence in reducing deposition is negligible. The present data fall into two groups (Fig. 10, Runs 1-16), $p > 0.70$ which represents transport largely by bedload and $p < 0.35$ which are all suspended sediment runs. The values of $p < 0.35$ are surprising in view of the measured values of $p \sim 0.60 - 1.00$ for the siltation pots and unconfined gravel bed. Clearly turbulence should have a minimal effect, reducing sedimentation. However Camp was arguing only for deposition from suspension to a bed of similar loosely-deposited material where resuspension could easily occur. Of various other factors that should be taken into consideration which increase the deposition rate over gravel, the most obvious is that gravel is porous and can physically entrap particles and prevent resuspension. Other possible factors are: that τ_0 or u_* measured in the outer boundary-layer are not satisfactory surrogate values for turbulence intensity close to the bed; that deposition also occurred from a bedload and finally that the possible influence of the ratio d/∂ has not been considered. McCave & Swift (1978) thought that the latter might become important when particles were of the order of 1mm in diameter, as in runs 14 to 16.

The physical nature of the laminar sub-layer in a surface gravel-layer is unknown and therefore it is difficult to quantify an effective thickness for the layer. This fluid-layer might be better described as a "dead" zone entrapping sediment by a presently unidentified mechanism. A possible approach to solving for deposition from a turbulent flow to the gravel void space might then be found by adopting a logitudinal mixing model similar to that described by Thackston & Schnelle (1970).

Formation of a surface sand seal

It is of some consequence whether or not fine sediment will enter the void space of a gravel bed. Beschta & Jackson observed that 0.55 mm sand formed a seal some 5 cm thick at the surface of their 15 mm gravel as sand grains bridged openings to void spaces and prevented further penetration of additional material. In contrast, in the present experiments 1.4 mm sand did not universally form a sand seal over 15.57 mm gravel (p. 9). A possible explanation for the "patchy" nature of infiltration of fine sediment into a graded gravel bed and the contrast between Beschta & Jackson's results and the present results is given below.

If equal diameter spheres are packed systematically to form a bed there is a maximum diameter of smaller grain size particles that may enter the interstices. The ratio of the two grain-sizes is 0.154 if the spheres are tightly packed and 0.414 if loosely packed (Fraser, 1935 - p. 919). Similarly, grains larger than the critical ratio can only be found in the void space if packed simultaneously with the large spheres. These observations have been reiterated recently by Pettijohn (1976 - p. 73). The ratio of the mean grain-size of the silting sands and the gravel in this investigation and Beschta & Jackson's falls in the range 0.0096 to 0.0899; consequently one would expect infiltration in a bed consisting of uniform gravel. In mixtures of particles, porosity varies spatially no matter how carefully the proportions are mixed (Fraser, 1935, p. 928 - 932) so that the degree of sand infiltration inevitably will be variable.

Most natural fluvial silted gravels are believed to have become silted after deposition (Fraser, 1935; Dal Cin, 1967; Plumley, 1948); this would seem to be confirmed by an analysis of several hundred alluvial gravel samples (Conkling et al., 1934) where it was found that the ratio of the secondary grain-size mode to the coarse mode was in the range 0.03 - 0.06 i.e. much less than the critical ratio - 0.154 (Pettijohn, 1975, p. 48).

The logarithmic velocity model and siltation

The logarithmic velocity model, frequently used to obtain mean flow data, is not applicable very close to a rough boundary where flow is complicated owing to separation behind roughness elements. In particular, using outer region observations, the estimation of momentum transfer close to the bed is not possible (Nowell, 1978). It follows that if sedimentation is controlled by the hydrodynamics close to, or within, the surface gravel layer (Einstein, 1968) then hydrodynamic measures should also be in this layer. The depth of this region is, from studies of depth limited boundary-layers in air and water, of the order of the roughness spacing (Mulhearn & Finnigan, 1978) or roughness height (Nowell & Church, 1979). In particular, Nowell & Church in an investigation intended to represent flow over a gravel substratum, found that a log-velocity model was not valid closer to the bed than $Z/D = 0.35$ and that turbulence intensity changed character below $Z/D = 0.20$. In the present report the lowest velocity determination was at 2.5 cm above the bed which is equal to $Z/D \simeq 0.20$. Consequently none of the velocity profile data should be expected to correlate with siltation processes if Einstein's (1968) hypothesis is correct.

Further investigations of the mechanics of siltation in gravel beds will require detailed hydrodynamic data very close to the bed or within the void spaces of the surface gravels.

CONCLUSIONS

Mean deposition rates of 6.7% hr^{-1} for low suspended sediment concentrations of fine sand are comparable to the rates reported by Beschta & Jackson (1979) (5.7% for coarse sand). Deposition rates for suspended sand concent rations in the range 42-263 mg l^{-1} and for Froude Numbers 0.05 to 1.2 are effectively constant; deposition being controlled by a mass-exchange mechanism at the sediment-water interface. At high concentrations of suspended sediment deposition rate increases. Deposition may be enhanced further as turbulence is damped. Sedimentation rates calculated from solid-walled siltation pot data are not representative of deposition in unconfined gravel beds.

Mean flow data, especially where derived from velocity profile data measured in the outer boundary layer, are inappropriate for siltation investigations concerned with processes occurring only one roughness height away from the bed. Progress in understanding the dynamics of fine sediment deposition over rough beds in shallow water is only likely to be achieved using sophisticated laboratory apparatus.

A number of factors which will influence deposition have not been included in this investigation. Rendon-Herrero (1976) considered the interference effect of mixtures of grain-sizes on the settling velocity.

Chow (1964) points out that advection by fluid transmission losses will locally affect deposition rates. Bed topographic variations may influence deposition (Laursen, 1975) although Einstein (1968) found no evidence for this. Finally Yao (1969) and Owen (1969) indicated that the surface chemistry of fine clay particles will influence deposition. In this respect it is interesting to note that Quashu & Buol (1967) refer to a natural sand and gravel layer, having a high clay and water content in contrast to other layers in the profile. Microscopic examination showed that clay particles accumulated on individual sand and gravel particles in an orientated manner; a phenomenon which may be related to the surface charge of particles (Einstein, 1970).

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REFERENCES

Adams, J.N. & Beschta, R.L. (1980) Gravel bed composition in Oregon coastal streams. Can.J. Fish Aqu. Sci. 37 (10) 1514-1521.

Bayazit, M. (1976). Turbulence characteristics in flow over large roughness elements. Disa Information 19, March, 26-29.

Beschta, R.L. & Jackson, W.L. (1979). The intrusion of fine sediments into a stable gravel bed. J. Fish. Res. Bd. Can. 36 (2) 204-210.

Blacknell, C. (1981). Sandy gravel accumulation in a fluvial environment. Geol. J. 16, 287-297.

Camp, T.R. (1943). The effect of turbulence on retarded settling. Proc. 2nd Hydraulics Conf., Univ. Iowa Studies in Engineering, Bull. 27, 307-317.

Carling, P.A. & Reader, N.A. (in press). Structure, composition and bulk properties of upland stream gravels. Earth Surface Processes and Landforms.

Chow, V.T. (1964). Handbook of Applied Hydrobiology. McGraw-Hill Book Co. Inc. New York, N.Y.

Church, M. & Kellerhals, R. (1978). On the statistics of grain-size variation along a gravel river. Canadian Journal of Earth Sciences 15 (7) 1151-1160.

Conkling, H.; Eckis, R. & Gross, P.L.K.(1934). Groundwater storage capacity of valley fill. California Division Water Resources Bull. 45, 279 pp.

Cordoba-Molina, J.F.; Hudgins, R.R. & Silveston, P.L. (1978). Settling in continuous sedimentation tanks. J. Environmental Engineering Div. A.S.C.E. 140 (EE6), 1263-1275.

Dal Cin, R. (1967). Le ghiaie del Piave. Mem. Mus. Tridento Sci. Nat. 16 (3) 1-117.

Deigaard, R. (1980). Longitudinal and transverse sorting of grain sizes in alluvial rivers. Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark, Series Paper No. 26, 108 pp.

Dobbins, W.E. (1944). Effect of turbulence on sedimentation. Trans. A.S.C.E., 109, 629-678.

Einstein, H.A. (1968). Deposition of suspended particles in a gravel bed. J. Hydr. Div. A.S.C.E., 94, (HY5) 1197-1205.

Einstein, H.A. (1970). Closure to discussion: - Deposition of suspended particles in a gravel bed. J. Hydr. Div. A.S.C.E., 96, (HY2), 581-582.

Fraser, H.J. (1935). Experimental study of the porosity and permeability of elastic sediments. J. Geol. 43, 910-1010.

Graf, W.H. & Acaroglu, E.R. (1966). Settling velocity of natural grains. Bull. Internat. Ass. Scient. Hydrol. XI Annees No. 4, 27-43.

Grass, A.J. (1971). Structural features of turbulent flow over smooth and rough boundaries. J. Fluid Mech., 50 (2), 233-255.

Herbert, D.W.M., Alabaster, J.S., Dart, M.C. & Lloyd, R. (1961). The effect of china-clay wastes on trout streams. Int. J. Air & Wat. Pollut. 5, 56-74.

Ippen, A.T. (1971). A new look at sedimentation in turbulent streams. J. Boston Soc. Civ. Engrs. 58 (3) 131-163.

Kline, S.J., Reynolds, W.C., Schraub, F.A. & Runstadler, P.W. (1967). The structure of turbulent boundary layers. J. Fluid. Mech. 30 (4) 741-773.

Krone, R.B. (1959). Second Annual Progress Report on the silt transport studies utilizing radioisotopes. Hydraulic Engineering Lab. and Sanitary Engineering Research Lab., Univ. California, Berkeley, California.

Krone, R.B. (1962). Silt transport studies utilising radioisotopes, Final Rept. Instit. Engineering Research, Univ. California, Berkeley, California.

Laursen, E.M. (1975). Discussion of: Estimation of washload produced on certain small watersheds. J. Hydr. Div. A.S.C.E., 101, 208.

Lee, D-Y.; Lick, W.& Kang, S.W. (1981). The entrainment and deposition of fine-grained sediment in Lake Erie. J. Great Lakes Res. 7 (3),224-233.

Lokhtin, V. (1897). Sur le mecanisme du lit fluvial. St. Petersburg [quoted more recently in Scheidegger (1970)].

Lumley, J.L. (1978). Two-phase and non-Newtonian flows: In: P. Bradshaw (Editor). Topics in Applied Physics, 12, Springer, New York, N.Y. 289-324.

McCave, I.N. (1970). Deposition of fine-grained suspended sediment from tidal currents. J. Geophys. Res. 75 (21) 4151-4159.

McCave, I.N. & Swift, S.A. (1976). A physical model for the rate of deposition of fine-grained sediments in the deep sea. Bull. Geol. Soc. Am. 87, 541-546.

Meland, N. & Norrman, J.O. (1969). Transport velocities of individual size fractions in heterogeneous bed load. Geografiska Annaler 51 A (3), 127-144.

Miller, M.C.; McCave, I.N. & Komar, P.D. (1977). Threshold of sediment motion under unidirectional currents. Sedimentology 24, 507-527.

Miner, N.H. (1968). Natural filtering of suspended soil by a stream at low flow. Pacific N.W. Forest & Range Experimental Station, U.S. Forest Service Research Note, PNW-88, 4 pp.

Mucher, H.J. & de Ploey, J. (1977). Experimental and micromorphological investigation of erosion and redeposition of loess by water. Earth Surface Processes, 2 (2-3) 117-124.

Mulhearn, P.J. & Finnigan, J.J. (1978). Turbulent flow over a very rough random surface. Boundary-Layer Met. 15, 109-132.

Newson, M. (1980). The erosion of drainage ditches and its effects on bedload yields in mid-Wales. Earth Surf. Processes, 5, 275-290.

Nowell, A.R.M. (1978). Dissipation of fine-scale structure in turbulent open channel flow. Wat. Res. Res. 14 (3) 519-526.

Nowell, A.R.M. & Church, M. (1979). Turbulent flow in a depth-limited boundary-layer. J. Geophys. Res. 84 (C8) 4816-4824.

Nuttall, P.M. (1972). The effects of sand deposition upon the macro-invertebrate fauna of the River Camel, Cornwall. Freshwat. Biol.,2,181-186.

Owen, M.W. (1969). Discussion of:- Deposition of suspended particles in a gravel bed. J. Hydro. Div. A.S.C.E. 95 (HY3), 1085-1087.

Pettijohn, E.J. (1975). Sedimentary Rocks. 3rd Edit., Harper Internat., New York, N.Y.

Plumley, W.J. (1948). Black Hills terrace gravels: a study in sediment transport. J. Geol. 56, 526-577.

Quashu, H.K. & Buol, S.W. (1967). Hydraulic and micromorphological properties of stream channel sediments. Water Res. Res. 3 (2) 465-469.

Renard, K.G. & Keppel, R.V. (1966). Hydrographs of ephemeral streams in the southwest. J. Hydr. Div. A.S.C.E. 92 (HY2), 33-52.

Rendon-Herrero, O. (1974). Estimation of washload produced on certain small watersheds. J. Hydr. Div. A.S.C.E. 100 (HY7), 835-848.

Rendon-Herrero, O. (1976). Closure to discussion of: - Estimation of wash-load produced on certain small watersheds. J. Hydr. Div. A.S.C.E. (HY7), 1061-1064.

Richards, K.S. (1979). Channel adjustments to sediment pollution by the china clay industry in Cornwall, England. In: Adjustments of the Fluvial System. D.D. Rhodes & G.P. Williams(Eds.) 309-331, Dubuque, Iowa, Kendall-Hunt.

Robinson, M. (1979). The effects of pre-afforestation ditching upon the water and sediment yields of a small upland catchment. School of Geography, University of Leeds, Working Paper 252, 70 pp.

Scheidegger, A.E. (1970). Theoretical Geomorphology. 2nd Edit. Allen & Unwin, London.

Schlichting, H. (1968). Boundary-Layer Theory. 6th Edit. McGraw-Hill, New York.

Smith, B.D. (1980). The effects of afforestation on the trout of a small stream in southern Scotland. Fisheries Management, 11 (2) 39-58.

Smith, N.D. (1974). Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream. J. Geol. 82, 205-223.

Sternberg, H. (1875). Untersuchungen uber langen und quer-profilgeschiebe-fuhrende Flusse. Zeitschrift fur Bauwesen, 25, p. 483.

Stow, D.A.V. & Bowen, A.J. (1980). A physical model for the transport and sorting of fine-grained sediment by turbidity currents. Sedimentology, 27 (1) 31-46.

Sundborg, A. (1957). C.R. Ass. Toronto, Ass. Hydrol. Sci., U.G.G.I., 1, p. 249. (quoted more recently in Scheidegger (1970)).

Thackston, E.L. & Schnelle, K.B. (1970). Predicting effects of dead zones on stream mixing. J. Sanitary Engineering Div. A.S.C.E. 96 (SA2) 319-331.

Turnpenny, A.W.H. & Williams, R. (1980). The effects of sedimentation on the gravels of an industrial river system. J. Fish Biol. 17, 681-693.

Vanoni, V.A. (1977). Sedimentation Engineering A.S.C.E. Manuals and Reports on Engineering Practice No. 54, A.S.C.E., New York.

Williams, G.P. (1970). Flume width and water depth effects in sediment transport experiments. Prof. Pap. U.S. Geol. Surv. 562-H.

Van't Woudt, B.D. & Nicolle, K. (1978). Flow processes below a gravelly river bed. J. Hydrology (N.Z.) 17 (2) 103-120.

Yao, K.M. (1969). Discussion of: - Deposition of suspended particles in a gravel bed. J. Hydr. Div. A.S.C.E. 95 (HY) 761-762.

Run	D (m)	U (m sec^{-1})	Q (m^{3}sec^{-1})	F -	Z_o (m)	U_* (m sec^{-1})	K_s (m)	τ_o Kg m^{-2}	S_e -	R (g min^{-1})	$\dot{\Delta}_b$ (g min^{-1}m^{-2})	Δ_b (g min^{-1}m^{-2})	Δ_p (g min^{-1}m^{-2})	Δ_p (% hr^{-1})	d (mm)	C_o (mgl^{-1})
1	0.113	0.897	0.099	0.726	0.0027	0.1146	0.0159	1.3388	0.0146	268	26.17	29.30	12.05	2.29	0.1896	45
1a	0.125	-	-	-	0.0075	0.2108	0.0261	4.5297	0.0455	-	-	-	-	-	-	-
2	0.153	0.265	0.049	0.047	0.0009	0.0255	0.0090	0.0663	0.0006	-	-	-	-	-	-	-
2a	0.138	0.364	0.049	0.098	0.0040	0.0565	0.0194	0.3254	0.0030	268	27.78	31.10	12.47	1.86	0.1896	91
2_s	-	0.355	0.049	0.093	0.0002	0.0248	0.0042	0.0627	0.0006	-	-	-	-	-	-	-
3	0.170	0.115	0.019	0.008	0.0040	0.0181	0.0194	0.0334	0.0003	268	27.67	30.97	10.04	0.38	0.1896	235
4	0.137	0.541	0.073	0.218	0.0083	0.1148	0.0283	1.3434	0.0126	268	24.30	27.20	36.59	8.12	0.1896	61
5	0.109	0.838	0.090	0.657	0.0006	0.0858	0.0073	0.7504	0.0084	268	22.85	25.58	23.06	5.33	0.1896	50
6	0.127	0.943	0.117	0.714	0.0016	0.1078	0.0122	1.1846	0.0118	268	26.83	30.03	9.98	2.18	0.1896	38
7	0.103	1.108	0.112	1.215	0.0029	0.2120	0.0165	4.5814	0.0539	253	25.52	30.26	14.38	3.14	0.1540	38
8	0.109	0.942	0.101	0.830	0.0038	0.1485	0.0189	2.2479	0.0252	253	26.54	31.47	10.36	2.91	0.1540	42
9	0.099	0.923	0.090	0.877	0.0022	0.1225	0.0143	1.5297	0.0186	253	25.46	30.19	11.94	2.89	0.1540	47
10	0.125	0.626	0.077	0.320	0.0029	0.0866	0.0165	0.7645	0.0111	253	24.31	28.83	14.10	3.28	0.1540	55
11	0.148	0.357	0.052	0.088	0.0050	0.0579	0.0218	0.3417	0.0030	253	23.34	27.68	20.35	3.96	0.1540	81
12	0.120	0.658	0.077	0.368	0.0023	0.0898	0.0146	0.8220	0.0085	253	22.84	27.08	18.66	3.49	0.1540	54
13	0.106	0.803	0.083	0.620	0.0042	0.1361	0.0199	1.882	0.0217	253	23.51	27.88	16.18	3.57	0.1540	51
14	0.141	0.381	0.053	0.105	0.0043	0.0635	0.0197	0.4110	0.0038	529	55.95	31.75	36.16	10.03	1.3963	168
14_s	0.070	0.461	0.053	0.309	0.0017	0.0650	0.0122	0.4307	0.0070	-	-	-	-	-	-	-
15	0.115	0.995	0.112	0.878	0.0048	0.1526	0.0208	2.3738	0.0255	529	50.16	28.46	11.10	3.72	1.3963	90
16	0.109	0.701	0.075	0.460	0.0014	0.0801	0.0111	0.6540	0.0073	529	53.06	30.10	28.68	8.78	1.3963	111
17	0.085	0.431	0.030	0.223	N/D	0.0845	N/D	0.7274	0.0104	3739	-	-	45.75	1.95	0.1540	1827
18	0.072	0.590	0.034	0.491	N/D	0.0901	N/D	0.8268	0.0135	8050	1241.14	46.25	41.28	1.73	0.1540	3900
19	0.056	0.545	0.025	0.540	N/D	0.0780	N/D	0.6206	0.0126	4944	764.22	46.37	34.64	1.53	0.1540	3336
20	0.091	0.687	0.050	0.530	N/D	0.0983	N/D	0.9858	0.0133	12653	1927.41	45.70	42.77	1.87	0.1540	4184
21	0.120	0.969	0.094	0.800	N/D	0.1118	N/D	1.2748	0.0138	6941	951.65	41.13	32.80	1.39	0.1540	1234
22	0.094	1.014	0.077	1.112	N/D	0.1263	N/D	1.6267	0.0213	35883	4650.03	38.88	42.36	1.81	0.1540	7757
23	0.089	0.980	0.071	1.099	N/D	0.1226	N/D	1.5327	0.0210	38534	5541.57	43.14	44.47	1.86	0.1540	9110
24	0.120	1.060	0.103	0.954	N/D	0.1572	N/D	2.5190	0.0210	1924	290.68	45.32	48.80	2.07	0.1540	312
25	0.120	1.060	0.103	0.954	N/D	0.1572	N/D	2.5190	0.0210	2806	362.71	38.78	43.93	1.91	0.1540	456

Note:-

Column 12 is the observed raw deposition rates. Columns 13-15 are values adjusted to a common arbitrary feed rate, 300g min^{-1}, by dividing raw deposition values by the respective feed rate and multiplying by 300.

Table 2. Data extracted from Beschta & Jackson Table 1, 1979 ranked in decreasing value of χ/U_*. χ was calculated from suspended sediment concentration data using Ippen's (1971) equation expressing a reduction in χ with high suspended sediment loads. U_* was calculated using equation (1) and a value of $\log \bar{z}_o = -5.72$ for a flat 15 mm gravel bed (Table 1, this paper). Suspended sediment concentration is significantly linearly correlated with the rank order of decrease in χ/U_* in columns 4 and 5. $P < 0.05$ in each case. The near-bed concentration (Column 3) is significantly linearly correlated with an increase in Froude Number $P < 0.05$ and the reduction in χ, $P < 0.001$.

Run No.	χ	χ/U_*	$C_{(1)}$ mg l^{-1}	$C_{(6)}$ mg l^{-1}	F
10	0.30	3.38	2800	200	0.53
16	0.32	2.99	2470	280	0.66
17	0.17	2.59	8970	1100	0.92
5	0.14	2.45	10980	260	1.08
11	0.19	2.34	7210	660	1.18
12	0.20	2.07	7480	1200	1.53
18	0.15	1.81	10740	1150	1.52

Table 3. Values of p_p in equation 7 (p. 11) for experimental runs 1, 2, 4-13.

[1] Data marked with an asterisk were not used to derive the mean values at each distance from the source.

	Distance from source (m)				
Run	1	2	3	4	5
1	0.5617	0.5444	0.5287	0.5120	0.4970
2*	0.5006	0.6462	0.8333	1.0747	1.3908
4*	0.5883	0.5605	0.5826	0.6051	0.6317
5	0.5025	0.4979	0.4933	0.4878	0.4839
6	0.7242	0.6819	0.6421	0.6051	0.5707
7	0.7101	0.6488	0.5920	0.5401	0.4926
8	0.6870	0.6372	0.5906	0.5459	0.5061
9	0.5665	0.5344	0.5039	0.4743	0.4473
10	0.5287	0.6094	0.5906	0.5716	0.5535
11*	0.5509	0.5850	0.6205	0.6571	0.6983
12	0.6023	0.5829	0.5635	0.5444	0.5271
13	0.5657	0.5398	0.5150	0.4913	0.4688
$\bar{x}$ [1]	0.6054	0.5863	0.5577	0.5303	0.5052

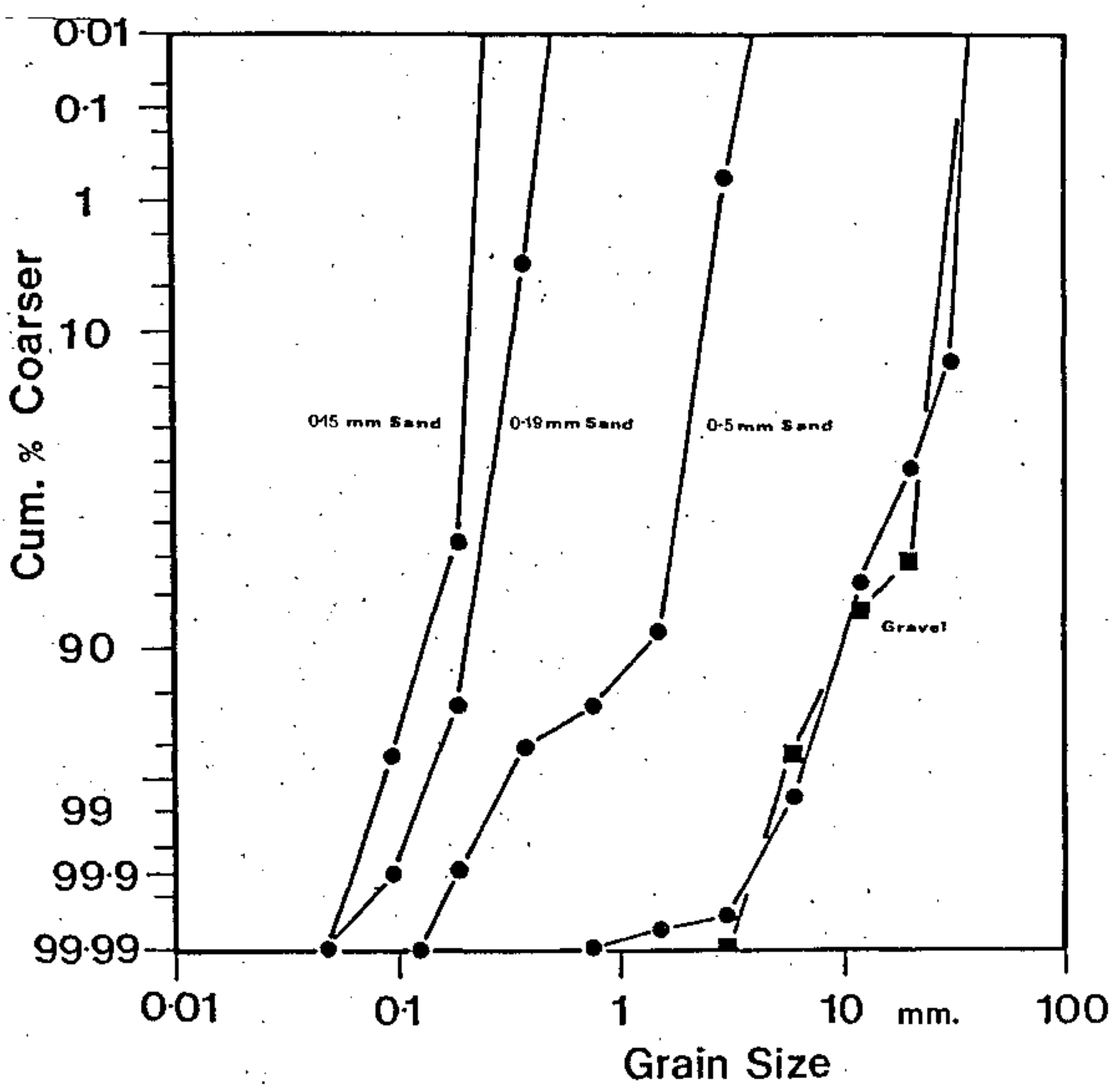

Fig. 1. Cumulative frequency curves of sediment grain sizes used in sand infiltration experiments. ● Gravel runs 1-16, ■ Gravel runs 17-25.

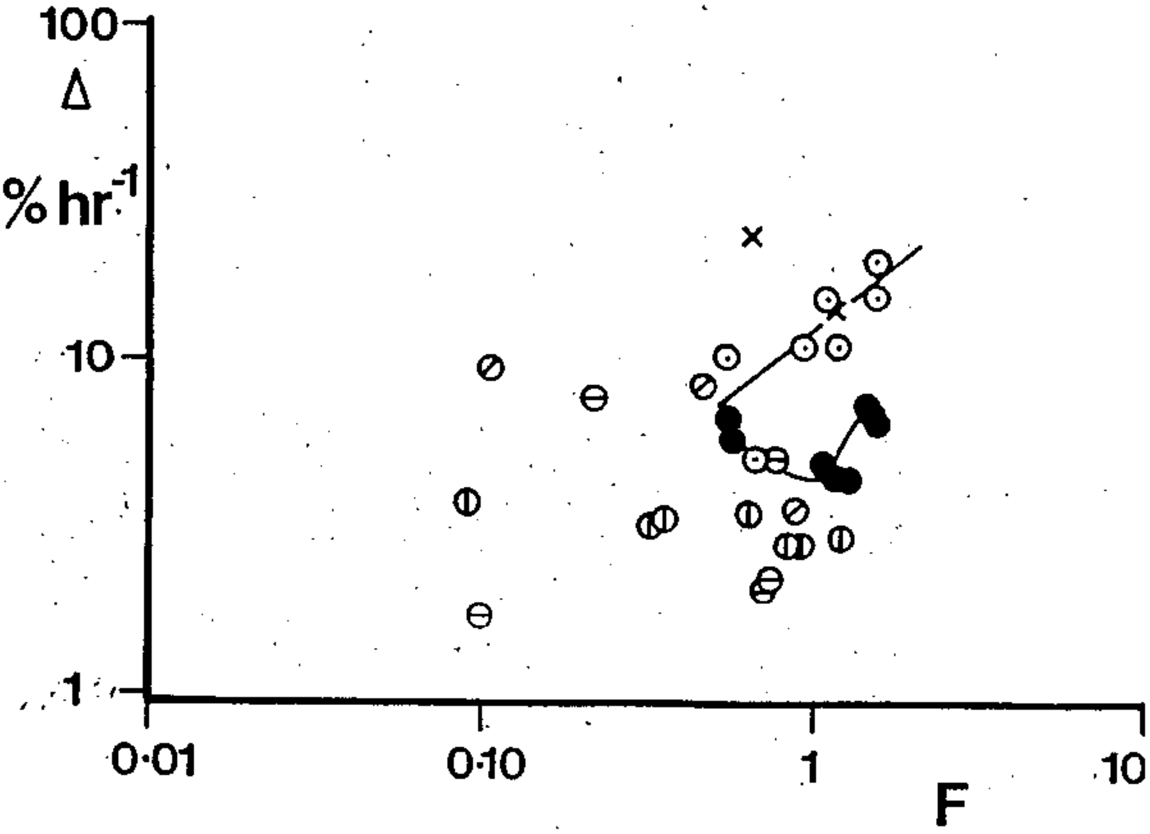

Fig. 2. Siltation rates obtained from pot data. Runs 1–16 ⦶ = 0.15 mm sand, ⊖ = 0.19 mm sand, ⊘ = 1.4 mm sand. Compared with pot siltation data of Beschta & Jackson (1979), x = 0.20 mm sand, ● = 0.5 mm sand – low concentrations, ⊙ = 0.5 mm sand for high concentrations. The regression equation curves are the functions in Beschta & Jackson's Figures 2 and 3 recalculated for % hr^{-1} units.

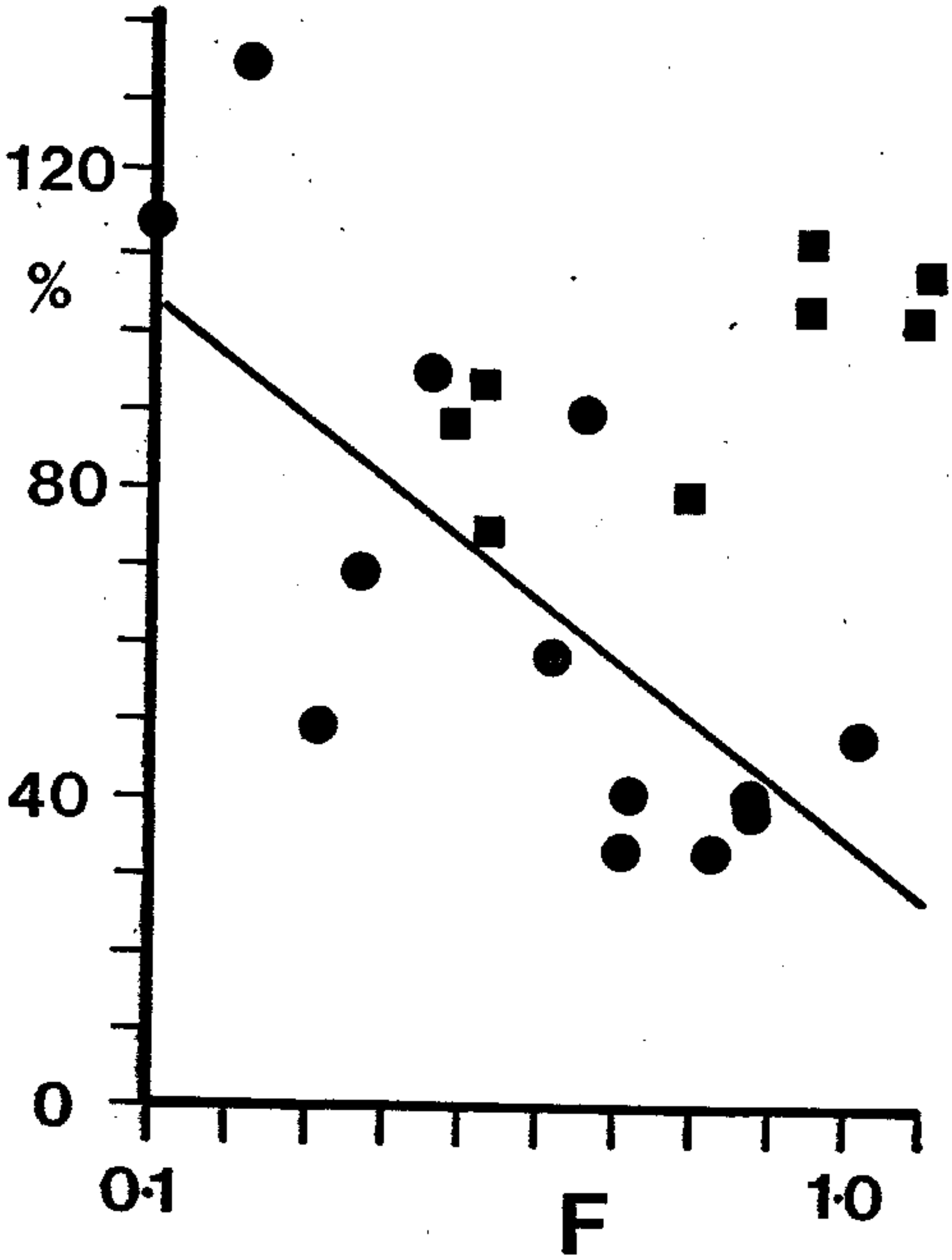

Fig. 3. Efficiency of siltation pots with solid walls, measured as a percentage of siltation in an unconfined gravel bed, decreases as Froude number increases. Dots and regression line refer to runs 1-16. The use of permeable pots in runs 17 -25 appear to increase efficiency at high Froude numbers; square symbols.

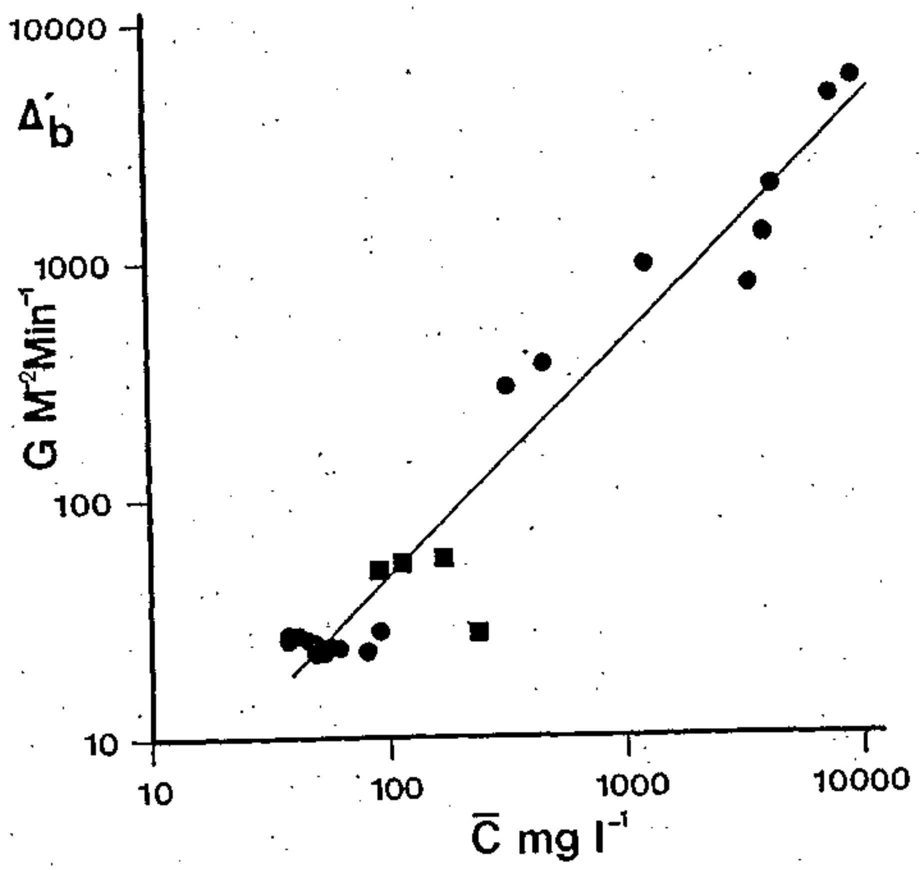

Fig. 4. Relationship of raw deposition rate to concentration of sediment in the fluid. Dots are for suspended sediment runs, squares are for bedload runs.

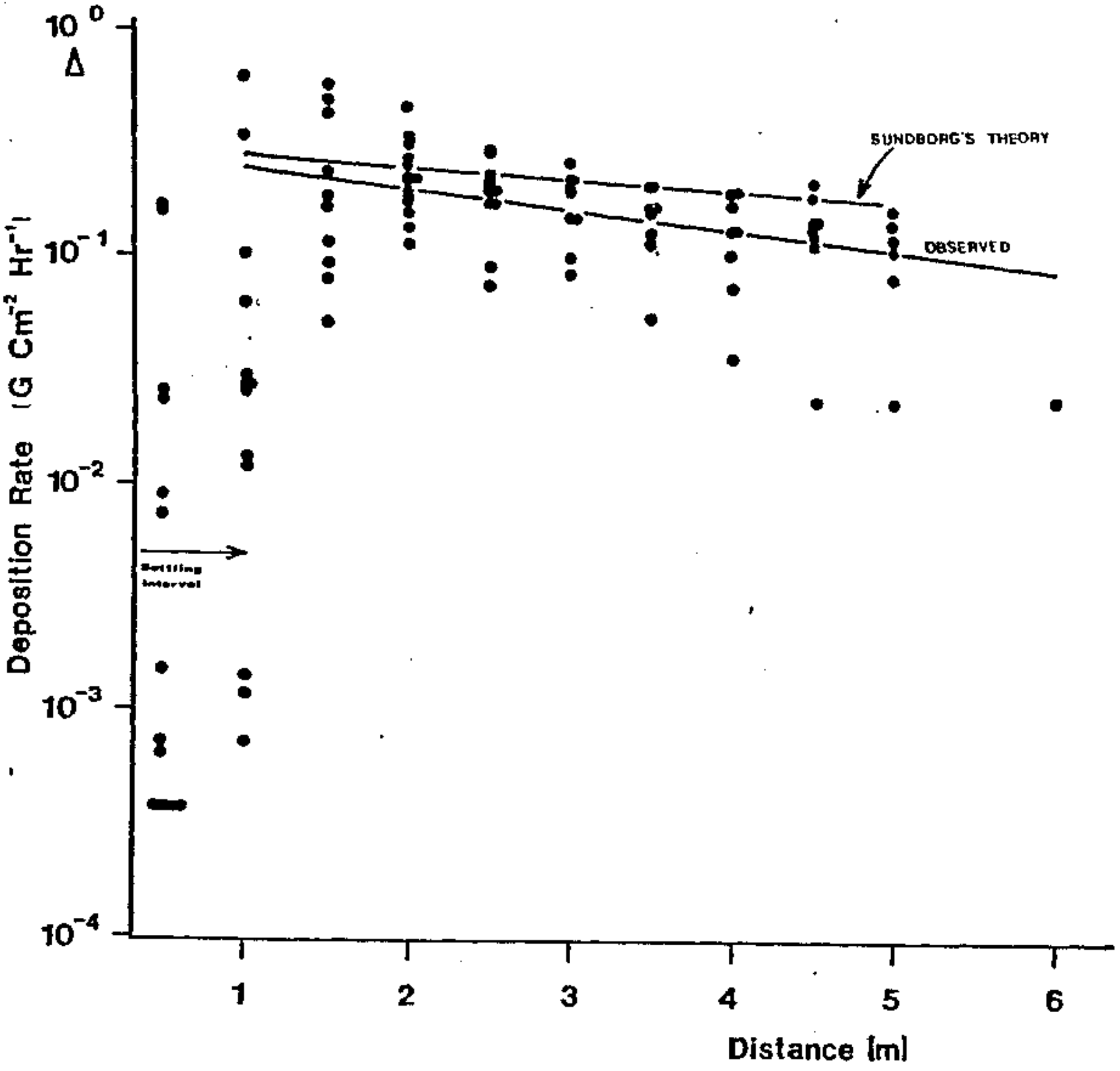

Fig. 5. Data for experiments 1, 2 and 4 to 13 showing the exponential decrease in deposition rate of fine sands from suspension. The observed regression curve (Equation 8 in text) deviates progressively with distance from the source (L = 0) from a theoretical deterministic equation of Sundborg. Notwithstanding this discrepancy the agreement between observed data and theory is good.

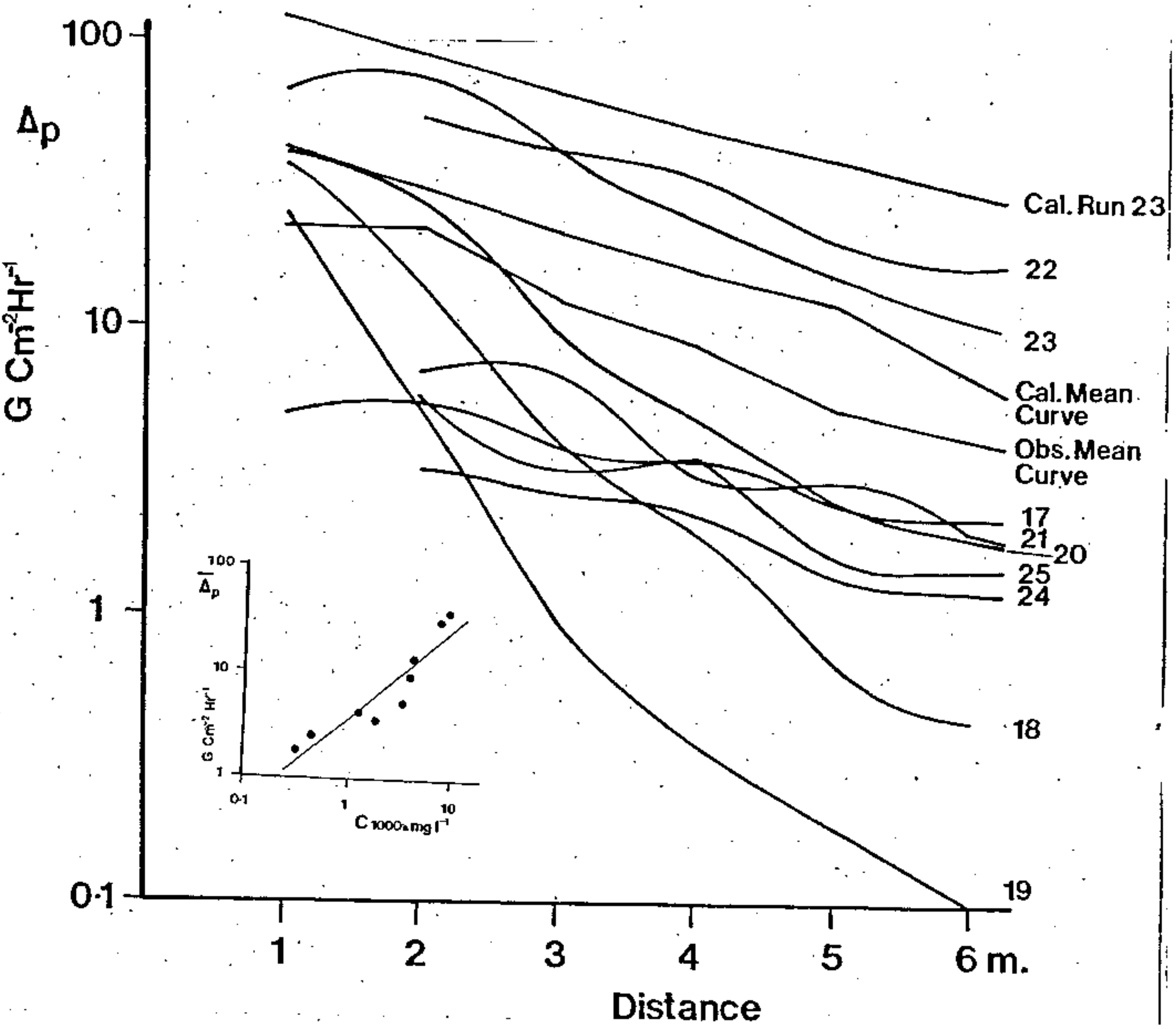

Fig. 6. Curves for experiments 17 to 25 showing the exponential decrease in deposition rate with distance from the source. Data points are not shown but occur at each 1 m interval. The wide spread of curves compared to Fig. 5 is owing to the wide range of suspended sediment concentrations in runs 17-25. The mean curve for all observed data is compared with the curve calculated from equation (7) with p set to 1.0. A calculated example for p = 1.0 is also given for run 23. The inset graph shows the increase in deposition rate in the pots as concentration in the flow increases.

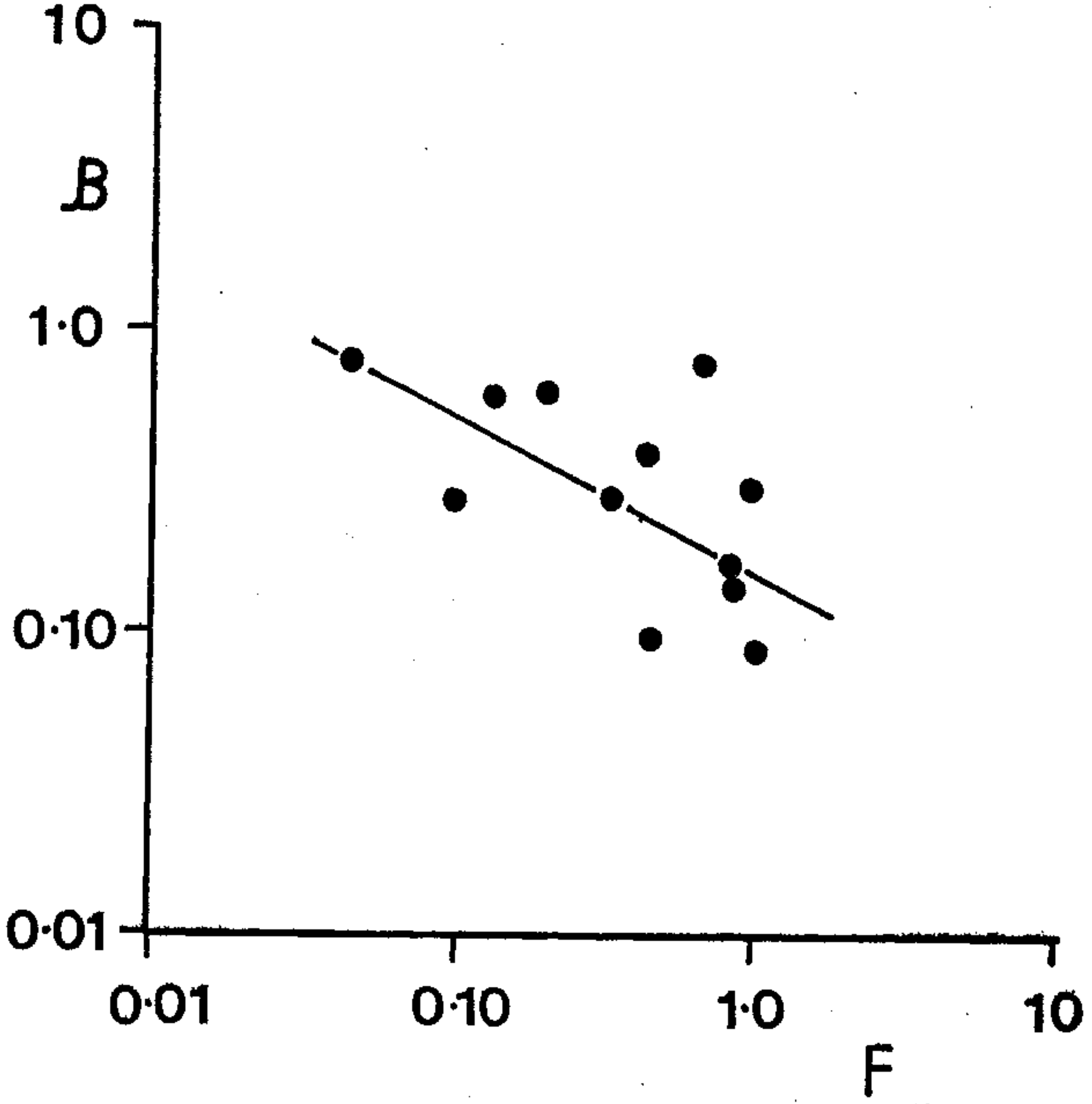

Fig. 7. Values of B in the regression equation $\Delta = a\ e^{-BL}$ (describing the downstream reduction in deposition rate with distance from a point source of suspended sediment) decrease in value as Froude Number (F) increases; indicating an increasingly even spread in deposition from suspension at higher Froude Numbers. Data for runs 1-16.

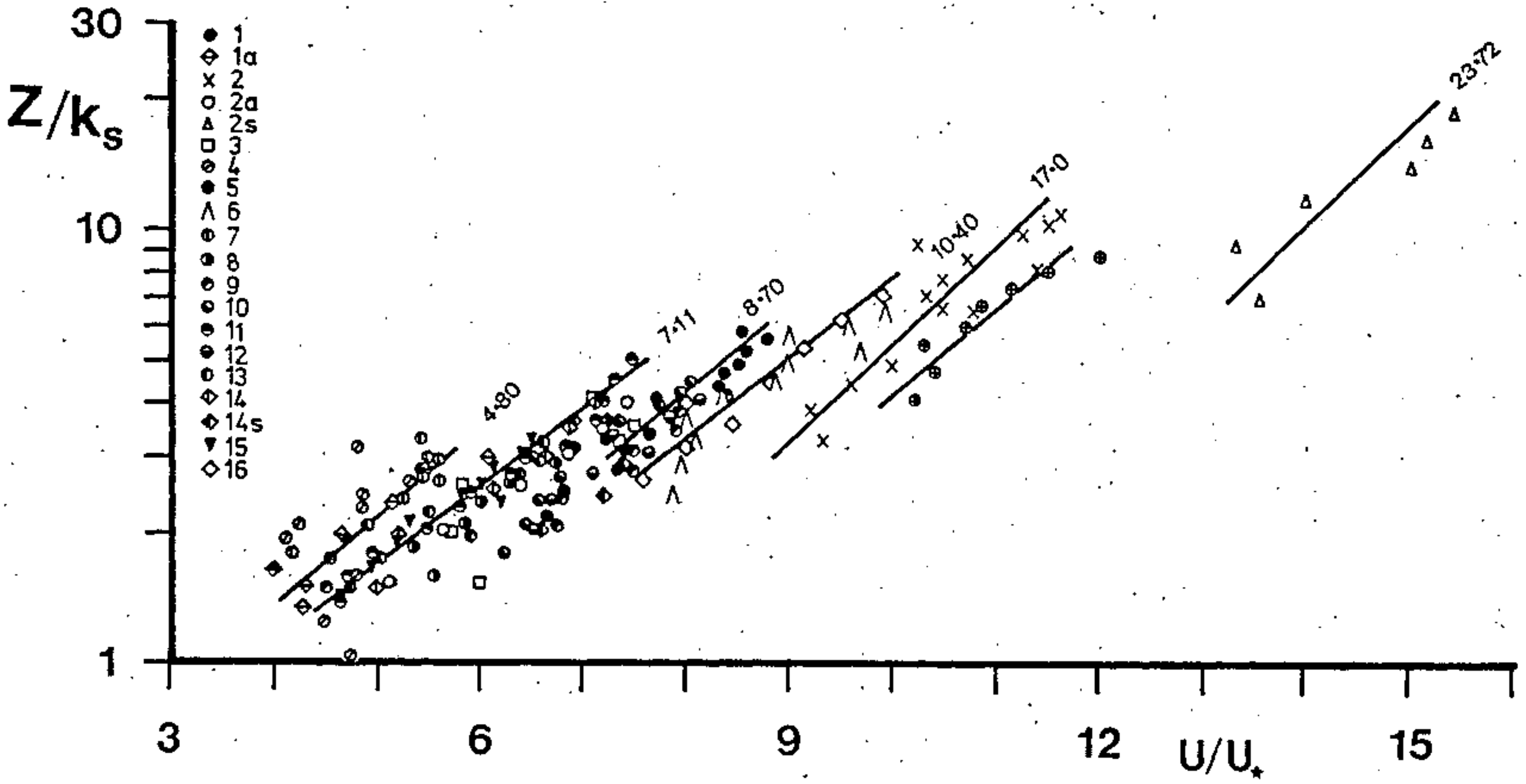

Fig. 8. Velocity profile data calculated from equation (9). The symbols refer to the experimental runs listed in Table 1. Selected profiles are drawn to show the general trend of the log-linear data sets. Figures above profiles are values of D/K_s showing the trend to increased values of D/K_s as U/U_* increases.

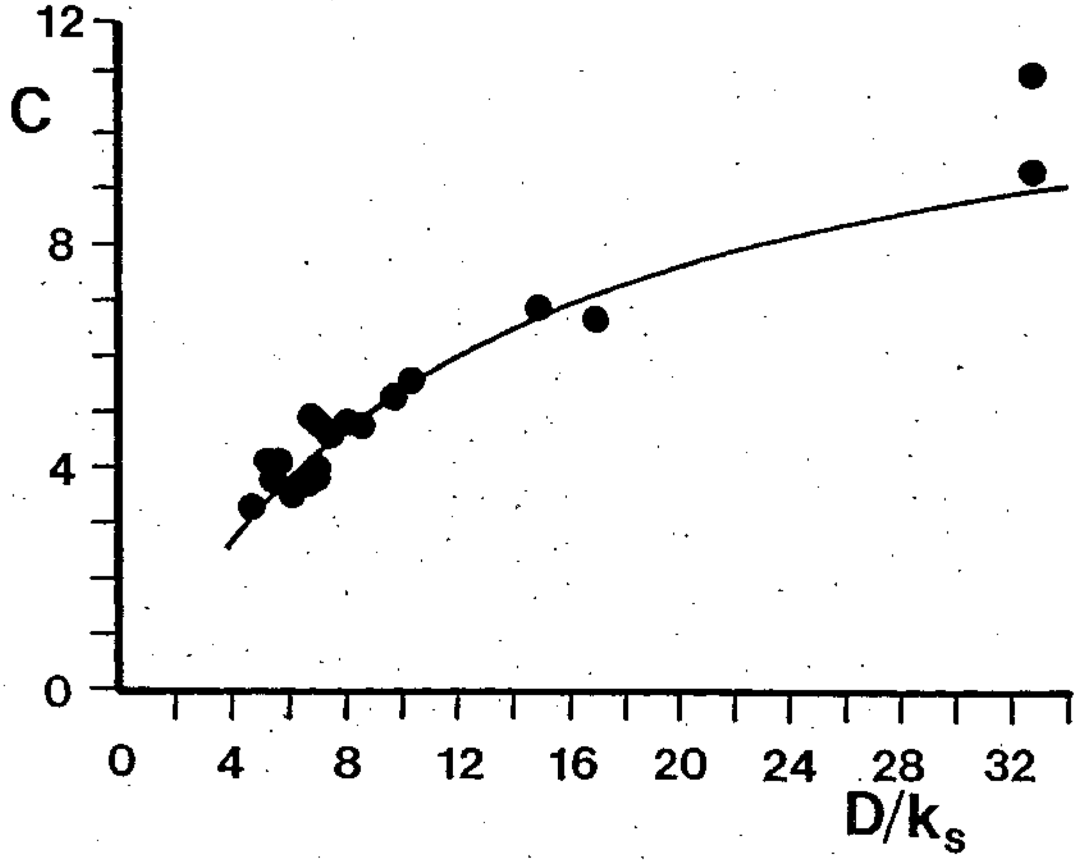

Fig. 9. The coefficient C in equation (9) as a function of D/K_s. The data indicates that a value less than 8 (commonly used for smooth boundaries) may be applicable to rough boundaries in shallow depths.

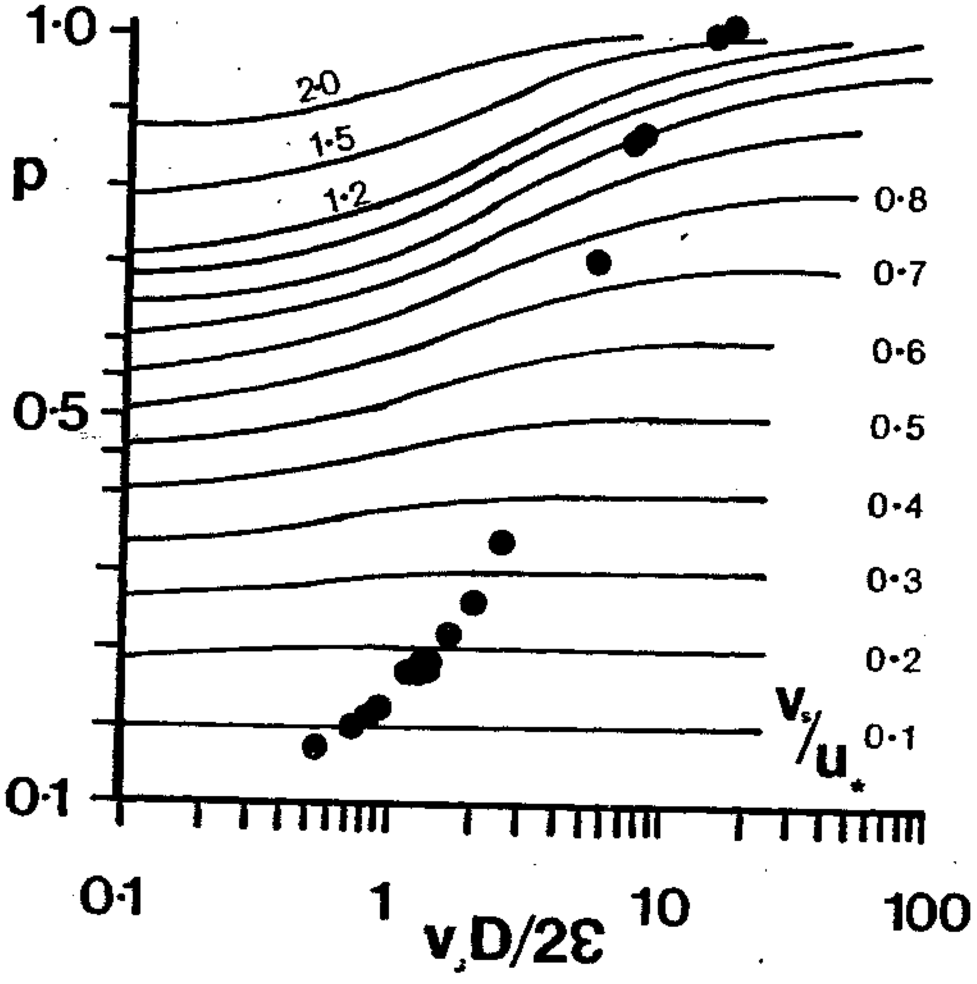

Fig. 10. Experimental data for runs 1-16 extracted from Table 1 plotted on Camp's (1943) graph relating the degree of sedimentation (p) to v_s/u_* and $v_sD/2\epsilon$. For small values of v_s/U_* turbulence (ϵ) has a negligible effect in reducing deposition. It is at these values that most of the experimental runs were conducted. However the possibility that turbulence promoted deposition by introducing particles into the gravel void space should not be neglected.