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Observation of the size, settling velocity and effective density of flocs, and their fractal dimensions

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Abstract

In situ instruments, particularly the instrument INSSEV (in situ settling velocity) have given new information on the sizes, settling velocities and effective densities of individual flocs within the spectrum of distribution. The low-density macroflocs (diameter $>\sim 150$ μm) contain a mixture of organic and inorganic constituents that become separated when the flocs are disrupted to form microflocs. Representation of the floc characteristics in terms of fractals reveals a range of fractal dimensions representing the distributions varying between 1 and 3, instead of the ideal value of 2. Measurements in estuarine turbidity maxima and on intertidal mudflats show that the fractal dimension is less than 2 in situations where turbulent shearing causes disruption of the flocs. At the same time increasing suspended sediment concentration tends to increase the fractal dimension. Measurements of size using an in situ Malvern sizer show that the floc size distribution is also affected by both turbulent energy dissipation and by concentration. Complementary laboratory studies suggest that, at a constant concentration, flocculation is enhanced by low shear, but that disruption occurs at higher shear. These experiments confirm the relationship between fractal dimension, shear stress and concentration.

Keywords: flocculation; settling velocity; effective density; turbulence

1. Introduction

Suspensions of fine sediment containing clay minerals tend to flocculate because of electrostatic charges and organic complexes on the particle surfaces, and because of the presence of mucal polysaccharides, produced by bacteria. In estuaries the suspended sediment population contains a spectrum of sizes. Individual particles are generally too small for in situ measurement, being dominated by clay size material. Microflocs, defined as being less than 150 μm in diameter, comprise those flocs which are sufficiently strong to withstand the maximum disruption, but which will aggregate to form larger macroflocs. The macroflocs are large and weak enough to be broken down into the constituent microflocs, and reform from them. Collision of the particles and microflocs is promoted by Brownian motion, turbulence and differential settling, though only a fraction of the collisions produce flocculation. The likelihood of collision is increased during periods of high concentration of particles. Flocculation may be enhanced at low shears, but at higher intensities turbulence will cause disruption of the flocs by stretching, or by collisions (Burban et al., 1989). Thereby, at low concentrations a small amount of shear enhances

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flocculation, whereas a higher shear causes a reduction in size and settling velocity (Van Leussen, 1988). An alternative explanation of the increase of floc size with shear at low shears has been discussed by Winterwerp (1998), who suggests that the increasing floc size is a result of the long time required for flocculation to an equilibrium, so that in laboratory conditions the flocs do not have time to grow to their optimum size as collisions are too infrequent. Biological factors mediate all of these processes, and they are not well controlled or assessed in laboratory experiments.

The smaller flocs are on average of higher density than the larger ones, and are stronger, as there are more particle contacts when more densely packed. There is also evidence from laboratory experiments that the strength of the particle bonds within the flocs decreases with increasing floc size (Al Ani et al., 1991). The larger flocs, despite being consistently of lower density, settle faster and contain most of the vertical settling flux of solids (Fennessy et al., 1997).

The simplest model of floc formation is derived from fractal theory. This depends on the successive aggregation of self-similar flocs producing a structure that is more or less independent of the scale considered. This is expressed as a fractal relationship between the flocs (Krone, 1978; Kranenburg, 1994).

There are various ways in which the fractal dimension can be calculated. Chen and Eisma (1995) used the relationship between the observed area A and the perimeter of the flocs p; where $A \sim p^D$, D being the fractal dimension. Kranenburg (1994) developed a relationship for effective density:

$$\Delta\rho_1 \sim \Delta\rho_2 \left(\frac{d_1}{d_2}\right)^{3-D} \tag{1}$$

where d is the floc diameter, and $\Delta\rho$ the effective density. He also derived an equation for the fractal relationship and floc yield strength, as well as bed properties.

Winterwerp (1998) developed a relation for settling velocity, showing essentially that:

$$W_s \sim d^{D-1} \tag{2}$$

where W_s is the settling velocity.

Consequently, flocs with a constant effective (or excess) density throughout the size range would have a fractal dimension of 3, and flocs with a constant settling velocity a fractal dimension of unity. Studies have been mainly carried out in the laboratory, and these have shown a fractal dimension of about 1.4 for very fragile flocs, and about 2.2 for strong estuarine flocs, and an average of about 2.0 (Kranenburg, 1994). From in situ photographic measurements of flocs in suspension Chen and Eisma (1995) concluded that those aggregated by differential settling were most likely to be characterised by low fractal dimensions. Conversely, high fractal dimensions were likely to have been formed, or restructured, by fluid shear. This range indicates that the state of packing of the particles varies considerably, and that the influence of non-uniform composition may be important.

Measurement of the size of flocs in the laboratory has been carried out in a variety of idealised situations to consider the effects of varying salinity and concentration (e.g. Owen, 1970), and of shear and concentration (e.g. Burban et al., 1989). However, there have always been questions about their relevance to the field because of differences in the natural organic fraction in laboratory prepared suspensions, and of disruption on sampling field suspensions for laboratory analysis. The ideal is for direct measurement of size and settling velocity in the field.

For about two decades the only method for field measurement of floc size and settling velocity was the Owen Tube (Owen, 1971). The use of this, and its derivatives, has recently been reviewed by Eisma et al. (1997). The basic principle is the measurement of the mass of particles settling with time in a water sample placed vertically. The mass is then related by Stokes' Law to the settling velocity and to the size. However, there are still discrepancies between systems when in use because of differences in sampling protocols and variable disruption (Dyer et al., 1996).

Recently a number of techniques have been developed for the direct analysis of floc size in situ (Eisma et al., 1996), and using miniature underwater video, for measurement of the settling velocity (Van Leussen and Cornelisse, 1993; Fennessy et al., 1994a). With direct measurement of both size and settling velocity, the effective density can be calculated via Stokes' Law. The effective density, also known as the excess density, or differential density, is the difference between the floc density and water density. Stokes' Law is valid up to a settling Reynolds Number of about unity, and this appears to be realistic for all but the largest estuarine flocs.

The advantage of the direct measuring systems is that the properties of individual flocs can be calculated (Fennessy et al., 1997), and provided a controlled volume is sampled, representative size, settling velocity and effective density spectra can be established. The INSSEV system described by Fennessy et al. (1994a) samples a fixed volume of the suspension, and it has provided the first in situ measurements of size, settling velocity and effective density. The purpose of this paper is twofold: (1) to present the fractal dimension of the natural floc population in different conditions; and (2) to consider the effect of turbulent shear on the floc characteristics using comparable video techniques.

2. The INSSEV system

The details of the operation of the system are given in Fennessy et al. (1994a). The instrument traps a sample of the flowing suspension in a stilling chamber by closure of a pair of flaps at a rate which is regulated to minimise the extra shear produced, and the consequent disruption of the flocs. A sliding trapdoor in the base of the chamber is then opened for a pre-set time to allow an acceptable number of flocs to settle into the clear water of a settling column. The filtered water in the column is of a known salinity, marginally higher than the ambient, to reduce secondary currents set up by opening of the sliding door, and by the settling flocs. The settling flocs are silhouetted against a light background, so that their outline and some elements of their structure can be observed by a miniature video camera. This records the settling, and the size and settling velocity of each individual floc are determined by direct measurement from the screen. The maximum dimension normal to the direction of settling is taken as the floc size, and the smallest detectable flocs are about 20 μm. The smallest settling velocity that can be determined is set by the duration of recording, normally 30 min, which is equivalent to a settling velocity of about 0.06 mm s^{-1}. The largest individual sizes observed are typically 600 to 800 μm. The effective density of each floc is calculated from Stokes' Law, and the applicability of this checked by the settling Reynolds Number. The representativity of the sampling can be checked by comparing the ambient concentration with that calculated from the combined floc masses. With the exception of highly energetic environments, good agreement is normally obtained.

The observed flocs show a wide range of shapes which do not appear to have been disrupted by sampling, and which compare with in situ photography (Eisma, 1986). There is a distinction between microflocs $<\sim$125 μm, which appear for the most part to be compact flocs which are robust and difficult to break down, and the larger macroflocs. The smaller flocs are almost spherical, with width to length ratios normally in the range 0.8 to 1.5. Within this range Stokes' Law can be considered to apply (Gibbs, 1985). The larger flocs often show more complicated outlines, and have variations in transparency that suggest a fractal type composition made up of smaller denser microflocs. The macroflocs sometimes have 'stringers' (Eisma, 1986), presumed to be composed of biological threads, which have microflocs attached. Observations indicate that estuarine flocs do not reach the large (cm) length scales of marine snow, probably because of the higher organic content of the marine snow, and the lower turbulence in the deep ocean. Nevertheless, the characteristics of the largest flocs are of particular interest since they dominate the mass in suspension, and the settling flux towards the bed.

3. Results

3.1. Estuarine turbidity maximum

Within the estuarine turbidity maximum there are regular variations during the tide of suspended sediment concentration and turbulent shear. The distribution of size and settling velocity of a typical estuarine sample taken in the Elbe Estuary (Fennessy and Dyer, 1996) is shown in Fig. 1 (top). Each cross gives the size and settling velocity of a floc, the diagonal lines show contours of effective density calculated from Stokes' Law. It is apparent that there are flocs with the same settling velocity, but with a

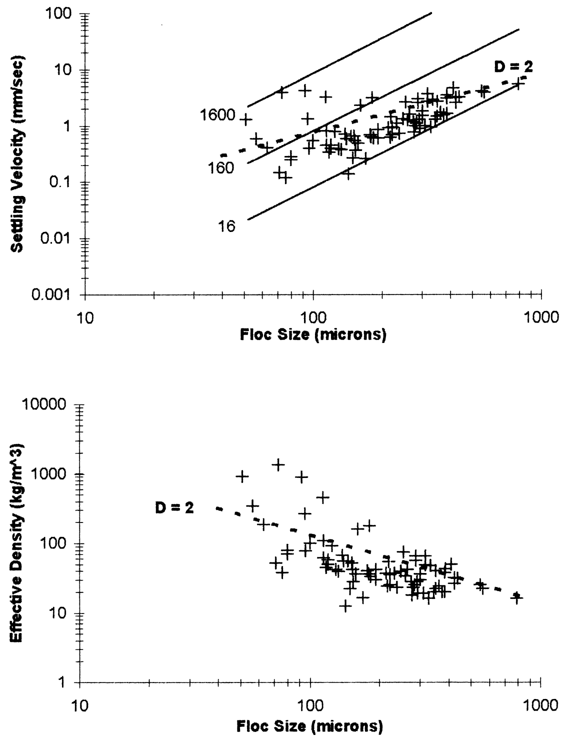

Fig. 1. Relationships between floc sizes and (top graph) settling velocities (mm s^{-1}) and (bottom graph) effective densities (kg m^{-3}) of individual flocs in an INSSEV sample from the Elbe Estuary. Diagonal full lines show the effective density (kg m^{-3}). The dashed line shows a fractal dimension $D = 2.0$.

wide range of sizes and densities, as well as flocs of the same size with differing densities and settling velocities. However, it is apparent that in the range less than about 180 μm some of the microfloc densities approach that of quartz (1650 kg m^{-3}), and these must be mainly inorganic. In contrast there are flocs of much lower density that could be composed of aggregations of much smaller particles, or with high organic contents. Measurements in the Elbe Estuary have shown that the slower-settling fraction has a higher organic content than the faster-settling fraction (Dyer et al., 1996). The fractal dimension calculated from Eq. 2 that is most representative for the distribution weighted by floc number or floc volume distribution is $D \sim 2.5$, though $D = 2$ may be more representative for the distribution weighted by floc mass. The effective density of the flocs as a function of size in the same sample is shown in Fig. 1 (bottom), again giving via Eq. 1, a best value of $D \sim 2.5$. If these fractal dimensions are extrapolated to smaller sizes and an effective density of 1650 kg m^{-3}, it appears that the primary particle size could be 0.7 to 1.0 μm with a settling velocity of the order 0.001 mm s^{-1}.

It is apparent from sequential sampling that in situations where the macroflocs are being broken down, a wide density range of microflocs is produced, the higher-density microflocs being of a different composition than the lower-density ones of the same size. Thus the macroflocs appear to be composed of two different components.

Measurements in the Tamar Estuary have been reported by Fennessy et al. (1994b). Fig. 2 (top) shows a sample taken at about high water when the current velocities were low, and the turbidity maximum was landwards of the sampling position. The majority of the flocs were of low and almost constant effec-

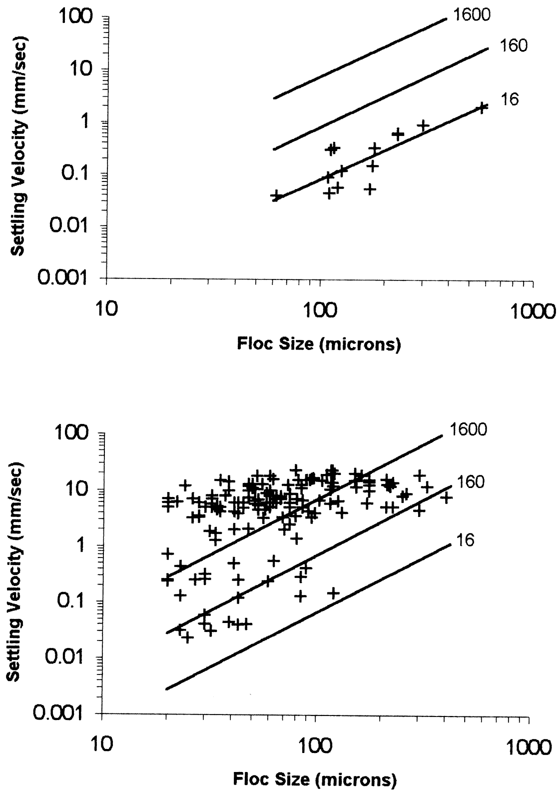

Fig. 2. Relationships between size and settling velocities of individual flocs from the Tamar Estuary. Top graph: at HW −0.22 h. Bottom graph: at HW +2.28 h.

tive density of about 16 kg m^{-3} throughout the size range, and consequently their mean fractal number is about 3. Although the largest flocs were 200 to 550 μm in size, their settling velocities were only about 1 mm s^{-1}. About 2.5 h later the surface ebb current had a velocity of 0.5 m s^{-1}. However, at the level of the INSSEV instrument (0.42 m above the bed), within the saline wedge, the water was almost stationary, but with a high-velocity shear at the interface just above. At that time the floc characteristics were different (Fig. 2, bottom), with an apparent boundary between macro- and microflocs at about 150 μm. Both macroflocs and high-density microflocs settled at about 3 to 25 mm s^{-1}. For a constant settling velocity the flocs would be represented by a mean fractal dimension of unity. In this case $D = 1.3$. Many of the high-density microflocs were observed to be crystals of hornblende and tourmaline, settling end-on, and a spherical settling approximation would not give a realistic density. In the microfloc population, however, there were also slow-settling low-density flocs. It appeared from acoustic sensors operating at the same time (A. Downing and C.E. Vincent, pers. commun., 1994) that the flocs $<\sim 150$ μm were being formed by break-up of a proportion of the macroflocs as they settled through the intense velocity shear at the stratification on the surface of the salt wedge. Under other conditions the heavy minerals were likely to be a significant constituent of the macroflocs. The salt wedge was being eroded by the shear at about 10 mm s^{-1} and flocs with a lower settling velocity may have been largely prevented from penetrating to the level of the INSSEV system by the entrainment occurring at the salt wedge interface. Consequently hydrodynamic sorting of the flocs was taking place and affecting the size distribution.

McCabe (1991) and McCabe et al. (1993) have also worked at the same location in the Tamar Estuary, under very comparable shear conditions and tidal state, with an in situ Malvern laser sizer (Bale and Morris, 1987). Over the high-water period the majority of the floc mass was in the size range which would have been below the detection limit of INSSEV (i.e. <20 μm). During the time of the salt wedge erosion the median floc size by mass was >160 μm. These results are in good qualitative agreement with those obtained with INSSEV.

At the same time as the laser sizer measurements, electromagnetic flowmeters were used to measure the characteristics of the turbulent velocities. The turbulent energy dissipation rate was calculated by spectral analysis of the turbulent fluctuations (McCabe, 1991). The dissipation rate ε can be related to the Kolmogorov turbulent micro-scale by the formula:

$$\eta_0 = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \tag{3}$$

where ν is the molecular viscosity. Also the effect of turbulence can be represented (Van Leussen, 1994) by the dissipation parameter G with the dimension s^{-1}

$$G = \left(\frac{\varepsilon}{\nu}\right)^{1/2} \tag{4}$$

Fig. 3 shows the relationship between the turbulent energy dissipation rate, the percentage of flocs by mass in the size band >160 μm, and the mass concentration. At all dissipation rates the percentage of large flocs decreased with increasing concentration, presumably because of the disruption caused by collisions. As the dissipation rate decreased, the turbulent length scales increased and the percentage of large flocs increased, for the same concentration. It appears that at that time the main flocculation activity occurred at concentrations in the range 50 to 400 mg dm^{-3}. At a concentration of about 300

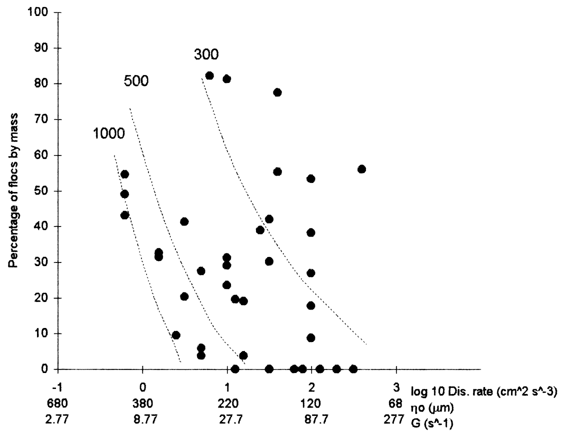

Fig. 3. Percentages of flocs greater than 160 μm at various concentrations (indicated by stippled lines, in mg dm^{-3}), against log. turbulent energy dissipation rate (cm^2 s^{-3}), turbulent microscale (μm), and dissipation parameter (s^{-1}).

mg dm^{-3} more than 40% of the flocs were larger than a Kolmogorov micro-scale of 160 μm, and with increasing dissipation rate and decreasing concentration a greater proportion were smaller than this length. The data can be represented by the formula:

$$\% > 160\,\mu\text{m} = 220 - 1.24G - 0.503C + 0.00418G^2 + 0.000336C^2 \quad (5)$$

with an R^2 value of 86.2%. G is in s^{-1}, and C in mg dm^{-3}. Thus both turbulent shear and concentration appear to affect the percentage by mass of large flocs, but concentration has the larger effect.

3.2. Intertidal mudflats

On intertidal mudflats tidal currents are generally low, and wave-induced shears become important. During calm periods turbulence levels will be low. Several deployments of INSSEV have been carried out on intertidal mudflats, with the instrument installed on the flats when exposed, and measurements taken over the high-water period. During the measurements, mean flows and turbulence, and wave-induced currents were measured close by.

Measurements were obtained for a week of tides on the mudflats at Portishead on the Severn Estuary which encompassed two periods of large waves, as well as calms. A total of 28 samples were taken over 6 tides. There is a high suspended sediment load within the adjacent estuarine waters, and this is advected backwards and forwards across the mudflats, being modified by the local conditions. The hydrodynamic measurements have been reported by Christie et al. (1996). During the periods of wave activity, the floc size and settling velocity distributions had the same general form as in other estuarine measurements, with low-density macroflocs up to about 800 μm in size, and both low- and high-density microflocs below a limit of about 150 μm. The mean fractal dimension of the 28 samples was 1.93 ± 0.43. There are several competing processes that are likely to have been influencing the results, including current velocity, wave-induced shear, suspended sediment concentration and advection from the main channel. Local current velocities were up to 0.25 m s^{-1}, but those in the main estuary channel ranged to 2.0 m s^{-1}. Wave-induced variance in velocities ranged up to 0.031 m^2 s^{-2}. Suspended sediment concentrations reached 1 to 5 g dm^{-3} at the beginning and end of the tidal covering, but decreased to about 0.2 g dm^{-3} at high water. The concentrations increased with the mean currents at times of high wave variance, and the fractal dimensions decreased with increasing mean velocity and decreasing concentration. During calm periods the concentration also increased with increasing mean velocity, but at a much lower rate. The fractal dimensions were about constant at about 2.3, independent of mean velocity and concentration. However, advection of flocs from the adjacent channel may have been important. Detailed analysis of the distribution spectra of size, settling velocity and effective density in relation to these variables is being made.

Similar measurements were obtained on intertidal flats in the Humber and Dollard Estuaries. Four samples obtained on the Skeffling mudflats of the Humber estuary gave a mean fractal dimension of 2.06 ± 0.27. Concentrations reached 0.8 g dm^{-3}, and current velocties were up to 0.45 m s^{-1}. Again lower fractal dimensions occurred at times of high velocity, and during lower concentrations.

In the Dollard Estuary current velocities and concentrations were lower. Fig. 4 shows the floc sizes and settling velocities obtained 0.5 m above the bed about 1.5 h before high water when the water depth was 1.35 m and the concentration was 664 mg dm^{-3}. There are two separate modes in the floc distribution. There is a very tight group of microflocs about 20 to 30 μm in diameter and with mean settling velocity of about 0.08 mm s^{-1}. This group is quite distinct from the macroflocs, which had lower density, a size range of about 80 to 400 μm and mean settling velocity of about 1 mm s^{-1}. The few flocs of intermediate characteristics suggest that only limited aggregation or disaggregation was occurring. This period was one of calm weather, with no significant wave effects, and of currents of less than 15 cm s^{-1}. The suspended matter had total organic matter contents up to 35% and was lifted off the exposed mudflats by the incoming tide. Fig. 4 also shows the effective density versus size calculated for the flocs. It is possible to fit lines with slopes appropriate to fractal dimensions of unity, indicating constant settling velocity, through each of the two modes. Thus it seems likely that the flocs are composed of two different elements with limited flocculation of one with the

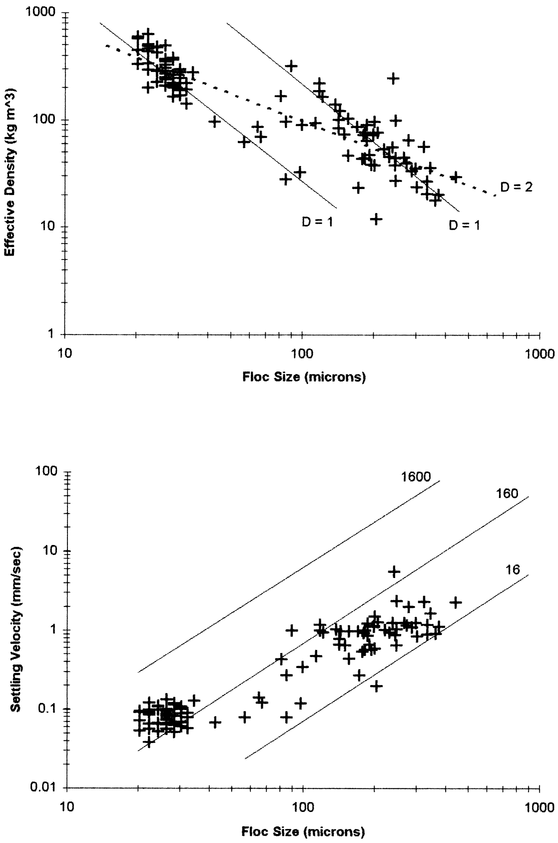

Fig. 4. Relationships between floc size and (top) floc effective density and (bottom) settling velocity for a sample from the Dollard Estuary taken during the early flood tide when the water depth was 1.35 m and the concentration 664 mg dm^{-3}, together with lines illustrating fractal dimension (D in top graph) and effective density (kg m^{-3}, lines in bottom graph).

other. Alternatively, a line for a fractal number of 2 can be drawn through both modes. Other samples taken during the period show similar results. The fractal approach appears to provide an inconclusive representation of the results.

3.3. Laboratory measurements

Laboratory measurements of floc size and settling distributions using the same video camera technique have been carried out by Manning and Dyer (1998) to examine the combined influence of concentration and shear on the floc characteristics. Suspensions of Tamar mud of known concentrations between 80 and 200 mg dm^{-3} were placed in an annular flume and then exposed to turbulent shearing by rotating a ring placed on the water surface, a method that is widely used in determination of cohesive bed erosion. Each suspension was sheared at a high rate for half an hour, and then the shear was reduced and the floc sizes were allowed to equilibrate at the new shear level for a further half an hour. This procedure was used to mimic the variation of natural shearing experienced by flocs in a tidal flow. The floc sizes and settling velocities were then determined by turning off the driving rotation and measuring the vertical component of the settling motion of the flocs at subsequent intervals. The relationship between the floc size of the largest four flocs in each visualisation and the turbulent shear and concentration is shown in Fig. 5. The shape of the curves suggests that the measurements above 0.1 N m^{-2} were all in the equilibrium range where floc aggregation and break-up were in balance (Winterwerp, 1998). The results are qualitatively similar to those of Tsai et al. (1987) and Burban et al. (1989). At low shears the size of the flocs at the lowest concentration was smaller than those at the higher concentrations. Above a shear of about 0.3 N m^{-2} the situation reversed, and the flocs were larger at the lower concentrations than at the higher ones. Additionally, settling velocities were highest for the highest concentrations at low shear, and were highest for the lowest concentrations at high shears. Again there was a crossover point at about 0.25 N m^{-2}. The effective density

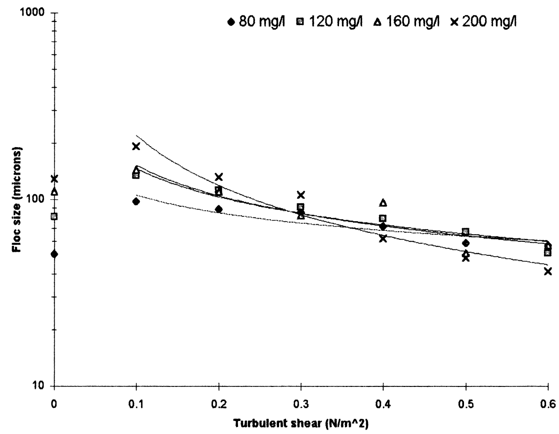

Fig. 5. Floc size for various concentrations (different symbols) against turbulent shear, derived from laboratory flume experiments.

variations were not as clear. Nevertheless, low shear produced low effective densities at high concentrations, but higher densities at low concentrations. The presence of these crossover points is consistent with the hypothesis that low shears at low concentrations enhance flocculation, whereas high shears and high concentrations promote disruption. Considering the maximum four flocs, the mean floc size D was given by:

$$D = 206.19W_s + 0.27G + 0.19C \quad (6)$$

where D is in μm, settling velocity W_s is mm s^{-1}, concentration C is mg dm^{-3}, and shear G (Eq. 4) is s^{-1}. The mean settling velocity was:

$$W_s = 0.261 - 0.00131G - 0.000924C + 0.00485D \quad (7)$$

However, these results remain to be compared with in situ measurements before they can confidently be used in predictive models.

The fractal dimensions have been calculated for each of the tests using Eq. 2, and are shown in Fig. 6. The average is 2.28 and the values range between 2.16 and 2.5. There is an increase in fractal dimension with shear stress, contrary to the field results, but a stronger increase with concentration at each stress, in agreement with the field results. However, the values are all >2 and are therefore considerably higher than many of the field results. This may be a reflection of the history of the flocs in the two situations. In the laboratory experiments the flocs were generated by aggregation under shear at shear stresses less than the maximum. In the field many of the flocs may not be in equilibrium with the ambient shear stresses and concentrations, and may still retain characteristics of the periods during the tide of low shear when differential settling was significant. Differential settling would be likely to produce less compact flocs.

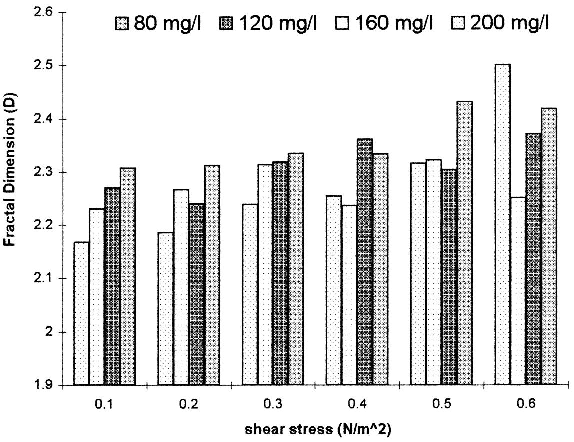

Fig. 6. Fractal dimension of floc distributions derived from flume experiments against shear stress (horizontal axis) and concentration (different shadings).

4. Conclusions

Floc size, settling velocity and effective density are affected by turbulent shear and suspended sediment concentration. Low concentrations and low shear appear to promote flocculation, whereas high concentration and high shear promote floc breakdown. The effect of concentration appears to be greater than that of shear. This is a confirmation in the field of results of published laboratory measurements.

Macroflocs break down to microflocs which are combinations of two components: one of high effective density, with high settling velocities, the other with lower densities and settling velocities. The low settling velocity microflocs are generally of higher organic content.

Representation of floc characteristics in terms of fractal dimensions gives results varying widely between 1.0 and 2.8. The higher values are associated with low mean velocities and high concentrations during periods of high wave-induced variance. When wave variance is small the fractal dimension reduces slightly at high mean velocities. Thus floc break-up tends to produce distributions with a more even settling velocity through the size range, i.e. a low fractal dimension. High suspended sediment concentrations lead to high fractal dimensions. These trends may tend to counteract each other. These results are supported by laboratory experiments on natural material, which also indicate that the floc history may be a significant factor. In view of these factors, fractal dimensions may only provide a generalised representation of floc characteristics.

Hydrodynamic sorting, in terms of the break-up of macroflocs in a shearing current, and differential advection of slower-settling flocs, is important in modifying the floc distribution.

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