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The use of optics for the *in situ* determination of flocculated mud characteristics

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Abstract
Morphodynamical predictive simulations of estuarine sediments require *in situ* mud floc data for model verification and calibration purposes. The limiting factor in many previous studies were the devices used for sampling, as flocs are very fragile. Instruments such as Niskin bottles, pipettes or the Owen tube are all very disruptive. This could be the reason that previous studies tended to show a much lower floc size range than is now known to exist. The presence of large estuarine macroflocs was observed by *in situ* photography and *in situ* laser particle size measurements, but these techniques still provided no indication of settling velocity or effective density, which are variable amongst floc populations.

In contrast, the video camera based instrument developed at the University of Plymouth, INSSEV (*in situ* settling velocity), measures floc size, settling velocity and density all simultaneously. This operates whereby flocs are trapped in an upper decelerator chamber and then allowed to fall into a settling column located underneath. A Puffin model UTC 341 high resolution monochrome Pasecon tube video camera, fitted with a $f/4$ macro lens and integral low heat LED illumination, views the flocs through a window in the side of the settling column, and hence the floc characteristics can be obtained. The camera utilizes a back-illumination system (i.e. a silhouetting technique) in which particles appear dark on a light background; this reduces image smearing and makes the floc structure more clearly visible.

A selection of INSSEV flocs are presented from deployments conducted in the upper Tamar Estuary during 1998. Low concentration neap tides revealed that optimum ambient flocculation conditions produced macroflocs approaching 0.75 mm in length and settling velocities of 4–5 mm s^{-1}. These macroflocs typically resembled ‘comets’ or ‘long stringers’. However, these stringer configuration macroflocs were in the minority and on average only represented 30–40% of the total suspended matter concentration.

Throughout the more turbulent and higher concentration spring tides, INSSEV was found to be very effective at measuring floc characteristics, even within concentrated benthic suspension layers of 8 g l^{-1}. Ideal flocculation conditions (in terms of floc size) transformed 95% of the ambient suspended particulate matter concentration present into large, fast settling, more rounded cluster-type macroflocs with settling velocities of 8–15 mm s^{-1} and effective densities under 50 kg m^{-3}. A number of the smaller macroflocs had their settling characteristics significantly improved by becoming interlinked with organic matter to form stringers with a string-of-pearls configuration. Although stringers were seen to occur during both neap and spring tides, the former ambient conditions tended to produce stringers which were only a third of the size of those typically observed at springs, and thus the neap tide stringers had comparatively lower settling velocities.

Keywords: INSSEV instrument, flocculation, floc size, settling velocity, effective density, turbulent shear stress, suspended particulate matter, Tamar estuary, turbidity maximum

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The ability to predict the distribution and settling rate of suspended particles in both time and space within an estuarine location is highly desirable, especially from the perspective of mathematical simulation models which are attempting to predict long term sediment accumulation and morphological changes. However, this is complicated by the flocculation potential of the muddy sediments. Flocculation is a process whereby the microscopic mud particles coagulate to form aggregates, which are larger but considerably less dense than their constituent components. These aggregates are known collectively as flocs. The size, settling velocity and density of flocs are recognized as important characteristics [1], as they are each functions of suspended particulate matter (SPM) concentration, turbulent shear stress (TSS), biological matter content and salinity [2].

Although numerous studies on flocculation have been conducted within controlled laboratory environments, it is now generally recognized that the acquisition of *in situ* floc data is a major requirement for both model calibration and to gain a greater understanding of floc formation. With this aim, good quality floc settling velocity data is a prime requirement. The limiting factor in many previous studies was the sampling devices used, as flocs are very fragile entities. Instruments such as Niskin bottles [3], pipettes or the Owen tube [4] are all very disruptive. This could be the reason that previous studies tended to show a much lower floc size range than is now known to exist. The presence of large estuarine macroflocs has been observed by *in situ* photography [5, 6] and *in situ* laser particle size measurements [7, 8], but these techniques still provided no indication of settling velocity or effective density, which are both extremely variable within floc populations.

However, the development of the video camera based floc sampling instrument known as INSSEV (*in situ* settling velocity) has provided a means by which floc characteristics can be sampled successfully *in situ*. It is therefore the aim of this paper to initially provide an overview of the present version of the INSSEV instrument. This will be followed by a selection of INSSEV floc data and images obtained from a recent series of deployments in the Tamar Estuary.

2. Instrumentation

The INSSEV instrument was originally developed ten years ago at the Institute of Marine Studies, University of Plymouth (UOP) by Fennessy *et al* [9], who provides a very detailed report on the theoretical design of the prototype INSSEV instrument. This section of the paper has drawn together the key operational points for the current version 3.1 of the INSSEV instrument, and this illustrates how the high quality images of the fragile estuarine flocs presented in this paper were obtained optically.

INSSEV has the distinct advantage of permitting the simultaneous *in situ* measurement of individual floc size, settling velocity and effective density. The sampling apparatus is a two-chamber device (see figure 1), with an integral underwater video camera which views the flocs as they settle within a lower settling chamber. The apparatus requires physical stability in order to both capture a floc sample of good integrity and to allow the camera to view the flocs precisely. Thus, to prevent any vertical and horizontal motion during a sampling event, it is secured to a heavy bed frame which sits on the estuary bed. This restricts the INSSEV system to making floc measurements within an Eulerian reference frame close to the estuary bed.

To initiate a floc sampling cycle, the upper decelerator chamber is allowed to flush with both flap doors open and the slide door closed. The flap doors are then closed slowly to isolate ∼3 l of estuary water in the decelerator chamber. The flaps are programmed to close at a rate such that the flow velocity in the chamber is reduced to zero, without inducing additional turbulence and causing aggregate break up. The rate of closure is chosen relative to near-surface current velocity measurements. A period of turbulence decay then commences once the flaps are fully closed. For practical purposes, a nominal period of 20 s was used for all of the INSSEV samples obtained in this study. Although a longer period further reduces the turbulence within the collected water sample, a greater percentage of the flocs will potentially settle onto the floor of the decelerator chamber prior to them entering the settling column.

A slide door in the base of the decelerator chamber is opened to allow some of the flocs present in the decelerator to settle into the 180 mm deep lower settling column. The settling column is pre-filled with filtered water of approximately 4–6 ppt higher salinity, and thus higher density, than the surrounding estuarine water. This is to minimize the potential transfer of turbulence from the decelerator chamber and the formation of secondary circulations. Also this positive density contrast prevents any possible Rayleigh–Taylor instability occurring. Column instability resulting from ambient temperature variations are regarded as low, since the sampling apparatus sits on the estuary bed for long enough to equilibrate. Most floc video systems experience temperature problems arising from heating by the camera illumination. This is minimized with INSSEV by the use of light emitting diode (LED) illumination.

To provide an optimal number of settling flocs in the settling column, the slide door remains open for a duration, T_{sd} (in s), relative to the ambient water concentration (C) in mg l^{-1}, and was estimated by

$$T_{sd} = 1860C^{-0.8}. \tag{1}$$

The group of flocs which were allowed to pass into the settling column were naturally segregated as they fell by the process of differential settling. Therefore, the fastest falling aggregates would be observed first by the integral video camera and these flocs would be recorded at the start of a sample record. Operational control of the decelerator chamber flaps and slide door stepper motors was by a microcomputer housed in the surface vessel. A detailed account of the INSSEV instrument electronic circuitry design is provided by Fennessy [10].

The INSSEV instrument requires a high resolution imaging system to be able to examine the flocs captured by the sampling apparatus. The complete video camera and recording system were constructed and supplied by Custom Camera Designs Ltd of Wells, Somerset, UK. The flocs within the settling column were viewed by a Puffin model UTC 341 high resolution monochrome all-magnetic Pasecon tube

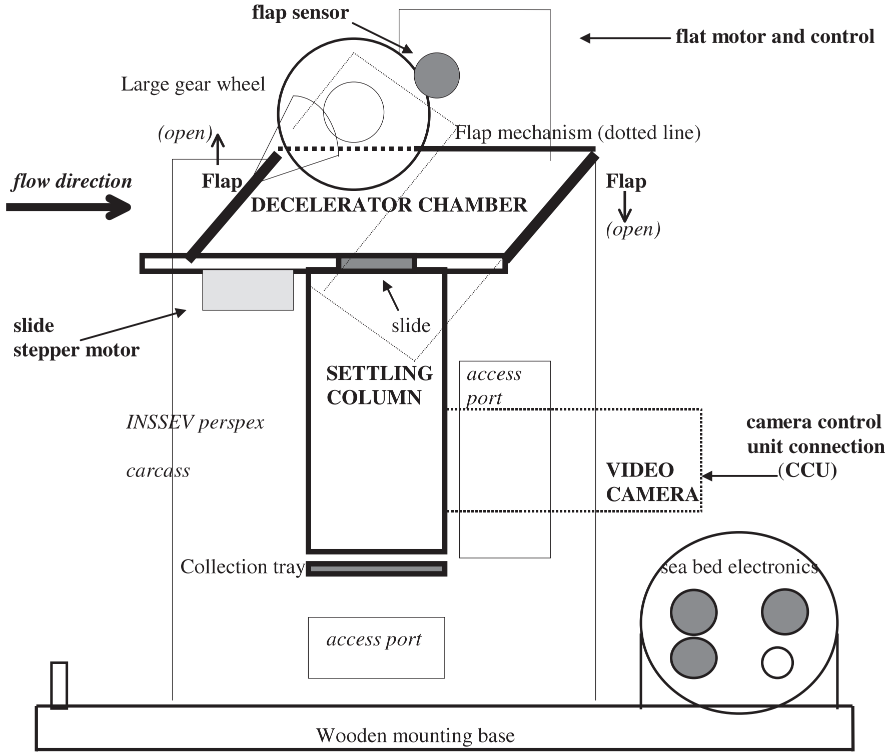

Figure 1. A schematic of the INSSEV sampling unit, version 1.3. The side elevation is shown with flaps closed (from Manning and Fennessy [13]).

video camera, with built-in integral low heat illumination. It had a 35 mm, $f/4$, macro lens fitted behind a 12 mm thick opal glass faceplate with an anti-reflective coating. The complete camera unit was modified for underwater use by containing all the electrical circuitry within an aluminium outer casing, approximately 260 mm in length and 95 mm in diameter. The camera utilizes a back-illumination system (i.e. a silhouetting technique) in which particles appear dark on a light background; this reduces image smearing, tube saturation and makes the floc structure more clearly visible. This back-illumination is provided by an annulus of six high intensity red 130 mW LEDs positioned around the camera lens. The camera's electronic circuitry senses the scene reflectivity and adjusts the voltage to the LEDs accordingly. The camera views through an aperture in the settling column wall at a depth of 110 mm below the slide door. It records all particles in the centre of the column which pass within a 1 mm focal depth of field, 45 mm (focal length) from the camera lens. The total image size is 3.3 mm high and 4.7 mm wide.

The video camera is connected to a CCU350WA electronic camera control unit (CCU) by a 20-core STC type 7-2-20C marine cable which enables real-time analogue video images to be displayed on a monitor in the surface vessel. Floc images are recorded by a Super VHS video cassette recorder which interfaces with the CCU. The CCU provides time referencing information which can be superimposed onto the recorded video images, and so aid in the processing of the raw floc data. The camera and video recorder combination has a practical lower limit of resolution of 20 μm. The INSSEV camera system has also been adapted for the observation of flocs during controlled laboratory experiments [11, 12].

Figure 2. INSSEV surface controls and video recording electronics.

In order to calibrate the video monitor, a scale ruler was placed in front of the camera lens, and both the vertical and horizontal dimensions of the screen were measured. For the auxiliary monitor, 1 mm in real size dimensions produced an on-screen image of 49.36 mm. The alignment of the camera axis to that of the settling chamber was determined by suspending a fine nylon plumbline in front of the camera lens and recording the image. This enabled the relative camera orientation to be established precisely in both vertical and horizontal planes, and the consistency of the image depth of field could also be evaluated. A comprehensive review of INSSEV calibrations and operational procedures can be found in Manning and Fennessy [13].

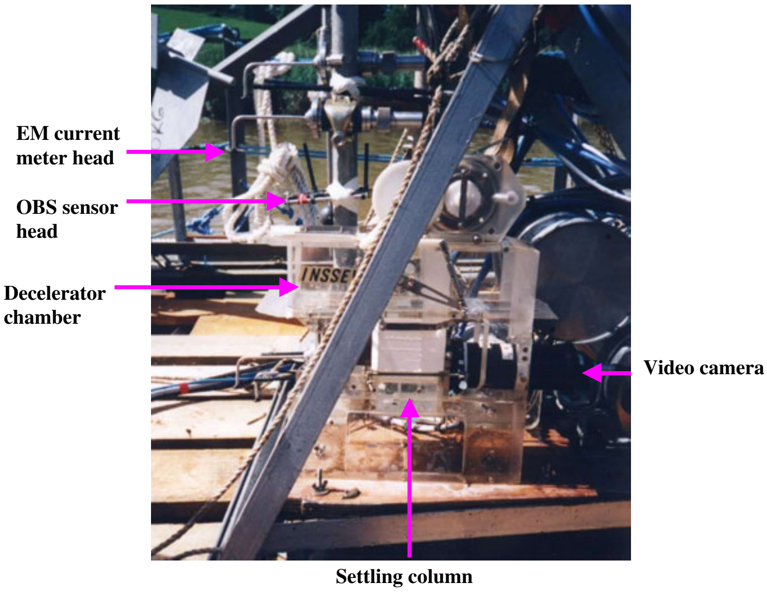

Figure 3. INSSEV mounted on estuarine bed frame together with the POST EMCM and optical backscatter sensors.

3. Methodology

To enable estuarine deployments, the INSSEV sampling unit was mounted on a specially fabricated bed frame. For the Tamar Estuary experiments, the bed frame was lowered to the estuary channel bed from the UOP research pontoon *R.P. AMAP-1* [14]. To prevent floc break-up occurring during sampling, the INSSEV decelerator chamber must always be accurately aligned parallel with the ambient current flow direction; any change in flow direction requires the re-orientation of the bed frame. Therefore, a 1.5 km long straight reach of the upper Tamar Estuary was chosen as the sampling location, as this would minimize lateral variations, particularly those occurring from the flow. A floc sample was taken every 10–30 min (dependent on ambient SPM concentration) at a height of 0.5 m above the channel bed. Complementary gravimetric water samples were also collected. All recording electronics were housed in the surface vessels (see figure 2), where floc samples could be viewed in real time.

To enable direct comparisons of floc properties to be made with the ambient hydrodynamic conditions, simultaneous high frequency measurements of current velocity and turbidity were obtained using the POST (profile of sediment transport) system [15]. This consisted of four two-channel miniaturized electromagnetic current meters (EMCM), eight optical backscatter (OBS) sensors and a pressure transducer to measure the water depth, which all recorded continuously at 18 Hz and were filtered at 5 Hz. The sensors were attached to a vertical pole laterally off-set from the INSSEV sampling unit. EMCM pairs measured the three orthogonal components of the flow at both 25 and 75 cm above the bed. Figure 3 illustrates the Tamar Estuary bed frame configuration.

Floc sizes and settling velocities were both measured directly from the video monitor display (manually), and these were then converted into the actual dimensions determined by the initial video image calibration. The flocs were measured for their dimensions both along the axis in the direction of settling (D_y) and the axis normal to it (D_x), from which a height:width ratio could be determined. This was then translated into a spherically equivalent floc diameter, D:

$$D = (D_x D_y)^{0.5}. \tag{2}$$

A rearranged Stokes' law relationship (equation (3)) was applied to the floc images sampled by INSSEV, which enabled the calculation of individual floc effective density (ρ_e) values:

$$\rho_e = (\rho_f - \rho_w) = \frac{W_s 18\mu}{D^2 g} \tag{3}$$

where W_s is the settling velocity, g is gravity and μ is the dynamic molecular viscosity. The effective density is the difference between the floc bulk density (ρ_f) and the water density (ρ_w). The water density was calculated from measured salinity and water temperature data using the International Equation of State of Sea Water, 1980 [16]. These values were also used to determine dynamic molecular viscosity. Equation (3) is only strictly valid for settling flocs when the Reynolds number (Re) < 0.5–1:

$$Re = \frac{\rho_e W_s D}{\mu}. \tag{4}$$

Authors such as Ten Brinke [17] have suggested the use of the Oseen modification [18], applied to equation (3), to allow for the increased inertia when $Re > 0.5$.

Fennessy *et al* [19] outlines a series of algorithms which allow raw INSSEV floc data sets to be converted into mass settling flux (MSF) rates. Floc data sets are then segregated into sub-groupings of floc size. To illustrate the above-mentioned processing techniques, an INSSEV sample collected on 5 August 1998 during a neap tide deployment run has been used (see figure 4). These computational routines have been applied to the selection of INSSEV results presented in the next section.

4. Results and discussion

Floc data was collected in the upper reaches of the mesotidal Tamar Estuary (SW England) from a mid-channel location,

SIZE BAND:	1	2	3	4	5	6	7	8	9	10	11	12
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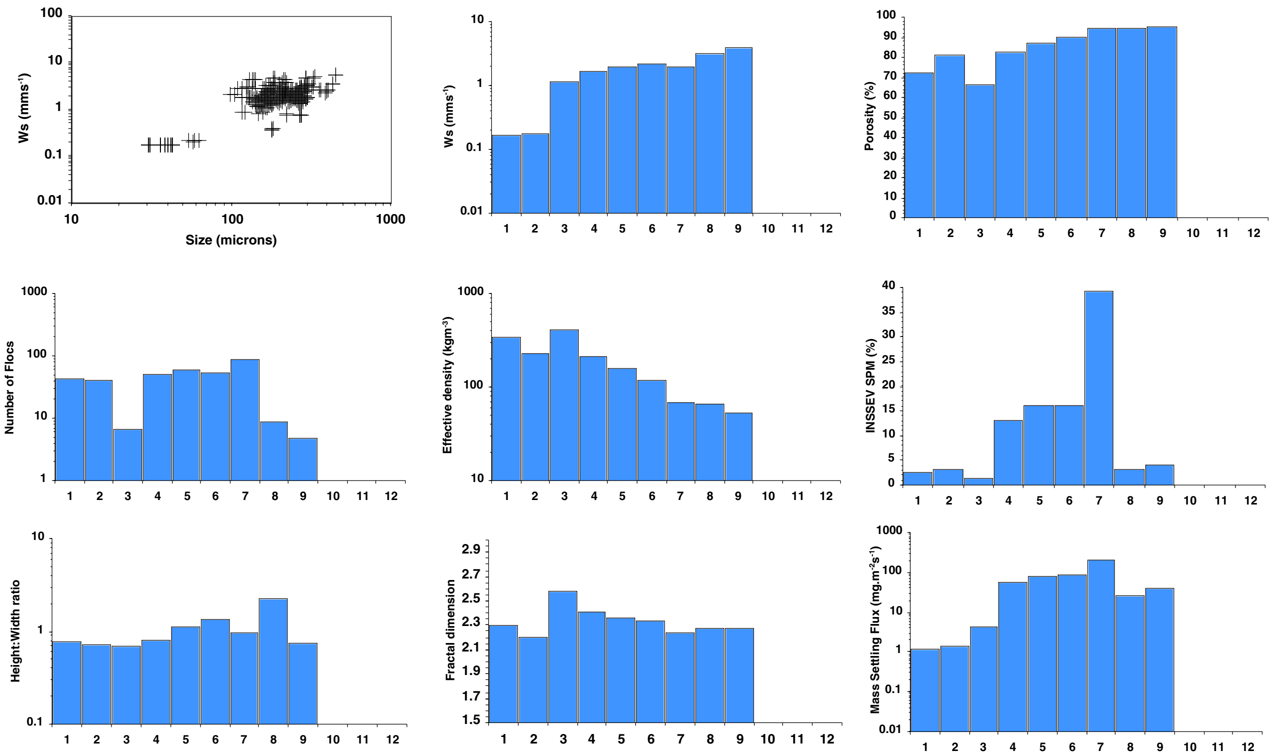

Figure 4. An example of a processed INSSEV data set. This INSSEV floc sample was collected on 5 August 1998 during a neap tide deployment run from a mid-channel station, near Calstock, on the Tamar Estuary.

near Calstock Boat Yard. This placed INSSEV directly in the passage of the turbidity maximum (TM) [20, 21]. INSSEV measurements were made during June, August and September 1998, where both spring and neap tidal conditions were experienced. The data acquisition was conducted on a sub-tidal temporal scale which permitted the direct examination of specific events. These deployments were part of the EC MAST III COSINUS project [22]. Prior to this structured series of Tamar Estuary deployments, the INSSEV instrument had only been previously deployed on a trial basis in the Tamar Estuary during low turbulent conditions and when the ambient SPM concentration was at a very low level (predominantly < 60 mg l^{-1}) [9].

It must be noted that the original monochromatic INSSEV images were recorded on analogue S-VHS video cassette tape and the floc images presented were obtained by digitization via a PC video image capture card. This produced a file 1216 kB in size (for a complete screen image) in an uncompressed Windows bitmap (.BMP) file format, with a total screen resolution of 720×576 pixels. This digitization process, together with the pausing action of the moving floc images, has resulted in a partial 'smearing' and 'softening' of the images printed in this paper. Thus original INSSEV video recordings have an even greater clarity and can display much finer floc detailing than those illustrated in this paper.

In line with previously published examinations of estuarine flocs, this paper utilizes the general floc size descriptive terms of macrofloc and microfloc. Manning [2] classifies macroflocs as those aggregates which exceed a spherically equivalent diameter of 160 μm, whilst the microflocs $D < 160$ μm.

4.1. Neap tides

During the neap tide experimental runs conducted in the upper Tamar Estuary, average river flow conditions were experienced (i.e. an annual mean river flow rate of $\sim$20 m^3 s^{-1}), which typically produced maximum surface current velocities of 0.55 m s^{-1} and these could entrain up to 700 mg l^{-1} of solids into suspension 0.3 m above the bed. A complete time series of the master variables at the INSSEV nominal sampling height of 0.5 m above the bed are summarized in figure 5. It must be noted that all velocity measurements are regarded as a positive velocity relative to the instrumentation rig, which is reoriented if the current direction changes (refer to section 3), and therefore local low water marks are indicated on the appropriate master variable diagrams.

Floc sample 05-9 was obtained at 13:25 h on 5 August 1998 during the early part of the flood, where the TSS had attained a peak shear stress of 0.55 N m^{-2} at 0.5 m, and the SPM was 262 mg l^{-1}. These conditions had encouraged flocs to form in the 120–320 μm size range (spherical equivalent size). These flocs accounted for 85% of the dry floc mass, with 40% of the total mass in the 240–320 μm size range.

Figure 6 shows the fastest settling flocs observed 45 s into the INSSEV sample 05-9 recording were primarily near-spherical, single-cluster, macroflocs 500 μm in diameter and falling at a speed of 6 mm s^{-1}. As only 3.8% of the total population attained a floc size of up to 430 μm, it could be

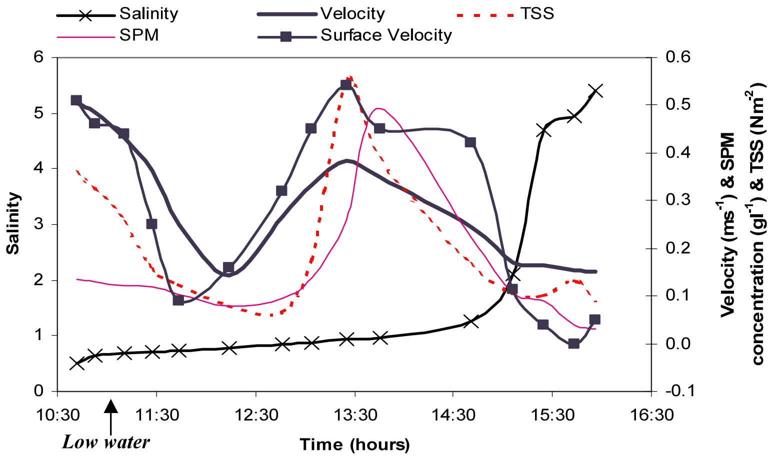

Figure 5. Time series of variations in salinity, flow velocity, SPM concentration and TSS for the neap tide on 5 August 1998. All observations were made 0.5 m above the bed (with the exception of the surface velocity), from a mid-channel station, near Calstock on the upper Tamar Estuary (SW England).

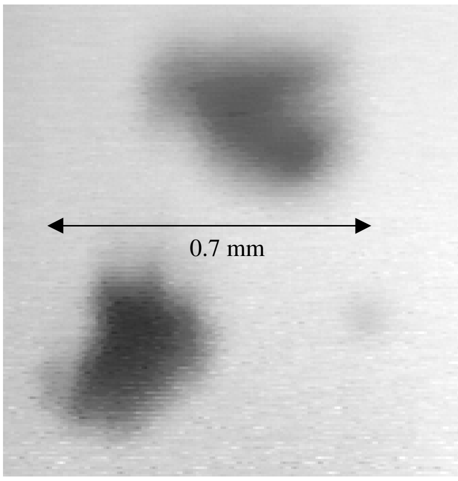

Figure 6. Two clustered macroflocs (sample 05-9, 45 s into record).

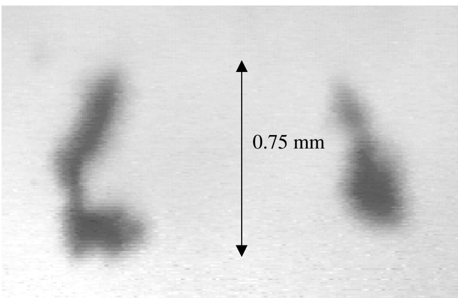

Figure 7. A moderately long stringer composed of a single macrofloc with a trailing organic tail (left) and a shorter 'comet-shaped' macrofloc (right) (sample 05-9, 82 s into record).

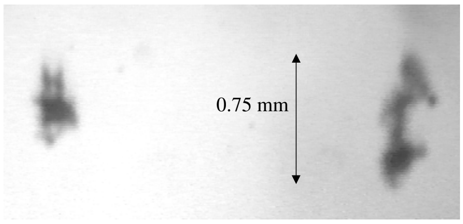

Figure 8. A loosely structured ragged macrofloc (left) and a moderately long stringer (right) (sample 05-9, 95.5 s into record).

assumed that the high turbulence shear stress had imposed a limit on the maximum floc size. A further 37 s into the record, figure 7 illustrates that the fast settling macroflocs encountered during this period were either of 'stringer' or 'comet-like' classification. The former, possessing Dy dimensions of $\sim$750 μm, were composed of a single macrofloc with a trailing organic tail, whilst the later comprised a larger rounded macrofloc nucleus with a short stumpy tail; their overall Dy length was approximately 500 μm. These macroflocs had settling velocities (W_s) of $\sim$4–5 mm s^{-1}, and fell without spinning or twisting. Again, figure 8 demonstrates the raggedness of the flocs encountered 95.5 s into the recording. This was most probably a consequence of the highly turbulent water column preventing the macroflocs from reaching their ultimate growth potential. These particular flocs were formed by the coagulation of a multitude of microflocs: however, as the resultant macrofloc becomes larger, so the aggregate becomes more susceptible to break up by the imposed turbulence. Their ragged appearance is a consequence of the turbulent shear randomly stripping poorly bonded microflocs from the macrofloc surface.

After a recording elapsed time of 138 s, the stringers of sample 05-9 were still seen to be 650 μm in length, but their W_s had fallen to $\sim$2 mm s^{-1}. Figure 9 shows that these stringers were a direct shape reversal of those observed earlier in the record. They now had a linked microfloc chain preceding a trailing upper small macrofloc core. In their entirety they resemble a 'seahorse'. Throughout a typical neap tidal cycle, the mean organic content of the SPM 0.5 m above the bed ranged between 14.5–28%, and these ambient conditions were reflected in the predominantly organic nature of the neap tide macroflocs.

To a degree, flocculation can be regarded as a hierarchical process. This has been reported extensively throughout the literature, primarily by Krone [23, 24], who suggested that flocs were constructed in a progressive order. Primary particles

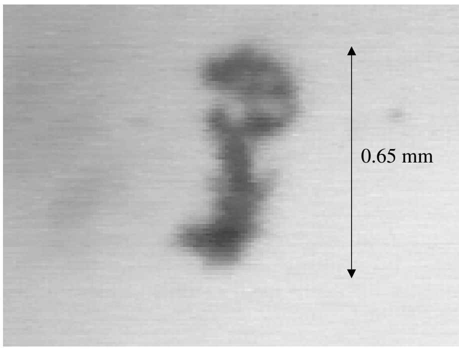

Figure 9. A small neap tide stringer (sample 05-9, 138 s into record).

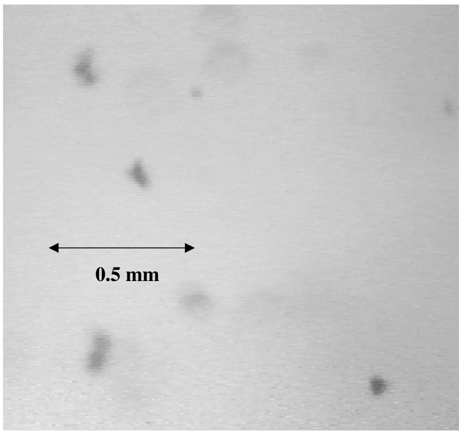

Figure 10. A selection of small slow settling microflocs, some of which are probably the result of macrofloc fracturing during a turbulent event which exceeded the original macrofloc structural integrity threshold (sample 05-8, 464 s into record).

glued together form zero-order flocs; these then coagulate to transform into first-order flocs, etc. This is also the basis of the present fractal modelling approach towards floc formation which is advocated by Winterwerp [25] and has been examined by Dyer and Manning [26]. The basic floc building blocks are generally regarded as microflocs which are less than 160 μm in size [2]. A selection of slow settling microflocs observed towards the end of the INSSEV sample 05-8 record are shown in figure 10. Microflocs are formed by the combination of a high frequency of orthokinetic interparticular contacts (which occur predominantly during very turbulent events), in tandem with the presence of strong biogenic glues on the particle surfaces. Hence, these microflocs are much denser than the more porous macroflocs; the flocs illustrated in figure 10 demonstrating effective densities in the region of 400–800 kg m^{-3}. In contrast, the macroflocs shown earlier in figures 6 and 7 had $\rho_e < 90$ kg m^{-3}. The reason the flocs in figure 10 were present as individual microflocs (i.e. not an integral component of a larger macrofloc) was most probably the result of a macrofloc fracturing during a naturally occurring estuarine turbulent event (prior to the INSSEV sampling) which exceeded the original macrofloc structural bonding strength. Whereas the destructive sampling nature of instruments such as Owen tubes means that, no matter what the composition of an ambient floc population, microflocs such as those displayed in figure 10 are found to be the most commonly sampled aggregates, i.e. deflocculation occurring due to artificially induced turbulence created by the sampling process or apparatus.

4.2. Spring tides

INSSEV samples collected on the spring tide of 24 June 1998 will primarily be used to illustrate how the more dynamic estuarine water column associated with the increased tidal range of spring conditions produces a significantly higher range in turbidity and a more turbulent water column than observed during the more sedate neap conditions, and thus an even greater variety in floc characteristics. The master variables (at the INSSEV sampling height) for the spring tide of 24 June 1998, which covered the end of the ebb through the low water period and on to the middle of the flood, are presented in figure 11. Peak surface current velocities were virtually double those recorded during the August neap tides and SPM was also an order of magnitude higher, particularly during the afternoon flood where a concentrated benthic suspension (CBS) layer developed in the near-bed region. The particularly low near-bed current velocities and turbulence shear stresses observed during the spring tide flood were a result of turbulence damping created by the CBS layer which developed between 15:30–17:00 h. The CBS layer was nominally 0.6 m high (i.e. the distance between the estuary bed and the lutocline) and it displayed a mean concentration of $\sim$5 g l^{-1}. CBS layer dynamics have been examined by both Dyer *et al* [27] and Mory *et al* [28].

INSSEV samples 24-1 and 24-2 were collected at 12:13 and 12:35, respectively. This was during the latter stages of the ebb where the ambient SPM was just under 1 g l^{-1}, but the TSS was still relatively high at approximately 0.5 N m^{-2}. A combination of the above ambient conditions were seen to prevent a fully optimum state of flocculation. However, a number of large fast settling flocs were observed early within the record of each sample. These were primarily irregularly configured stringers measured during sample 24-2 (see figure 12). The stringers were composed of four angular shaped macroflocs ranging from 250–400 μm in spherically equivalent diameter, again each interconnected in-line by organic fibres. This floc had a cumulative length of 1.9 mm and a W_s of 7 mm s^{-1}. The mean organic content was lower during spring tides (10–14%) and this meant that the resultant flocs had a higher overall mineral composition.

The advent of a CBS layer developing during the flood tide had the net result of producing an abundance of large macroflocs in suspension. This was demonstrated by INSSEV sample 24-9 (see figure 13) which was collected at 16:00 h from within the main body of the advecting TM, where the ambient concentration was 5.6 g l^{-1}, and consequently restricted the turbulent energy and the TSS to 0.36 N m^{-2} at 0.5 m above the bed. The floc characteristics for sample 24-9 revealed that the floc population was weakly bi-modal. Although there was a sub-group of slow settling ($W_s < 0.3$ mms^{-1}) flocs in the 30–70 μm size range, they only constituted 9.5% of the total population. The majority of the particulate mass, 49%, was contained within the larger sized aggregates ranging from 240 to 480 μm, with a further 25% of the dry floc mass contained in the macroflocs exceeding 480 μm. This cluster of large flocs

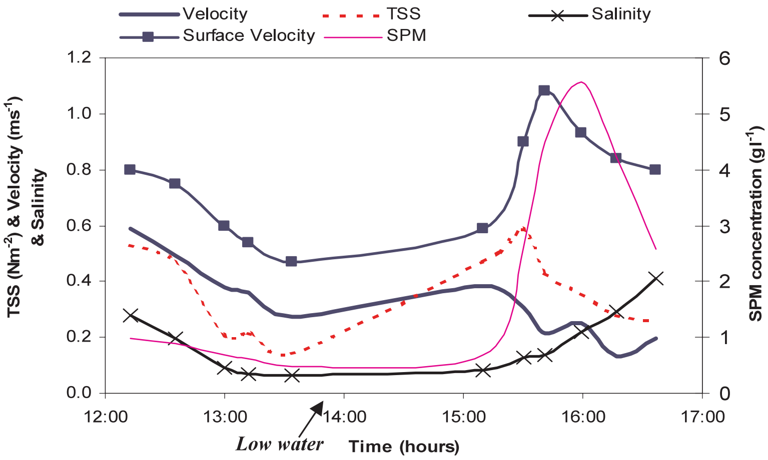

Figure 11. Time series of variations in salinity, flow velocity, SPM concentration and TSS for the spring tide on 24 June 1998. All observations were made 0.5 m above the bed (with the exception of the surface velocity), from a mid-channel station, near Calstock on the upper Tamar Estuary (SW England).

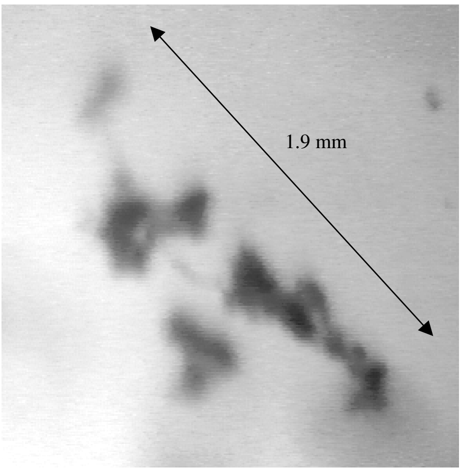

Figure 12. Long interlinked stringer comprising two clustered macroflocs (sample 24-2, 50 s into record).

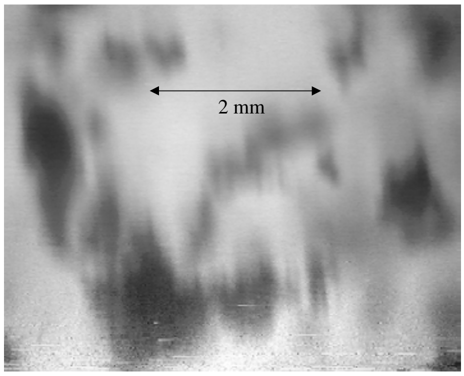

Figure 13. Numerous clustered macroflocs settling early in the record of a CBS sample (sample 24-9, 20 s into record).

had settling velocities between 4–8 mm s^{-1}. This indicated a significant increase in flocculation efficiency within the TM environment.

Analysis of the most commonly occurring fast settling macroflocs indicates that the CBS was comprised mainly of large ragged cluster-type macroflocs (figure 14). A detailed enlargement (figure 15) of one of the flocs encountered early in the sample 24-9 record indicated that a high proportion of the macroflocs had been flattened (height:width ratios of 0.8–0.9) from non-destructive inter-macrofloc contacts, which possibly occurred during settling within the CBS layer. These macroflocs reached the INSSEV camera field of vision just 17 s after being released from the upper deceleration chamber. This means that these very porous (>96%) macroflocs had effective densities of only 40–60 kg m^{-3} and a resultant W_s of 10–15 mm s^{-1}. The ability to be able to measure floc characteristics from directly within a CBS layer, as well as in dilute suspensions, demonstrates INSSEV's flexibility for sampling flocs from within most estuarine ambient conditions. Further examples of spring tide flocs were obtained from deployments conducted on 21 September 1998. INSSEV sample 21-5 was acquired at a period when the flood tide had entrained 1.1 g l^{-1} of solid matter into suspension and the ambient current produced a TSS of 0.42 N m^{-2} (at the INSSEV sampling height). The fastest settling flocs viewed during sample 21-5 were seen 30.7 s into the recording and are illustrated in figure 16. As with the June spring tides, these flocs resemble the common ragged cluster type (figure 16(a)) displaying D_x and D_y of 1 and 1.25 mm, respectively, and falling at a rate of 12 mm s^{-1}. However, the other macrofloc captured in the same frame (figure 16(b)) shows that the joining of two aggregates only 0.5 mm in diameter produced a floc with similar settling characteristics to those of the large single-cluster macrofloc (figure 16(a)).

Of particular interest was a very unusual type of stringer which is illustrated in figure 17. Possessing an overall length of 2 mm, its construction of five small spherically clustered macroflocs (D ranging between 350–420 μm) interlinked in-line by fine organic strands make it resemble a 'string-of-pearls' configuration. By interconnecting small macroflocs of moderate settling velocity ($W_s \sim$ 2–3 mm s^{-1}) in this manner so they act as a single entity, this type of stringer will therefore produce a significantly higher net settling velocity ($W_s \sim 10$ mm s^{-1}) and thus increase the mass settling flux displayed by the matter in suspension. It is the fine balance between the turbulence and SPM concentration which creates the ideal conditions to permit this level of flocculation [29].

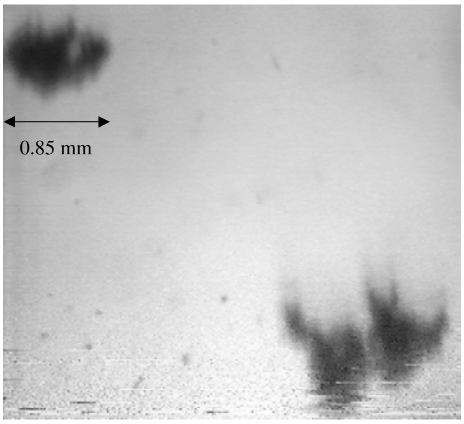

Figure 14. Ragged macroflocs settling (sample 24-9, 16.7 s into record).

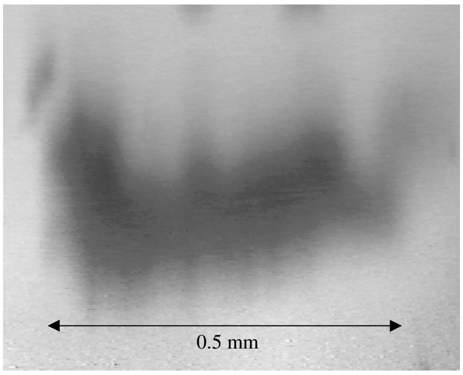

Figure 15. Large macrofloc flattened from non-destructive inter-macrofloc contacts possibly occurring within the CBS layer (sample 24-9, 19 s into record).

One factor which is instrumental to the flocculation process is that of interparticular cohesion. Earlier work on flocculation suggested that mud particle coagulation in estuaries occurred primarily by the balance of net electrostatic forces produced by the saline water. Figure 11 shows that the salinity did not rise above 0.5 during the entire spring tide deployment. Even salinities during the neap tides described in the previous subsection very rarely exceeded 4. These are both much lower saline levels than the salinities of 10–15 which previous authors have advocated must be present to create an effective level of flocculation for clay mineral particles. Therefore it can be assumed that the majority of the flocculation occurring was mainly due to interparticle adhesion by organic based extra-cellular polymeric substances (EPS), primarily mucopolysaccarides. Biochemical analysis revealed that total carbohydrate concentrations were up to seven times greater during spring tide conditions than at neaps. However, even though these natural adhesives are able to bind mud particles together, they are not strong enough to create a macrofloc strength which is capable of surviving a very destructive sampling and measuring procedure. Thus the advantage of the low intrusive optically based INSSEV system is very evident.

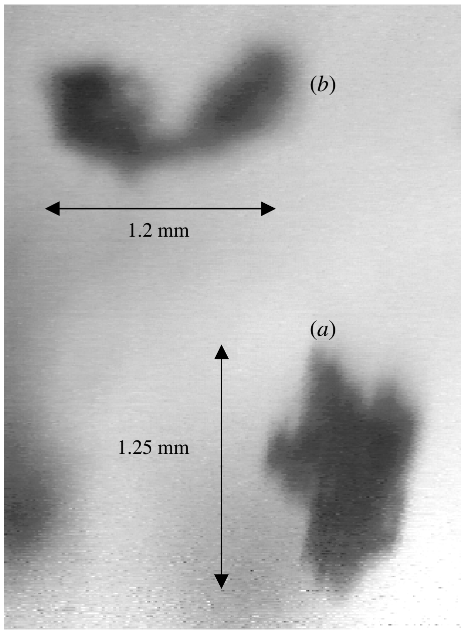

Figure 16. A ragged cluster-type macrofloc (*a*) and a simple stringer composed of two macroflocs interlinked by organic fibres ((*b*); sample 21-5, 30.7 s into record).

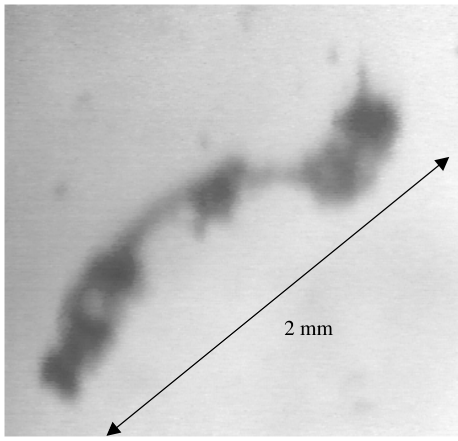

Figure 17. An example of a ‘string-of-pearls’ type macrofloc (sample 21-5, 42 s into record).

5. Conclusions

The INSSEV images presented in this paper from deployments in the upper Tamar Estuary during neap and spring tidal conditions revealed a plethora of floc configurations. The lower concentration neap tides produced a mixed size range of flocs, and during their most floc-productive conditions the macroflocs approached 0.75 mm in length with settling velocities of 4–5 mm s^{-1}. These highly organic (up to 28%) macroflocs typically resembled ‘comets’ or ‘long stringers’. However, these stringer configuration macroflocs were in the minority and, on average, only represented 30–40% of the suspended matter.

During spring tides, the combination of conditions permitting optimum flocculation (i.e. TSS $\sim$ 0.33–0.38 N m^{-2} and SPM $>$ 4 g l^{-1}) transformed 95% of the ambient SPM concentration into large, fast settling, rounded cluster-type macroflocs. The spring tide flocs were less organic than those observed during neaps: however, the level of natural adhesive present (at springs) was up to seven times greater. Analysis of the INSSEV record showed that these clustered aggregates had effective densities <50 kg m^{-3}, which meant that they were 90–96% porous. Thus they were of a very fragile construction. A number of the smaller macroflocs had their settling characteristics significantly improved by becoming interlinked with organic matter to form stringers with a string-of-pearls configuration. Although stringers were seen to occur during both neap and spring tides, the former ambient conditions tended to produce stringers which were only a third of the size of those typically observed at springs, and thus the neap tide stringers had comparatively slower settling velocities.

The influence of organic matter within natural estuarine mud flocs is very evident from both the INSSEV video records and gravimetric analysis. This mixed structural composition can create potential calibration problems with other types of *in situ* floc measuring sensors, for example laser diffraction or optical back-scatter based instruments. Also, these above-mentioned systems would not be able to provide information on the important characteristics and dynamics which a floc population demonstrates, whereas a more visually based optical instrument such as INSSEV would.

Qualitatively, the high quality INSSEV video records have shown at both a microscopic and macroscopic level the complex variability of floc types which exist in an estuarine water column, both throughout changing tidal conditions and within an individual floc sample record. To predict these evolutionary patterns on a variety of temporal and spatial scales is a very complex exercise. This is due to a lack of fundamental understanding about *in situ* mud flocculation, primarily because of the absence of good quality floc data. The INSSEV floc observations show that simple fractal models only provide a first approximation to the structure and characteristics of natural mud flocs. Therefore *in situ* data collection is a necessity and instruments which cannot measure all important floc components accurately can leave the analysis of such data extremely open to misinterpretation and error. Therefore, from a quantitative perspective, INSSEV has the unique ability of allowing the size–spectral division of the mass settling flux and associated floc characteristics to be calculated for a representative floc population. This is of great importance for accurate numerical sediment transport simulation model calibration.

In summary, for the determination of mud floc characteristics, the low intrusive nature of the optically based INSSEV system makes it a distinct improvement over previous instruments such as field settling tubes, *in situ* photography and laser particle sizers. Since its initial inception, the INSSEV instrument has significantly contributed towards the understanding of estuarine floc formation and the characteristics demonstrated by such flocs during varying levels of turbulence and SPM concentrations. Successful floc measurements have even been made from within CBS layers close to the estuary bed, where SPM concentrations can approach 8 g l^{-1}. Other recent successful INSSEV deployments include those conducted in the lower reaches of the Gironde Estuary in France as part of the EC TMR SWAMIEE project [30].

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