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A Model for the Settling of Non-uniform Cohesive Sediment in a Laboratory Flume and an Estuarine Field Setting

Mary C. Ockenden

HR Wallingford
Howbery Park
Wallingford
Oxon. OX10 8BA, UK

ABSTRACT

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A numerical model for deposition of non-uniform cohesive sediment at a point was applied to laboratory and field settings. The results were compared with those from a uniform sediment model applied to the same settings. In the non-uniform (distributed) model, classes of sediment (representing different floc sizes) each had a corresponding settling velocity and critical shear stress for deposition. The models were applied to laboratory deposition tests in an annular flume. Tests with steady and slowly decelerating flow were both modelled. The distributed sediment model was shown to be a much better model of deposition in decelerating flow in the closed system of the annular flume. The model was shown to be sensitive to the settling velocity of the class corresponding to the largest flocs. The importance of more accurate methods of determining floc size and settling velocity distributions was recognised. Both models were also applied to field measurements of deposition during a tide made in the Mersey Estuary. Both models gave a reasonable fit to the data, but the distributed sediment model did not significantly improve the uniform sediment model for field use. External influences and advection of sediment from outside the immediate area were shown to affect the field measurements.

ADDITIONAL INDEX WORDS: *Cohesive sediment, deposition, laboratory tests, field measurements, critical shear stress, settling velocity, non-uniform sediment, numerical model, floc size distribution, annular flume, Mersey Estuary.*

INTRODUCTION

The process of deposition of cohesive sediment depends on a combination of different factors, including the size, settling velocity and strength of the settling units. These units may be single particles or, more likely, aggregates or flocs which may be loosely or strongly bound together. The flocs have a settling velocity very much larger than the settling velocity of the primary particles. The degree of flocculation depends on many parameters, including the mineralogy, size, pH and ionic strength of the particles and the chemical composition of the suspending water (Van Leussen, 1988).

A simple representation of deposition was formulated by Krone (1962). It is expressed as:

$$\frac{dm}{dt} = \left(1 - \frac{\tau_b}{\tau_d}\right) w_s c \qquad \tau_b \leq \tau_d$$

$$\frac{dm}{dt} = 0 \qquad \tau_b > \tau_d \qquad (1)$$

where dm/dt = rate of change of mass on the bed per unit area (kg m^{-2}), τ_b = applied bed shear stress (N m^{-2}), τ_d = critical shear stress for deposition (N m^{-2}), w_s = settling velocity of flocs (m s^{-1}), c = concentration of suspended sediment (kg m^{-3}).

This equation uses the fact that there is a value of the bed shear stress (τ_d) below which all suspended cohesive sediment will eventually be deposited. This value of τ_d is typically in the range 0.05 N m^{-2} to 0.1 N m^{-2}. Given the same settling velocity and concentration, the rate of deposition depends on the actual bed shear stress, with maximum rate when the bed shear stress is zero, and minimum (zero) when the bed shear stress is equal to the critical shear stress for deposition. Equation 1 indicates that above this critical shear stress no sediment will be deposited. This may be true for a uniformly flocculated sediment, but such a sediment is unrealistic in nature. However, for engineering applications it is often necessary to model cohesive sediment transport in quite complex situations, and the errors due to using a uniform sediment may be quite small compared to

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errors introduced as a result of other assumptions. Nevertheless, improvements in the understanding of the processes are constantly being sought. A uniform sediment can be approximated by using representative values for the parameters in Equation 1; the median settling velocity is often taken as a representative value of w_s, as half of the flocs settle faster than this and half slower. Equation 1 can be refined to model a non-uniform sediment by relating the median settling velocity to the concentration, as found to be applicable in previous studies (DELO, 1988).

Several models have been formulated for a distributed sediment, with different sized particles which have a range of strengths and settling velocities (MEHTA and PARTHENIADES, 1975; MEHTA and LOTT, 1987; KRISHNAPPEN, 1991). Most of the models have been developed from laboratory tests where sediment is contained in a closed system. VERBEEK *et al.* (1991) proposed a model based on floc strength, in which the input parameters are based on laboratory deposition tests. It has been shown that there can be significant differences between the behaviour of cohesive sediment in the field and in the laboratory, because of the difficulty of reproducing the same physical, chemical and biological environment. Algorithms for numerical models, which have been based on the results of controlled laboratory tests, still need to be tested for field settings. Thus, for engineering purposes, it is important to be able to make field measurements which can then be used to calibrate simple models for predicting cohesive sediment transport.

Until recently, measurements of deposition have been from tide to tide, or even less frequently. However, recent measurements in the Mersey Estuary (DISERENS *et al.*, 1991) recorded deposition during several tides with associated hydrodynamics. This has enabled numerical models to be tested for short-term deposition predictions.

The purpose of this study was to use the field data recorded in the Mersey Estuary to test and compare a deposition model for a non-uniform cohesive sediment with a model for uniform sediment. The models were first tested on laboratory data.

MODELLING METHOD

A simple deposition model was written by the author in which a time history of bed shear stress and suspended sediment concentration was prescribed during a tide. This was a simplification of the Siltation at a Point (SAP) model of DELO and OCKENDEN (1989). Deposition onto the bed was modelled according to Equation 1. When applied to a closed system such as a laboratory flume, only the initial concentration was prescribed and deposition predicted by the model resulted in a change in the concentration in suspension. When using field data from the Mersey Estuary as input to the model (with concentrations prescribed at each time step), deposition was recorded as a mass of material on the bed, which was converted into a depth of material by assuming a density of 80 kg m^{-3} for newly deposited material. A settling velocity of the material was calculated from available field data.

The model was then developed to allow for a non-uniform sediment by dividing the sediment into classes in a manner similar to that of MEHTA and LOTT (1987). The model assumes that the sediment is divided into N classes of flocs, each having a unique settling velocity, concentration and critical shear stress for deposition. The total sediment deposited on the bed, Δm, during a time interval, Δt, is given by the sum of the individual amounts deposited from each class:

$$\Delta m = \sum_{i}^{N} w_{si} \phi C_i C(t) \left(1 - \frac{\tau_b}{\tau_{di}}\right) \Delta t \qquad (2)$$

where w_{si} = settling velocity for sediment class i, ϕC_i = proportion of total concentration comprising sediment class i, $C(t)$ = total concentration at time t, τ_{di} = critical shear stress for deposition of sediment class i. Sediment class i deposits only if $\tau_b \leq \tau_{di}$. Each class of sediment flocs is assumed to act independently of the others.

Additional field measurements are needed to determine the actual frequency distributions of concentration and settling velocity. The distribution of floc size can be measured by using a technique of image analysis. Several systems for *in situ* observation of flocs have been developed recently. Floc size analysis can either be made from a series of still photographs, as in the system described by EISMA *et al.* (1990), or from video images, as in the system described by DEARNALEY (1991). The analysis technique is similar in both cases, involving identification of particles and calculating their dimensions. Care is needed in interpreting results and particularly when comparing results from different systems, where different threshold and noise levels may have been chosen. These difficulties are described by EISMA *et al.* (1990).

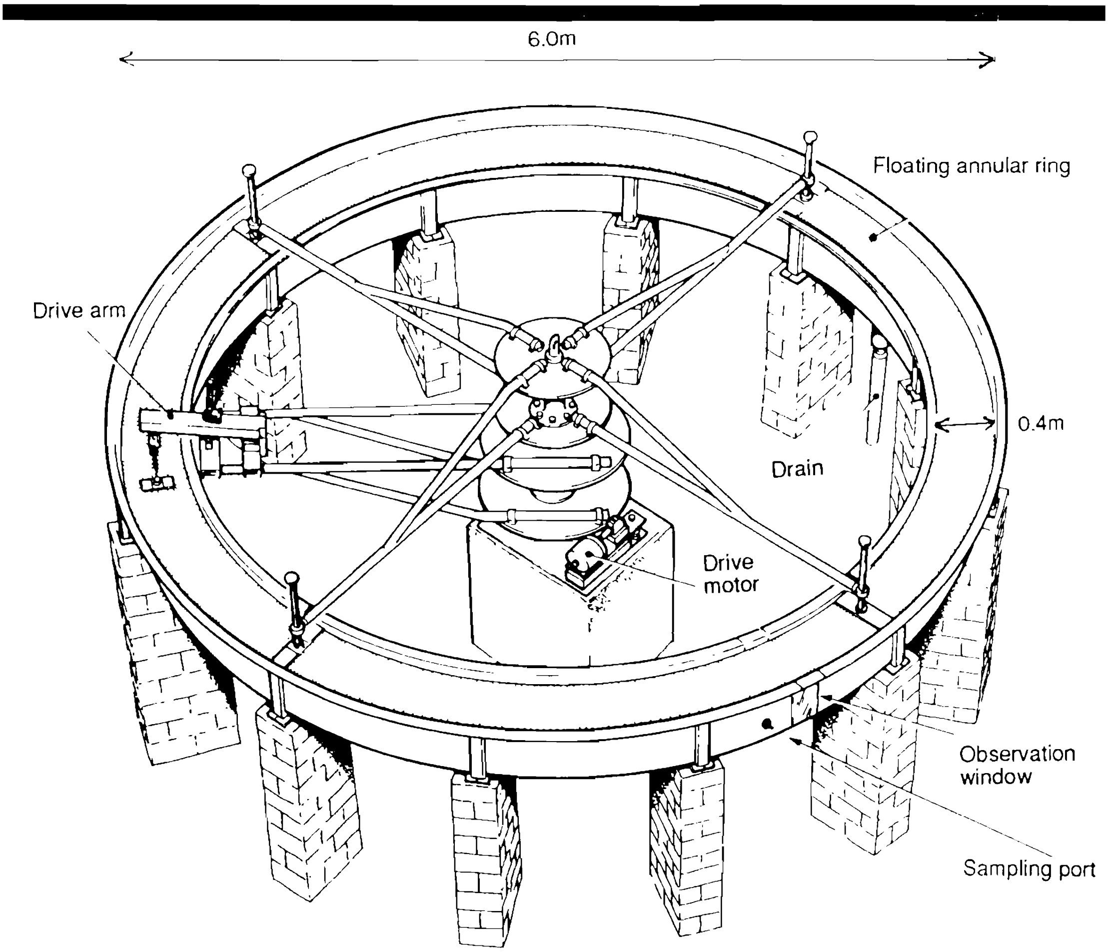

Figure 1. The HR Carousel.

In this study, the video image analysis described by DEARNALEY (1991) was used on samples collected from the Mersey Estuary; results were used as input for the distributed sediment model. The system involves suspending an open ended tube (approximately 0.05 m in diameter) in the water, aligned with the flow, to capture a quantity of sediment. The tube is then removed from the water, turned upright and the sediment is filmed as it settles in the tube, particularly during the period immediately following removal of the tube (0–10 minutes). By analysing consecutive images, settling particles can be identified and measured for size and settling velocity. The system is not truly "*in situ*", as it does not operate underwater, but the method of capture of sediment is similar to that used with Owen tubes (OWEN, 1976). The mouth of the tube is sufficiently wide to allow flocs to enter without significant break-up: EISMA *et al.* (1990) reported that the aperture of 32 mm through which particles passed on their *in situ* camera system was sufficient to avoid break-up of the flocs at velocities less than 1.2 m s^{-1}. Whilst enclosure within any column will affect the turbulence of the flow (VAN LEUSSEN, 1988), the effect will be least immediately after removal of the column from the water.

MODELLING LABORATORY TESTS

Apparatus

Deposition tests were conducted in the laboratory using the HR Carousel. The carousel flume (Figure 1) is an annular flume, with an outer diameter of 6 m, a channel width of 0.4 m and depth of 0.35 m, and has a detachable roof 0.09 m thick.

The flume stands approximately 1.1 m off the ground, supported by 12 brick pillars. The channel and the roof are constructed of fibre glass, with a 0.12 m long perspex (plexiglas) section in the channel for viewing. The roof fits into the channel, and floats on the fluid. Fluid motion in the carousel flume is induced and maintained by the drag between the roof and the fluid surface as the roof rotates.

The driving mechanism for the roof consists of a DC torque motor with a drive arm attached to the roof. The speed of the motor is controlled by a micro computer to an accuracy of 0.1% of the maximum speed. This produces a mean water velocity range in the flume from zero to approximately 0.7 m s^{-1}, with a corresponding applied shear stress range from zero to approximately 0.7 N m^{-2}.

The sampling system consists of two port holes, one on each wall of the flume, 80 mm above the floor. During tests, fluid is continuously extracted from the carousel flume by a peristaltic pump and passed through a constant temperature water bath and a densimeter before being returned to the carousel flume. Bottle samples of the fluid are taken from time to time and analysed gravimetrically to maintain an accurate calibration.

The average shear stress exerted by the fluid on the bed has been measured and calculated by several methods. These include direct measurement of the energy input to the roof through a calibrated strain gauge, measurement of the near bed velocity profiles in the flume using laser doppler anemometry and direct measurement of the shear stress along the base and side walls using flush mounted shear stress probes. Both different roof rotational speeds and different flow depths have been investigated. In addition, the shear stress distribution along the bed was predicted by a numerical model developed by Polytechnic South West to predict the hydrodynamics in the carousel (GRAHAM *et al.*, 1992). The shear stress on the bed was shown to be linearly related to the radius. This has resulted in a better understanding of the secondary circulations in the channel. The secondary, radial component of shear stress is typically less than 10% of the circumferential value at a given radius.

For the laboratory deposition tests, mud from near Eastham Dock in the Mersey Estuary was homogeneously mixed into a suspension (approximately 1 kg m^{-3} mud, 30 kg m^{-3} NaCl) and poured into the carousel to a depth of 0.1 m. Two sets of carousel tests were run: in the first set, the shear stress was held at a high value for one hour to mix the sediment into suspension, and then dropped suddenly to a lower value and held constant for several hours (step tests). In the second set, the shear stress was again held at a high value for an hour to mix the sediment into suspension, and then slowly decreased to a lower value over 1, 2 or 4 hours (slow deceleration tests). This lower value was then held constant for a further hour.

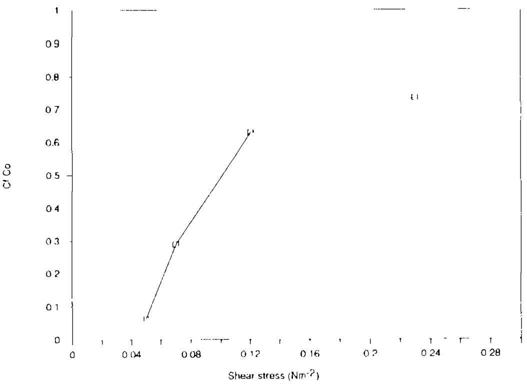

Figure 2. Ratio of final equilibrium concentration, C_f, to initial concentration, C_0, as a function of bed shear stress.

Model Input

Several researchers (MEHTA and PARTHENIADES, 1975; VERBEEK *et al.*, 1991) have carried out deposition tests in annular flumes, in which the shear stress was dropped in discrete steps from a high value (which retained most of the sediment in suspension) to a lower value, which allowed some of the sediment to deposit. It was found that the final concentration in suspension when the system reached equilibrium depended on the shear stress, and that, for a given shear stress, the ratio of the final concentration, C_f, to the initial concentration, C_0, was independent of the initial concentration. The ratio C_f/C_0, based on data from the HR Carousel, is given in Figure 2. The resulting curve shows that, for Eastham mud, for a shear stress below about 0.05 N m^{-2} all sediment eventually fell out of suspension. About 50% of the sediment fell out of suspension below a shear stress of approximately 0.08 N m^{-2}, which is often used as a representative value for modelling deposition using Equation 1.

In order to provide a measure against which the

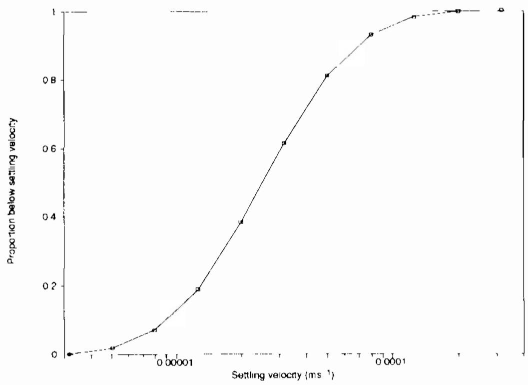

Figure 3. Settling velocity distribution used to model carousel tests.

distributed sediment model could be compared, a uniform sediment model, based on Equation 1, was used to model the carousel tests, using a critical shear stress for deposition of 0.08 N m^{-2}. The settling velocity was varied to obtain the best fit to the step tests (first series) using a settling velocity which was proportional to the concentration, with a minimum settling velocity for low concentrations (<0.1 kg m^{-3}). Owen tubes are not able to measure settling velocities very accurately at low concentrations because of the very small quantities of sediment involved. The same settling velocity with concentration relationship was then used in the second set of tests.

The distributed sediment model was used with 11 classes of sediment, each of which was given a settling velocity and critical shear stress for deposition. A log-normal distribution was chosen for settling velocity, showing a shape typical of a measured settling velocity distribution. The settling velocity distribution is shown in Figure 3; the median settling velocity is approximately 0.00003 m s^{-1}.

There are many factors which affect the flocculation of mud particles, such as salinity, concentration, presence of organic particles, pelletisation (Van Leussen, 1988). In the laboratory, it is very difficult to simulate the exact conditions which are found in the field. In the carousel, there was very little organic activity (the suspension was made with tap water with salt added), and the depth of flow was only 0.1 m, which did not give particles the same opportunity to flocculate. For this reason, the settling velocities in the carousel were considerably lower than would be expected in the field.

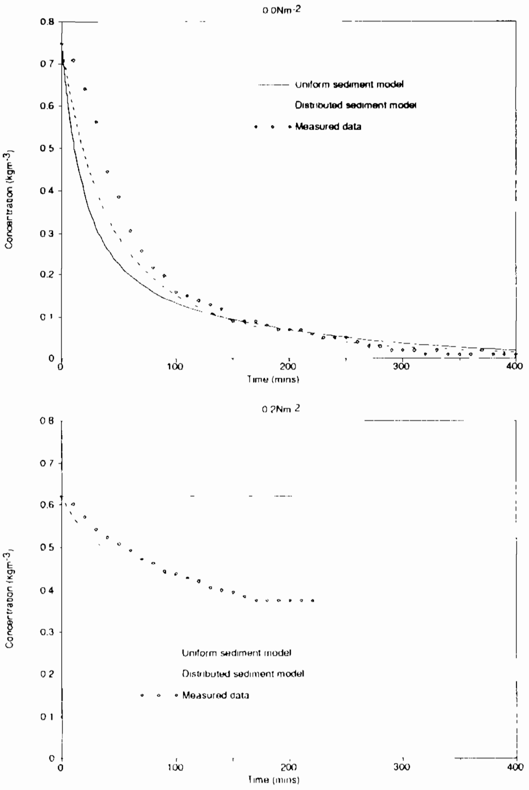

Figure 4. Carousel deposition tests under constant shear stress. Measured and predicted concentration in suspension for τ_b = 0.0 N m^{-2} (top) and τ_b = 0.2 N m^{-2} (bottom).

The sediment classes were divided into bands of equal width of log(settling velocity). The sensitivity of the settling velocity was tested. The critical shear stress for deposition in the model was estimated from Figure 2. The ratio C_t/C_0 represents the proportion of sediment which remains in suspension above the corresponding shear stress.

Results

Figure 4 shows the predicted concentration in suspension from the uniform sediment model and from the distributed sediment model, along with the measured concentrations in the step tests (first series). For the step test where the shear stress is reduced to zero, both models give a reasonably good fit to the measured data, particularly towards the end of the test. However, there is a noticeable delay in the measured settling once the

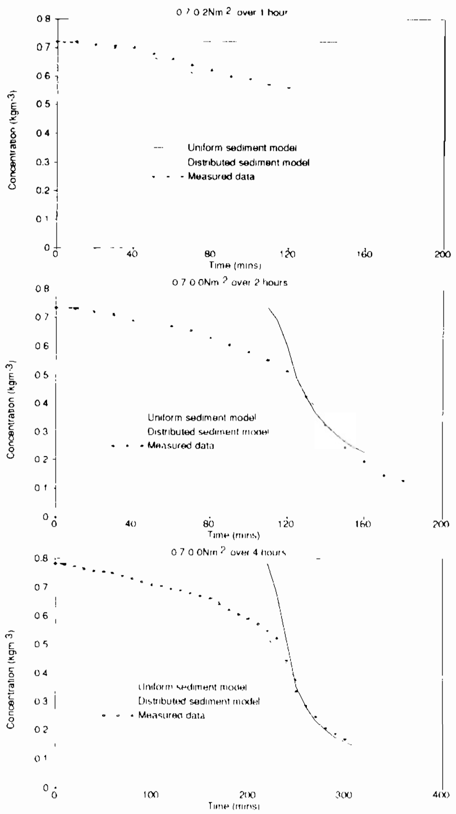

Figure 5. Carousel deposition tests under slowly decreasing shear stress. Measured and predicted concentration in suspension for τ_b from 0.7–0.2 N m^{-2} over one hour (top), τ_b from 0.7 0.0 N m^{-2} over two hours (middle), τ_b from 0.7 0.0 N m^{-2} over four hours (bottom).

shear stress has been reduced to zero, near time = 0, which is not predicted by the models. This is because the shear stress on the bed in the carousel is generated by movement of the roof, and even though the roof has been stopped, the shear stress does not immediately disappear.

For the step test where the shear stress is reduced to 0.2 N m^{-2}, the uniform sediment model predicts no deposition at all because the critical shear stress for deposition is constant at 0.08 N m^{-2}. The distributed sediment model predicts too much deposition at first. However, later in the test, the model under-predicts the measured deposition.

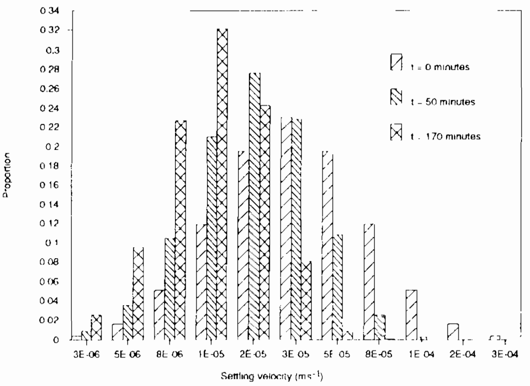

Figure 6. Change in settling velocity distribution during carousel deposition test under constant shear stress (τ_b = 0.0 N m^{-2}).

Figure 5 shows the predicted and measured suspended sediment concentrations during tests where the shear stress was reduced slowly from the initial value to a lower value over 1, 2 and 4 hours. It is clear that the uniform sediment model is unable to model the slow deposition which occurs during deceleration of the flow. This is particularly noticeable when the shear stress is reduced slowly to 0.2 N m^{-2} (top figure, deceleration over 1 hour), when the uniform sediment model predicts no deposition at all. In contrast, the distributed sediment model gives quite good results at the start of each test during the deceleration phase. In all these tests, the distributed sediment model predicts the highest rate of deposition at the point where the deceleration of the flow stops. In general, this highest rate of deposition (shown by rapid drop in concentration) is not as high as that measured in the tests where the shear stress is dropped to 0.0 N m^{-2} (middle figure, deceleration over 2 hours and bottom figure, deceleration over 4 hours), but is too high in the tests where the shear stress is reduced to 0.2 N m^{-2} (top).

The predicted change in sediment distribution during a step test in the carousel is shown in Figure 6, which shows the proportions of each class (banded according to settling velocity) at times during the test. The proportion of particles of lower settling velocity is seen to increase during the test.

The distributed sediment model is shown to be a better model of deposition in the carousel, particularly for slowly decelerating flow. However, it requires more input data and thus is more difficult to use. The current application is based heavily on empirical relationships. The sensitivity of the model was tested, both to values of the input parameters and to the way in which the sediment classes were banded. The sediment was banded

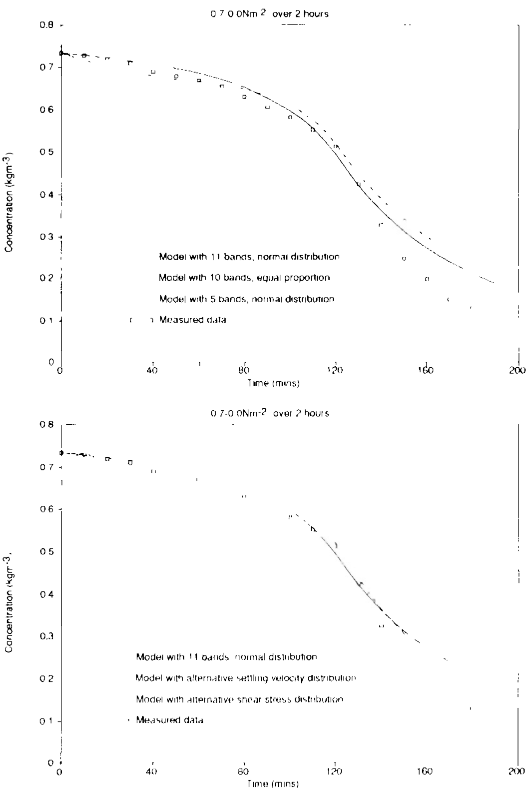

Figure 7. Measured and predicted concentration in suspension, showing sensitivity to different numbers of sediment bands and distribution of sediment bands (top) and sensitivity to settling velocity distribution and shear stress distribution (bottom).

in different ways: five bands instead of 11, and 10 bands of equal proportion. For these tests, the input was calculated from Figures 2 and 3. The sensitivity to these is shown in the top part of Figure 7, (0.7 to 0.0 N m $^{-2}$ over 2 hours). The model was not particularly sensitive to the effect of different banding with all input giving a reasonable fit to the measured data. With any of these inputs, the model still underestimated the amount of deposition in the later part of the test. The most pronounced effect of the change in banding was due to the size of the band of highest settling velocity (or highest shear stress for deposition), as this determined the amount of deposition at the start of the test. Both the five bands of input and the equal proportions overestimated the deposition at the start, as the top band was larger in both cases than for the original input. It was concluded that the resolution into classes should be finer for the classes with higher settling velocities. The lower part of Figure 7 shows the results of sensitivity tests on the settling velocity and the shear stress for deposition. In each case, apart from the parameter being tested, the other input data was as for the original input data (11 bands, normal distribution). In the case of the settling velocity, the median settling velocity remained the same as in Figure 3, but the standard deviation of the distribution was reduced so that there were fewer particles with high or low settling velocity. As a result, the model did not predict enough deposition at the start, but matched the measured data reasonably well for a short period when the concentration in suspension had dropped to half its initial value. However, although not shown here, the model was more sensitive to a change in the value of the median settling velocity. For the alternative shear stress distribution, each band was allowed to settle at a higher shear stress (the top and bottom of the distribution remained the same). The model gave a reasonable fit at the start of the test, but sediment settled too quickly in the middle of the test. Once again, neither the change in settling velocity nor the change in shear stress allowed enough deposition at the end of the test. This suggests that the settling velocities of the smaller particles in the model were too low, and that the normal distribution used for the settling velocity distribution should have been truncated at the lower end. It is therefore important that this information is determined more accurately. A step towards this is being made with the development of equipment for *in situ* measurement of floc size and settling velocity.

MODELLING FIELD DATA

Data Collection

Field data from DISKERENS *et al.* (1991) collected on mudflats in the Mersey Estuary on both spring tides and neap tides in November 1990 were used to test the models. The measurement site was on the south side of the estuary on mudflats adjacent to a disused dock at Eastham (Figure 8). A small bed frame (approximately 1 m in diameter, 1 m high) was positioned on the mudflats. Extending tubular legs approximately 2 m long were sunk into the mud to prevent the frame from moving. Water levels recorded at the site showed a symmetrical tide curve, with a maximum water level at the site of 5.5 m on spring tides and 4 m on

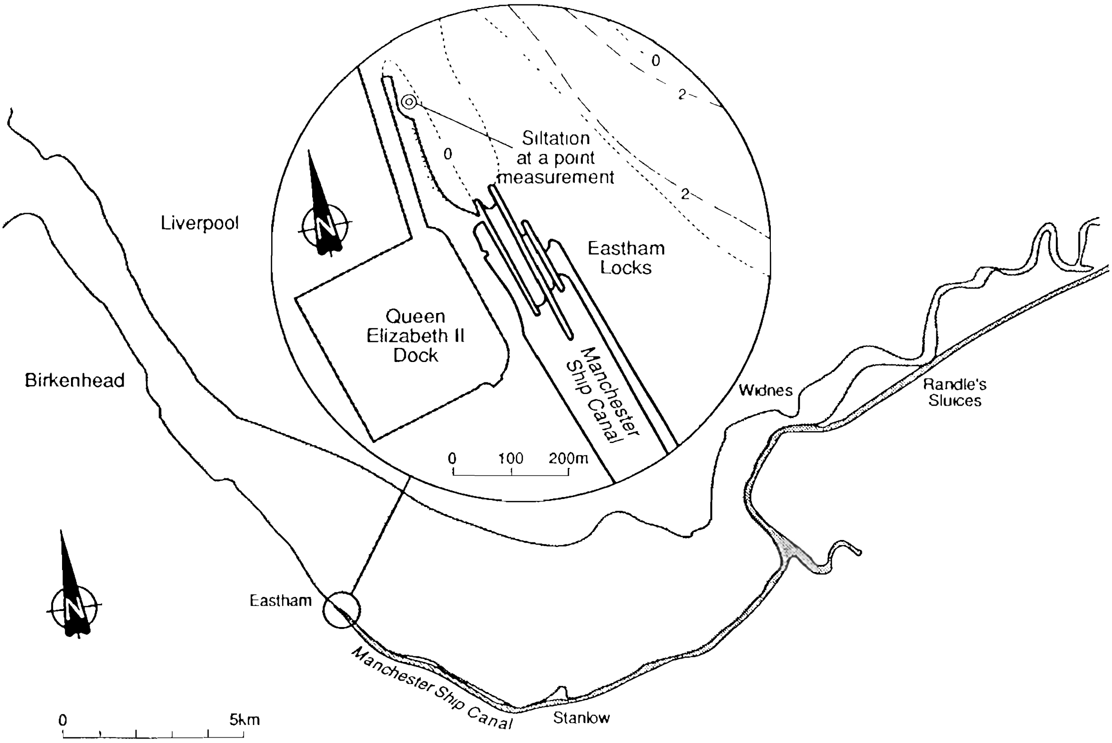

Figure 8. Location of field measurements on inter tidal mudflats in the Mersey Estuary.

neap tides (Figure 9). The site was submerged for approximately 3.5 hours either side of high water (HW) on both spring and neap tides.

The site was sheltered with very little wave activity on this occasion, so bed shear stresses were calculated from fitting a logarithmic profile to the velocities measured at three heights above the bed (0.1 m, 0.5 m and 1.0 m). Tidal currents were measured with Braystoke propeller current meters; the horizontal speed was averaged over 10 minute periods. Suspended sediment concentrations were recorded with Partech optical backscatter turbidity probes mounted at 0.1 m, 0.5 m and 1.0 m above the bed. These were calibrated with samples of sediment collected from the measurement site. The bed elevation at one point was recorded throughout the tide using an ultrasonic probe pointing vertically downwards at the bed. When positioned 0.1 m above the bed, the ultrasonic probe signal is averaged over an area of approximately 20 mm; the frequency of the probe is 5 MHz which gives a very high resolution (± 0.25 mm) for changes relative to a fixed reference point. Cables from the instruments were taken up the mudflats to the Dock wall where data were logged automatically into a computer.

The 10-minute averages of bed shear stress, suspended sediment concentration and bed level from a spring tide on 20 November 1990 are shown in Figure 10 against time relative to high water. The shear stress shows two periods of low stress, which were also observed in the current speeds measured at each height and on each tide monitored. This indicated that the currents at this site were not simply related to the tidal elevation as might be expected in the main channel. The second period of low velocity was probably due to an eddy formed behind the Dock entrances on the ebb tide. However, current direction information was not available to confirm this. Figure 10 shows that the largest changes in bed level occurred during the two periods when the shear stresses were very low (0–40 minutes after HW and 120–160 minutes after HW). However, deposition was also mea-

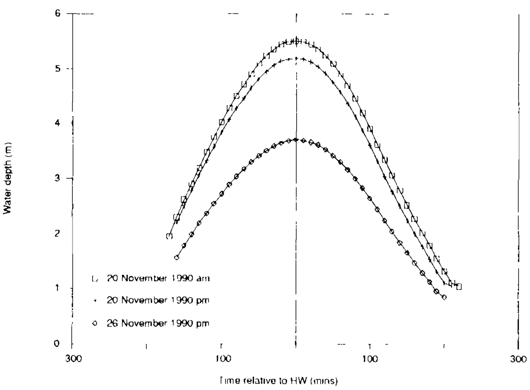

Figure 9. Water depths recorded at Mersey field measurement site during spring tides on 20 November 1990 and a neap tide on 26 November 1990.

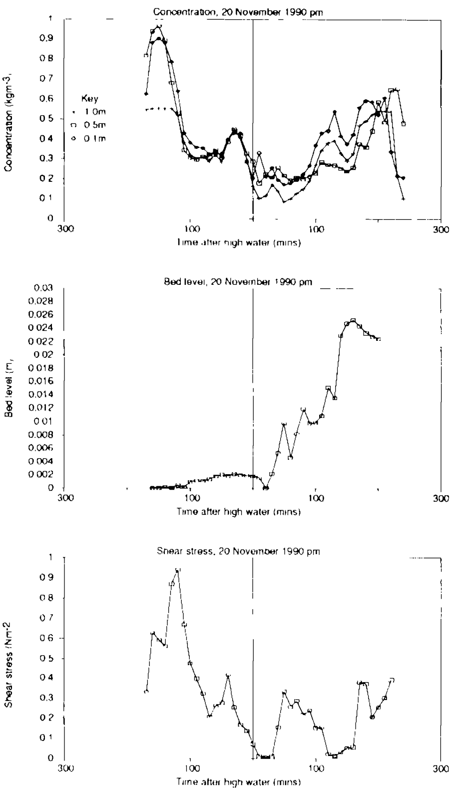

Figure 10. Concentration in suspension, bed shear stress and bed elevation recorded during a spring tide in the Mersey Estuary, UK, 20 November 1990.

sured during the period 40–120 minutes when the shear stress was quite high (up to 0.3 N m^{-2}).

Model Results

The measured field data from the Mersey Estuary were used as input to the distributed sediment model and the uniform sediment model. For the distributed sediment model, a floc size distribution was determined from video image analysis of samples collected from the Mersey. The samples were filmed immediately after removal of the collection tube from the water. Figure 11 shows the measured floc size distributions at concentrations of 0.381 kg m^{-3} and 0.058 kg m^{-3}. This figure indicates that the distribution of floc size depended on the total concentration in suspension with a higher proportion of larger particles at higher concentrations. In the field, the concentration in suspension during the deposition period was 0.3–0.5 kg m^{-3}, so the data in Figure 11 were used as the starting floc size distribution for the model. The settling velocity distribution was calculated from Owen tube measurements taken in the Mersey in 1990, using the proportions from the sediment size bands. In the absence of other information, the critical shear stress for deposition of each sediment band was taken from the carousel measurements.

For the uniform sediment model, settling velocities were calculated from Owen tube measurements in which the median settling velocity, w_{50} (m s^{-1}), was found to be related to the concentration in suspension, C (kg m^{-3}), according to:

$$w_{50} = 0.005C \tag{3}$$

The critical shear stress for deposition was taken to be 0.08 N m^{-2}, a typical value below which all sediment would be deposited.

The predicted depth of deposition was based on a density of 80 kg m^{-3}, which represents a soft, unconsolidated deposit. Figure 12 shows the depth of material on the bed predicted with both the distributed sediment model and the uniform sediment model for three of the measured tides.

One noticeable feature in each of the three tides is that the settling lag observed in the measured deposition (shown as a delay between the low shear stresses and the actual deposition on the bed) is not predicted by the model. From these figures, this delay appears to be about 10–20 minutes. The delay between the measured deposition and the predicted deposition is even more noticeable with the distributed sediment model because the sediment begins to deposit at higher shear stresses.

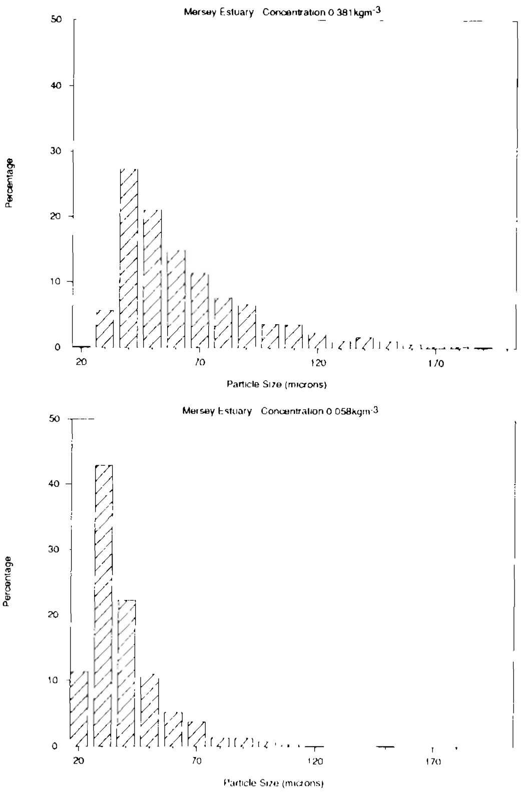

Figure 11. Floc size distribution measured with video image system in the Mersey Estuary for concentrations of 0.381 kg m⁻³ (top) and 0.058 kg m⁻³ (bottom).

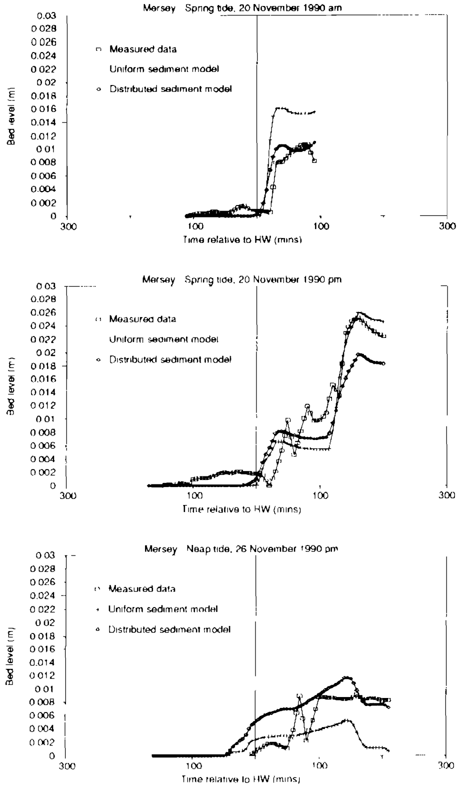

Figure 12. Measured and predicted bed elevation change in the Mersey Estuary; spring tide, 20 November 1990 am (top), spring tide, 20 November 1990 pm (middle), neap tide, 26 November 1990 pm (bottom).

The improvement of the distributed sediment model is less obvious in this application to field data than with the closed system of the carousel. For this case, many more assumptions have to be made; for instance, the sediment distribution is determined entirely by the deposition which has taken place. If the concentration increases from sediment advection, then the sediment distribution is assumed to be the same as that of the currently predicted distribution. This situation is realistic if the same processes are happening over a large area, but not if the point of interest is affected by sediment being advected in from somewhere with different hydraulic conditions.

Figure 13 shows the predicted concentration in suspension from the distributed sediment model, compared with the actual measured concentration, for the neap tide on 26 November 1990. For this run, the model assumed that, starting from a specified initial concentration, the concentration of material being advected in will be exactly the same as the concentration left in suspension after deposition of the sediment (like a closed system). This figure shows that the measured drop in concentration recorded just past high water matches the predicted fall in concentration quite well, indicating a local effect. However, after this period the measured and predicted values diverge quite widely, with the predicted concentration falling to zero, and the actual measured concentration increasing. This indicates that there is an additional influence in the field, with sediment being advected in from somewhere further away with significantly different hydrodynamic conditions. This is not represented in either model. However, these models provide a way of separating the local effects from the advective effects, which is very useful in itself.

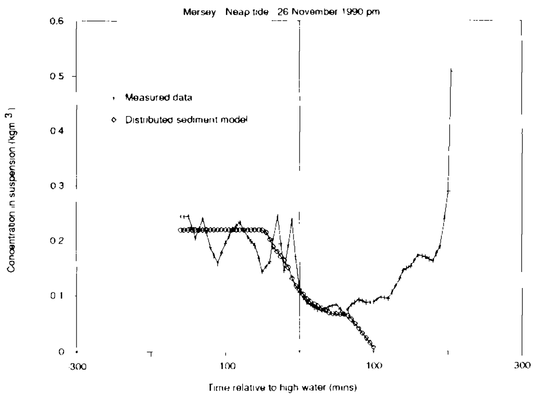

Figure 13. Measured and predicted concentration in suspension showing local deposition effect over HW and advection effect after HW.

DISCUSSION

The process of differential deposition due to different floc sizes is much better represented in the distributed sediment model as indicated by the laboratory tests. The inclusion of different floc sizes is a considerable improvement in the physical representation of the deposition process. However, the effect of flocculation or break-up of flocs where this balance changes after the start of the model is not included. For instance, the flocculation which may occur during a quiescent settling test in the laboratory is likely to be different from the flocculation which occurs (or is prevented) during a slow deceleration test. This is one reason why the predicted maximum deposition rate in the carousel deposition tests was lower than the observed rate. Once zero shear stress was reached, there may be larger flocs formed by collision and cohesion of the flocs which were settling at that stage of the test. This process is particularly important at high concentrations where collisions occur more frequently.

Given the number of additional influences which are present in the field, the distributed sediment model does not significantly improve the uniform sediment model for field use. However, it is important to note that the field data mentioned in this paper provide a rare opportunity to test numerical models with short-term field measurements. Both uniform and non-uniform sediment models gave a reasonable fit to the measured field data, so that the equations used to predict deposition (Equations 1 and 2) were shown to be adequate under the natural conditions measured in the Mersey Estuary. For many complex engineering applications, where assumptions often have to be made for practical reasons such as availability of data or computer processing power, a uniform sediment model may still be adequate.

Progress is being made towards providing the appropriate input data for a distributed sediment model using the video imaging technique. However, further development is needed on such image analysis systems so that *in situ* measurements of floc size and settling velocity are more readily available for calibration of more complex models of deposition.

CONCLUSIONS

The distributed sediment model described in this paper based on classes of flocs each with their own settling velocity and critical shear stress for deposition was a better model of deposition than a uniform sediment model when applied to the closed system of the HR Carousel, particularly for deposition in slowly decelerating flow. The process of differential settling of different sized aggregates was represented more closely with the distributed sediment model, although flocculation which may occur after specification of the initial distribution was not included.

The distributed model was not particularly sensitive to the number of classes, but was sensitive to the settling velocity of the class representing the largest flocs. The resolution into classes should be finer for the classes with higher settling velocities.

The distributed sediment model was shown to be an adequate model for deposition in the field, although it was not significantly better than a uniform sediment model. External influences which advect sediment to the point being modelled were not represented. However, the model could be used to separate the local effects from the advected effects. The importance of using field data to evaluate models was emphasised.

A settling velocity distribution and associated distribution of shear for deposition were required for the distributed sediment model: these data are becoming more readily available with techniques for *in situ* measurements of settling velocity and floc size distribution.

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□ RESUMÉ □

Un modèle numérique de dépôt de distribution des sédiments cohésifs a été appliqué en laboratoire et sur une zone expérimental. Un modèle des sédiments uniformes a été appliqué aux mêmes zones. Pour le modèle de distribution des sédiments, chaque classe de taille des sédiments (représentant différentes tailles de flocs) est caractérisée par sa vitesse de sédimentation et sa contrainte de cisaillement critique de dépôt. Les modèles ont été appliqué en laboratoire pour des essais de sédimentation en canal circulaire. Les essais de modélisation physique furent réalisés en régime d'écoulement permanent et graduellement diminué. Le modèle de distribution de sédiments s'est avéré être un modèle plus performant pour les régimes graduellement diminués. Il s'est aussi montré sensible à la vitesse de sédimentation notamment dans la classe correspondant aux flocs les plus gros. Il est donc important d'avoir des méthodes plus précises de détermination de la taille des flocs et de leur vitesse de sédimentation. Les deux modèles furent également appliqué lors des campagnes de mesures de sédimentation réalisées dans l'estuaire de la Mersey en Grande Bretagne. Il ont montré une assez bonne adéquation aux données mais le modèle de distribution de sédiment n'a pas significativement amélioré le modèle uniforme dans le cas d'application sur le terrain. On a pu mettre en évidence que les mesures recueillies étaient soumises à des influences externes à la zone étudiée.