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INTERACTION
BETWEEN
MUD AND SAND

Field measurements of settling velocities and floc sizes in the ferry channel near Holwerd

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TKI MUSA project

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About the MUSA project

Estuaries and tidal basins form the transition zones between land and sea. They contain important habitats for flora and fauna and are extensively used by people, like for navigation. For ecological and navigational purposes, it is important to understand and predict the evolution of channels and shoals, including sedimentation rates and the composition of the bed sediments. The bed material of large estuaries and tidal basins largely consists of mixtures of mud and sand, with predominantly sandy channels and mainly muddy intertidal areas. The interaction between sand and mud, in combination with currents and waves, leads to complex dynamics in these areas, with migrating channels and shoals.

Much is known about the behaviour of the individual sediment fractions, but the knowledge and understanding of sand-mud interaction remains limited, as do the available tools and models to accurately predict the bed evolution and sediment transport rates in sand-mud areas. Existing models, like the ones by Van Ledden (2003), Soulsby & Clarke (2005) or Van Rijn (2007) have only limitedly been verified with observations due to a lack of good quality observational data. Also, none of the available approaches cover the complete spectrum of sand-mud interaction, which includes settling, erosion processes induced by the combination of waves and currents, and the bed shear stress. Therefore, in practice sand and mud fractions are often treated separately. This decoupled approach limits the predictive capacity of numerical models, and therefore the impact of human intervention such as deepening of channels and port construction on maintenance dredging volumes and other morphological changes.

In the MUSA-research project, a consortium of contractors, consultants and research organizations join forces to increase the understanding of sand-mud dynamics by means of fieldwork campaigns and laboratory experiments, and to implement this knowledge in engineering tools and advanced models for the prediction of mud and sand transport and associated morphology in tidal conditions with both currents and waves.

Summary

Settling velocities and floc sizes have been studied in laboratory conditions and in field conditions (Holwerd site, The Netherlands) using a simple mechanical insitu settling tube (PIRANHA-tube) and a sophisticated video camera system (LABSFLOC2). The results of the laboratory and field tests are described, analyzed and compared

The laboratory tests involved settling velocity and floc size measurements of various sediment samples collected in the MUSA-Project. The sediment samples were used to make uniform suspension (concentrations in the range of 100 to 5000 mg/l) in saline water (salinity of 35 ppt). Subsamples were taken and transferred to the settling chamber of the video-camera system. The observed floc sizes are in the range of 50 to 350 μm. The characteristic settling velocities are in the range of 0.5 to 15 mm/s; most values are in the range of 1 to 10 mm/s. The settling velocity increases with concentration in the low concentration range (< 500 mg/l), most likely caused by flocculation processes. The median settling velocities are relatively low (2-5 mm/s) for initial concentrations > 1500 mg/l (except for very sandy samples). The reduction of the settling velocity for higher concentrations may be caused by hindered settling processes affecting the macro-flocs, but it may also partly be related to imperfections of the sampling and test procedures which involves the preparation of base suspensions with very small amounts of mud and sand. Although there is considerable scatter, the settling velocities show a weak increase of the median settling velocity for increasing percentage of sand; the settling velocity increases from about 2 tot 8 mm/s for very muddy samples to about 4 to 14 mm/s for very sandy samples. The settling velocity range of 2 to 8 mm/s for muddy samples is rather high in comparison to the settling results of the traditional sedimentation methods (from settling tube measurements), which typically give median values mostly in the range of 0.1 to 2 mm/s for muddy samples. Analysis of the basic LABSFLOC2-camera data of the floc populations shows that the amount of data with floc sizes < 30 μm is extremely small: often zero and up to 4% in some cases. Based on this, two conclusions are possible: particles/flocs < 30 μm are not present in the samples or the LABSFLOC2-instrument is not capable to observe particles/flocs smaller than 30 μm. In the latter case, the median floc size and the corresponding median settling velocity may be overestimated, although the mass-averaged settling velocity will be little affected.

The field measurements involved settling velocity and floc size measurements at the tidal site of Holwerd in The Netherlands on 24 May 2022 using the PIRANHA-tube and the LABSFLOC2-video camera system. The settling tests results of the LABSFLOC2-instrument (HR Wallingford, UK) show the presence of particles and flocs with sizes in the range of 20 to 400 μm. The bulk of the data points are in the range of 50 to 250 μm; the number of data points with particle and floc sizes < 30 μm is rather small (mostly < 2% and maximum 4% for test S01). The median floc size is in the range of 80 to 160 μm (120±40 μm). The median settling velocity of the LABSFLOC2-method is in the range of 2 to 12 mm/s.

Comparison of the settling velocity distributions shows that the results of both instruments are reasonably similar for high initial concentrations > 2000 mg/l; the median settling velocity is in the range of 1.5 to 2 mm/s. The results of both methods deviate significantly for low initial concentrations. The PIRANHA-settling tube produces a median settling velocity of the order of 0.05-0.1 mm/s for an initial concentration of about 400 to 500 mg/l, whereas the LABSFLOC2-method gives a median settling velocity of the order of 3 to 7 mm/s. The main causes for these deviations at low initial concentrations are: i) the observation/presence of the larger macro-flocs > 160 μm is underestimated by the mechanical settling tube, as the fragile flocs may have been broken upon or during sampling (bias towards smaller sizes); and ii) the observation/presence of the individual particles and micro-flocs (< 30 μm) is severely underestimated by the LABSFLOC2-video camera instrument (bias towards larger sizes); sizes smaller than about 30 μm are less frequently measured. Analysis of the floc data measured by the LABSFLOC2-instrument shows that the total mass of sediments in the samples is underestimated by maximum 20%, which may seem a low value, but it represents a rather high amount of fine flocs are not observed by the LABSFLOC2 -instrument. The error in the mass-averaged settling velocity will, however, only be a few percent.

Recommendations are given for further work on settling velocities using both instruments.

Contents

1 Introduction

The settling velocity is an important parameter for sedimentation studies in muddy environments. It is largely dependent on the amount of flocculation. Often, flocculation processes are promoted in conditions with saline water (marine conditions) and high concentrations.

Two types of studies on settling velocities and floc size have been performed in the MUSA-Project:

- Measurement of settling velocities and floc sizes in laboratory conditions;
- Measurements of settling velocities and floc sizes in field conditions (Holwerd ferry channel, Wadden Sea, The Netherlands).

The laboratory study involved has been done by Prof. A. Manning of HR Wallingford (UK) and University of Plymouth (UK) using the LABSFLOC2-instrument.

For the measurements of settling velocities and floc sizes in the field, the following methods and instruments are used:

1. In situ settling test (IST): the sampling instrument (bottom-withdrawal tube or side-withdrawal tube; Van Rijn 2012) is used to take a water-suspended sediment sample and is afterwards used as a settling tube;
2. Laboratory settling test (LST): water-suspended sediment samples are taken by a cylinder-type of sampler (Van Dorn sampler) with valves on both ends or by a pump sampler; the samples are returned to the laboratory (sometimes on site) for a settling tube test;
3. Settling velocities derived from moving particles and flocs recorded by a camera system (LABSFLOC2-instrument): two options are possible:
   a. camera can be lowered into the water column or
   b. water samples are taken and immediately analyzed by camera recordings in on site laboratory.

Prof. A. Manning from the University of Plymouth and HR Wallingford took part in the field measurements on 23, 24 and 25 May 2022. He operated and analyzed the results of the LABSFLOC2-instrument.

In this report, the results of the laboratory and field tests are described, analyzed and compared.

2 Methods, instruments and procedures

2.1 General

In this section, the measuring equipment, the test setup and the test procedures are explained, both for laboratory and field conditions at the Holwerd site in The Netherlands.

The measuring instruments are provided by WaterProof (mechanical PIRANHA settling tube) and by HR Wallingford (LABSFLOC2-video camera system; Prof. A Manning).

2.2 Laboratory experiments

2.2.1 Test setup and procedure

The overall test procedure of the laboratory tests, is as follows:

- preparation of suspension in a jar with a magnetic stirrer;
- extraction of water-sediment sample using a pipette;
- transfer of sample to settling column connected to video-camera system (LABSFLOC2-instrument);
- recording and registration of settling particles and flocs by video-camera system;
- analysis of floc recording data to produce particle/floc sizes and settling velocities; floc densities based on Stokes settling equation.

2.2.2 LABSFLOC2 instrument

The video-based LABSFLOC2-instrument can be used to measure floc sizes, and floc settling velocities simultaneously within a natural settling process with minimal interference to the aggregates.

The video-based LABSFLOC2 (Laboratory Spectral Flocculation Characteristics) is widely regarded as a benchmark system when measuring a wide range of floc characteristics, dynamical properties and types. It is a portable laboratory instrument utilizing a low-intrusive, high resolution video camera to observe flocs as they settle in a settling column constructed of Perspex, see Figure 2.2.1. The video camera utilizes a back-illumination system, whereby floc images are manifested as silhouettes; i.e., particles appear to be dark on a light background. This reduces image smearing and renders the floc structure more visible. A subsample is extracted from field water-sediment samples or laboratory jar/bottle/flume samples and is immediately transferred to the camera-connected column using a modified pipette (maximum 50 ml). The perspex settling column has a square cross-section of 100x100 mm^2 and a vertical length of 350 mm. The video camera, the centre of which is positioned 75 mm above the base of the column, views all particles in the centre sheet (1 mm depth; 45 mm from the camera lens) of the column with as they settle from within a predetermined sampling volume. The total image volume is nominally 6 mm high, 8 mm wide and 1 mm deep. The digital floc images are captured at a frame rate of 7.5 Hz (one frame is 0.113 s), at a resolution of 1600 × 1200 pixels, with an individual pixel nominally representing 5 μm.

A modified pipette (standard Pipette filler: Thumb Wheel type of 25ml together with either a 25ml or 50ml polycarbonate pipette) is used to carefully extract a subsample with flocs from the available mud suspension with known sediment concentration. The procedure comprises a volume of the suspension containing the flocs so that it is to a height of 50 mm (marked to the top of the tape on the pipette, see Figure 2.2.1) in the pipette near the open orifice end (i.e. fluid head). The sample volume in the pipette is of the order of 2,500 mm^3 = 2.5 ml (sample height=50 mm; diameter$\cong$8 mm). The vertically held pipette is brought into the settling column and the flocs can freely settle due to gravity through the pipette opening (diameter 6 to 7 mm) into the settling column. The pipette is held in contact with the top of the settling column for a specific duration, nominally based on the SSC; the lower the SSC, the longer duration the pipette is held there; this controls the number of flocs entering the clear water column and thus prevents the column and video camera view of the settling flocs becoming saturated and too cloudy. Thus, the pipette contact time can be adjusted to control the release of a sample volume with sufficient number of flocs (volume adjustment). The orifice of the pipette is approximately 6 to 7 mm in diameter, so that it can maintain the upper vacuum to retain the captured suspension, but large enough to not restrict large macro-flocs passing through into the settling column. Thus, the flocs allowed to pass into the settling column are naturally segregated as they fall by the process of differential settling. Therefore, the fastest falling aggregates are observed first by the integral video camera and these flocs are recorded at the start of a sample record.

The perspex internal grid of the settling column assists with the flocs settling in a more vertical plane for 2/3 of the settling distance. The internal grid is not present in the lower part of the column so as not to restrict the optical view of the camera. The camera views the flocs in a image sheet which is 6 mm high, 8 mm wide and 1 mm thick (1 mm depth of field) in the centre of the settling column. The flocs settling through the camera image sheet come from a 1 mm thick, 8 mm wide and 50 mm high volume in the pipette (control volume of 1x8x50= 400 mm^3 = 0.4 ml), see Figure 2.2.1.

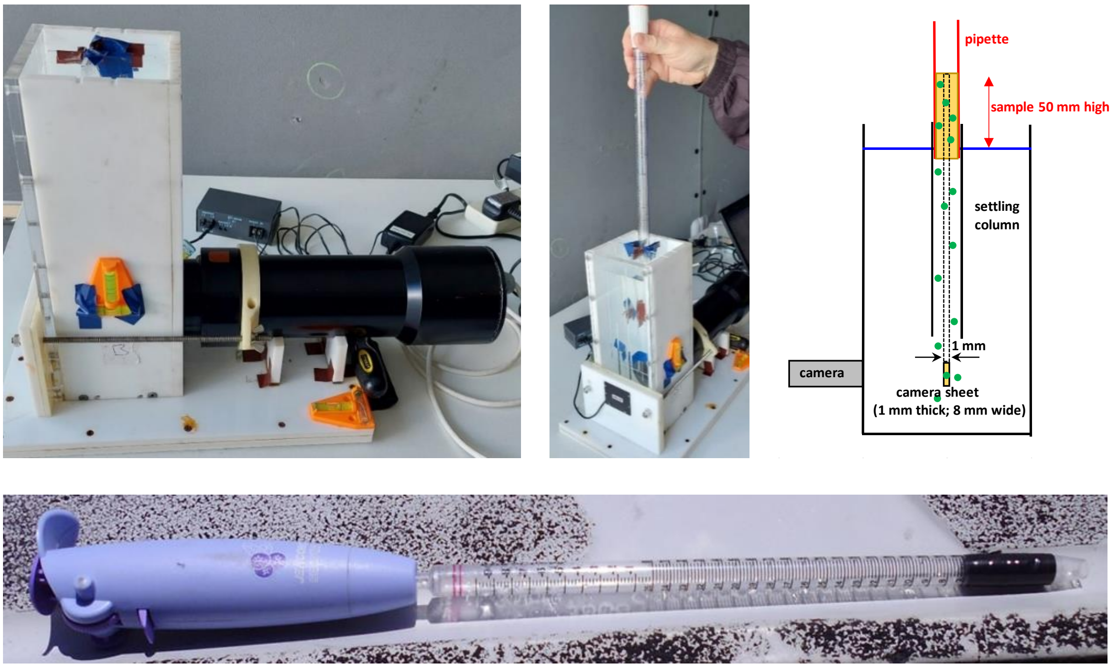


Figure 2.2.1 *LABSFLOC2-instrument as used on the field site of Holwerd (NL)*

The floc collection and sub-sampling protocols are both proven floc sampling techniques, which permit minimal floc interference and flocs representative of the ambient population, especially in terms of floc size and settling velocity distributions.

The floc sampling techniques also provide control volumes, which enable mass-balancing of the floc sample and permits settling flux estimations. Extensive testing of this sampling protocol has revealed that this technique creates minimal floc disruption during acquisition and transfer to the column. Furthermore, the settling column is filled with water of the same temperature and salinity as the in-situ fluid; this reduces the risk of a negative density effects.

This controlled volume with known concentration permits the calculation of the total sediment mass in the settling column. The LABSFLOC2-instrument can measure minimum particle sizes of 5 μm and maximum floc sizes of 8 mm in diameter and settling velocities approaching 45 mm/s.

The sphere-equivalent floc diameter is calculated from the measured major and minor axis of each observed two-dimensional floc ($D=(D_{major} x D_{minor})^{0.5}$). Each floc settling velocity is determined by measuring the vertical distance that the floc travels between a sequence of frames. The Stokes settling velocity law is used to compute the effective floc density. Based on image-analysis algorithms, the floc porosity, fractal dimensions, floc dry mass and the mass settling flux of a floc population are computed. The computed dry mass of the measured particles and flocs can be compared with the total mass in the settling column (i.e. a mass-balanced referenced floc population), thus providing an estimate of the efficiency and reliability of each sampling procedure.

The mass settling flux (MSF) is generically defined as the product of the suspended sediment concentration SSC and the settling velocity (w_s). It becomes the depositional flux in quiescent waters. The MSF can be calculated from LabsFloc-data by multiplying the SSC represented by an individual floc, by its respective settling velocity. If all individual floc settling fluxes are summed for a single population, the sample total MSF can be calculated. Similarly the MSF for a specific size-fraction can be calculated. Thus, spectral estimates of mass settling flux can be made.

The reliability of the LABSFLOC2-settling velocity and effective density estimates are demonstrated by tests of the settling of pure sand grains (Manning et al., 2013). Particles of Redhill 110 fine sand were released and video-registrated by the LABSFLOC2-system. Redhill 110 has a d_{50} of about 110 µm, with a d_{10} of 70 µm and a d_{90} of approximately 170 µm. Table 2.2.1 shows the predicted settling velocities (Soulsby et al., 1997; van Rijn, 1984) corresponding to these sizes.

Table 2.2.1 *Properties of Redhill 110 sand*

Size fraction	Size (mm)	Settling velocity (Soulsby, 1997) (m/s)	Settling velocity (Van Rijn, 1984) (m/s)
d10	0.07	2.9E-03	3.2E-03
d50	0.11	7.1E-03	8.0E-03
d90	0.17	1.6E-02	1.9E-02

Figure 2.2.2 shows the measured settling velocity of around three hundred Redhill 110 sand grains. The results show that the LABSFLOC2-observations correctly identify the range of settling velocities of the Redhill sand and produce density observations which closely follow the 1600 kg//m^3 excess density (ρ_s - ρ_w) contour which relates to pure sand.

Detailed information is given by Manning, 2006; Manning and Dyer, 1999, 2007; Manning et al. 2006, 2007, 2010, 2011, 2013, 2017. Van Leusen and Cornelisse (1996) have used and described a different video-camera system.

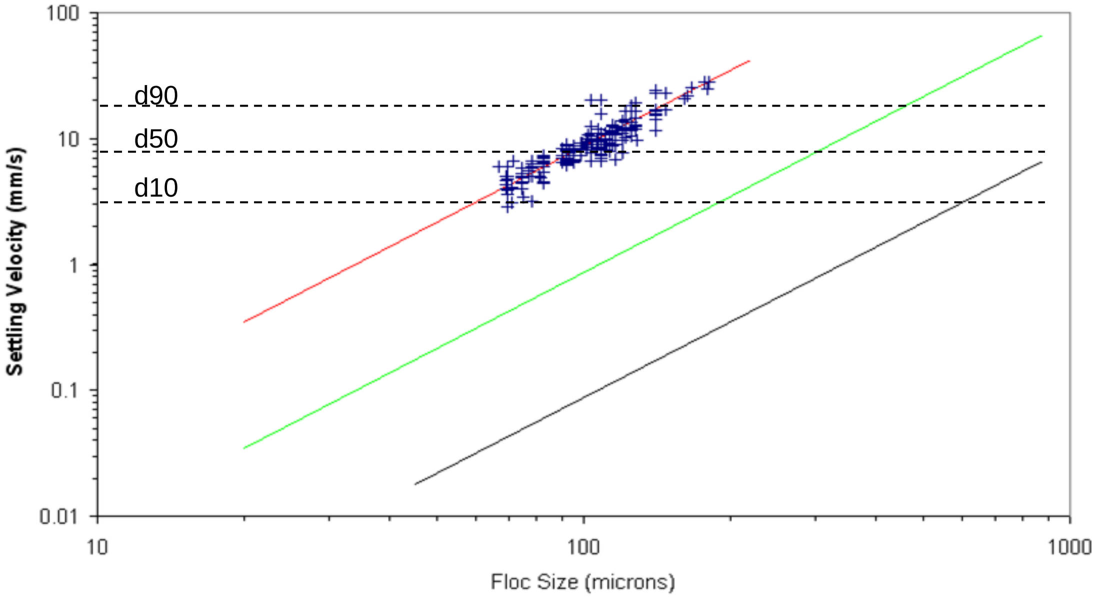


Figure 2.2.2 *Settling velocity vs. floc size for a 100% sand sample. Diagonal lines represent contours of constant Stokes equivalent effective density: red = 1600 kg/m^3, green = 160 kg/m^3, and black = 16 kg/m^3*

2.3 Field experiments

2.3.1 Field site

The measurements were executed on 24 May 2022 near the ferry landing pier at the village of Holwerd in the Dutch part of the Wadden Sea, see Figure 2.3.1.

The water samples were taken from location B (at 1 m above the local bed) at the end of the small wooden pier close to the ferry pier for determination of settling velocities by two instruments (LABSFLOC2-instrument) and the mechanical PIRANHA-settling tube. Background data of current velocities (Aquadopp), water levels, mud concentrations (OBS) and particle size (LISST-100X; Agrawal and Pottsmith, 2000) over the tidal cycle were measured from a bed-standing frame connected by cables to the survey boat of WaterProof.

The water depth at location B varied between 1.5 and 4 m over the tidal cycle, see Table 3.2.1.

Tidal data on 24 May 2022:
HW at 6.00 hours; LW at 12.15 hours; HW at 18.15 hours; Tidal range≅ 1.7 m.

The local bed consists of soft, muddy sediments with wet density of about 1400 kg/m^3 and dry density of about 650 kg/m^3 based on a bed sample taken on 24 May by using the Van Veen-grab, see Figure 2.3.2.

The local bed was so soft that a wooden stick with diameter of 25 mm could easily be pushed into the bed over a length of 1 m (required force about 1 kg/cm^2 = 98 KPa).

Figure 2.3.1 *Sampling location Holwerd pier*

Figure 2.3.2 *Mud sample taken with Van Veen-grab at location B*

2.3.2 Instruments

Insitu settling tube (PIRANHA-instrument)

The PIRANHA-instrument (P-instrument) is a combination of a water-sediment sampler and a settling tube (IST-method) by placing it in upright position standing on its tail fin, see Figure 2.3.3.

The P-instrument has valves on both ends and is lowered in horizontal position with open valves to the sampling point in the water column. The valves are closed by pulling a rope and the instrument is raised in horizontal position and transferred to the on-site laboratory where it is gently turned over a few times to create a homogeneous suspension and then placed in vertical position to start the settling process (t=0). Small subsamples of water and sediments are taken by opening a small tap at the side of the tube at preset times over a period of 3 hours (side withdrawal method). The volume of each sample is noted; the sediment is removed from the sample by filtration (Figure 2.3.4), the sediment sample is dried and weighed to determine the sediment concentration of the subsample. The settling velocity curve can be derived from the decrease of the sediment concentration over time, see Table A.2 of ANNEX A.

The settling process in a homogeneous (well-mixed) suspension with height h and sediment particles of the same size and thus constant settling velocity (w_s) can be described by a balance-type of equations: $h dc/dt + w_s c = 0$ resulting in an exponential decrease of the sediment concentration $c = c_o \exp((-w_s/h)t)$ with c_o=initial concentration at time t=0. If the concentrations at time t=0 and at time t are known (measured), the settling velocity can be determined by applying the theoretical exponential relationship. Thus, only 2 measurements are sufficient. However, this relationship is only valid for a homogeneous (i.e. well-mixed) suspension with a constant settling velocity and can not be applied for a mixed mud-sand suspension with a wide range of settling velocities and/or in stagnant water.

Therefore, another method is used, which is known as the pipette method, similar to the classic ANDREASEN-ESENWEIN pipet method for laboratory conditions (Van Rijn, 2012). The basic principle is that the concentration at a point decreases as function of time. Particles having a settling velocity greater than that of the size at which separation is desired will settle below the point of withdrawal after elapse of a certain known time (Guy et al 1966 US geological survey). A subsample taken at time t at height h_s below the surface of the suspension contains only particles/flocs with a settling velocity smaller than h_s/t. The mass fraction smaller (percentage x100%) is given by the ratio of the concentration at time t and the initial concentration co at time t=0.

The PIRANHA-tube sedimentation method is used in a slightly different way, because the settling height varies over time due to the subsamples taken regularly. The settling height is calculated at each time based on the volume of the subsample and diameter of the settling tube. This introduces additional errors. Furthermore, the regular opening of the tap may introduce small error due to eddy production in the suspension. This may result in an underestimation of the settling velocity, notably of the smaller fractions.

The most accurate sedimentation methods are:1) the continuous measurement of the deposited mass on an underwater balance at the bottom of a settling tube (Bishop, 1934) and 2) the traditional hydrometer which uses a float in a high-concentration suspension (MUSA report particle size and settling velocity, 2023). Both methods are typically laboratory methods and difficult to apply in field conditions. Comparative laboratory measurements show that the settling results of the side-withdrawal tube method (PIRANHA method) are in good agreement with the settling results of the hydrometer results (MUSA report on particle size and settling velocity). This also means that the side-tap does not introduce much error.

An additional field sampling error of the PIRANHA-method may be the breakup of flocs in to smaller flocs due the vibrations generated during closure of the valves on both ends of the tube resulting in more smaller flocs with a lower settling velocity. This error can only be evaluated by comparing with settling results of other methods (additional laboratory studies required).

It is noted that the PIRANHA-tube is designed for the measurement of the settling velocity of mud particles and microflocs. It can not very accurately measure high settling velocities of sand and macroflocs (range of 5 to 10 mm/s), because the first subsample is taken after 1 minute so that initial eddies have died out. It is assumed that 100% of the sediment has settling velocity < 10 mm/s corresponding to 120 micron sand.

The P-instrument is an insitu-side-withdrawal tube and is a modified copy of the FIPIWITU, which has been developed by Deltares around 1990 (Van Rijn, 2012; Van Leussen and Cornelisse, 1996). Another type of mechanical insitu-settling tube is the bottom-withdrawal tube (Owen-tube; Van Rijn, 2012). This latter method may give practical (inaccuracy) problems as it requires the removal of a soft mud sample from the bottom end of the tube.

Van Kessel (2003) gives a detailed discussion of all possible errors related to the determination of settling velocity, particularly for settling tube measurements.

Figure 2.3.3 *PIRANHA-instrument; In situ settling tube*

Laboratory settling tube

For comparison with the settling test results of the PIRANHA-instrument, a simple laboratory settling tube (LST-method) was also used to perform settling tests with water-sediment samples from the Holwerd site. The LST-method consists of a vertical Perspex cylinder (column) with a small tap on the side of the tube at 70 mm above the bottom of the tube, see Figure 2.3.4. The tube is filled with a sample of about 2 liters taken from the field site. A rod with a small plate at the bottom end is used to create a homogeneous suspension by gently moving the rod up and down in the column with water-sediment sample. The settling process starts when the rod is removed from the tube (t=0). Small subsamples of water sand sediments are taken by opening a small tap at the side of the tube at preset times over a period of 3 hours. The LST was operated in the delivery van of WaterProof at the site (on site laboratory).

Figure 2.3.4 *Laboratory settling tube with tap on side; water-sediment sampler; filtration set*

LABSFLOC2-instrument

This instrument is described in Section 2.2.2.

Water-sediment samples from the field site were transferred to the LABSFLOC2-instrument operated in the delivery van (onsite laboratory) of WaterProof.

Other instruments

The following sensors were mounted on a steel frame which was lowered to the bed (Figure 2.3.6):

Aquadopp:	acoustic doppler instrument for measuring current velocity in a single point
OBS:	optical sensor for measuring mud concentration
LISST100X:	optical instrument for measuring in situ particle size distributions; two size-ranges are available:1.25-250 microns (Type B) and 2.5-500 microns (Type C) utilizing a collimated laser diode and a specially constructed annular ring detector; scattering at 32 angles is the primary information that is recorded by the ring detector; results were not used as the water was much too turbid for realistic measurements.

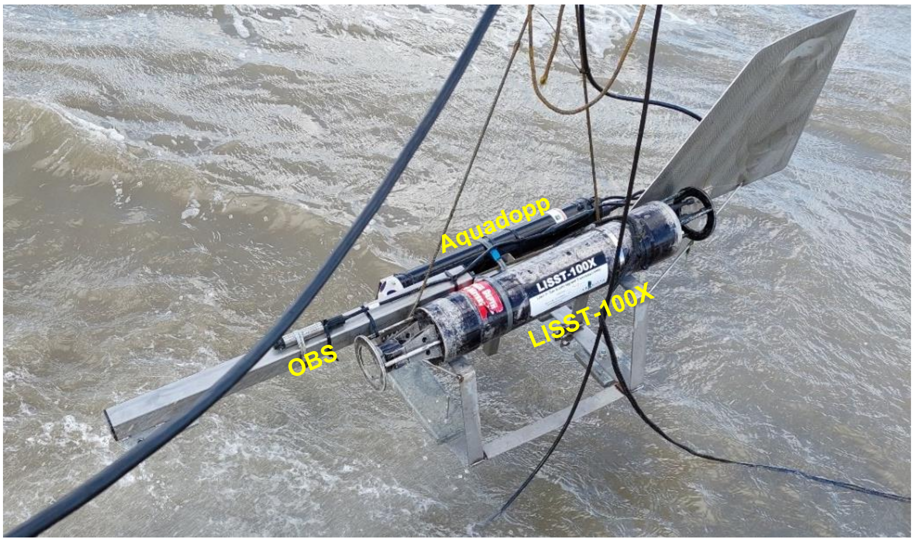


Figure 2.3.6 *Bed frame (fish); Aquadopp for velocity; OBS for mud concentration; LISST-100X for particle size.*

2.3.3 Type of measurements and procedures

The type of measurements and the procedures involved are, as follows:

1. Insitu-settling test (IST-PIRANHA method) using PIRANHA-instrument: the P-instrument was used to collect water-sediment samples at location A for performing a settling test on site (mini laboratory inside van of WaterProof); two samples were taken at 10.00 hours (round 1) and 14.00 hours (round 2) on 24 May 2022, see Figure 2.3.7A,B;
2. Laboratory settling test (LST-PIRANHA method) using sample taken with PIRANHA-instrument: water-sediment sample was collected using the P-instrument; the sample was transferred to a separate settling tube and returned to the mini-laboratory for a settling tests (Figure 2.3.7C); two samples were taken around 10.00 hours (round 1) and 14.00 hours (round 2) on 24 May 2022;
3. Laboratory settling test (LST-pump method) using sample taken with peristaltic pump: water-sediment sample was collected using a pump sampler (peristaltic pump); intake of pump hose was attached to the P-instrument; the sample was pumped into a separate settling tube and returned to the mini-laboratory for a settling tests (Figure 2.3.7D); two samples were taken around 10.00 hours (round 1) and 14.00 hours (round 2) on 24 May 2022;
4. LABSFLOC2-instrument;
   - small subsamples (5 ml) using a pipette were taken from the P-instrument just before the start of the settling test and transferred to the settling chamber of the LABSFLOC2-instrument;
   - small subsamples were also taken and analyzed from a series of water-sediment samples taken by a simple mechanical sampler (Van Dorn type sampler; Figure 2.3.4) over the tidal cycle (interval of 1 hour per sample).

Figure 2.3.7 *PIRANHA-instrument: A: lowered with open valves; B: raised with closed valves; C: samples transferred to settling tube; D: pump sample into settling tube*

2.3.4 Errors involved

Both types of instruments (video-camera systems and mechanical settling tubes) have different types of errors. Van Kessel (2003) has given a detailed discussion of the various types of errors. He distinguishes the following error sources:

1. Sampling errors
The sediment characteristics in the sample should be representative for the local suspended sediment concentration, size, density, shape etc. Fragile macro-flocs may be easily broken due to vibrations using mechanical tubes with valves on both ends.

2. Unaccounted physical processes in the sampling instrument
Physical processes that may not be captured by the sampling instrument are
- The generation of convective flows inside the instrument measuring volume due to temperature differences between the volume inside the instrument and ambient fluid. For example, temperature differences of 1 ^oC may give rise to a convective flow of 0.1 mm/s which may be high with respect to the settling velocity of mud;
- Particle interaction due to differential settling, resulting in particle collisions and associated processes of coagulation, aggradation and flocculation;
- Upward return flow due to the downward settling of particles, influencing the settling of other particles.

3. Data analysis errors
Examples of errors in the analysis of data are
- Assuming that concentrations in the sample volume are homogeneous at the start of the settling process, whereas that may not be the case;
- Using the settling law of Stokes, whereas it may be invalid for the experimental conditions;
- Errors in the floc size detection software (particle shading);
- Errors in the filtering and weighing procedure for determination of mass concentrations.

3 Analysis results of laboratory and field data

3.1 General

In this section, first the analysis results of settling velocities and floc characteristics derived from the settling tests performed in the laboratory of Prof. A Manning are described in Section 3.2 (samples from 2 sites in The Netherlands: Western Scheldt Estuary and Noordpolderzijl-channel, 1 site in Belgium: Scheldt tidal river; 1 site in UK: Plymouth Estuary and 1 site in Bangladesh)

After that, the analysis results of the field data based on the measurements at the Holwerd site in the Wadden Sea (The Netherlands) are presented in Section 3.3.

The basic field data of the PIRANHA-tests and the LABSFLOC2-tests are given in Appendix A.2 and A.3. Further details of the LABSFLOC2-protocols, methodology and set-up, and results from both the MUSA laboratory experiments and MUSA fieldwork, will be outlined in respective MUSA-HRW reports by Prof. A. Manning.

3.2 Laboratory data of LABSFLOC2 instrument

3.2.1 Setup, instrumentation and procedures

Various sediment samples collected in the MUSA-Project were tested in a settling tube attached to a video-camera system (LABSFLOC2) by Prof. A. Manning in Plymouth, UK.

The sediment samples of MUSA were used to make uniform suspension with low concentrations < 500 mg/ (C1-code) and high concentrations <> 1500 mg/l (C2-code) in saline water (salinity of 35 ppt). A reasonable amount from the original sediment sample is taken to make a 'stock slurry'. Artificial seawater is used to ensure that there are no additional nutrients, sticky bio-polymers, etc that may be present in real seawater. The stock slurry is stirred and a subsample is taken to determine the base suspended sediment concentration (SSC) of this stock. A smaller amount from the stock SSC is transferred to a jar and diluted to get as close as possible to the pre-determined SSC.

The initial concentration values of all tests are shown in Table 3.2.1.

The suspension in the jar is stirred by an accurately controlled magnetic stirrer to enhance flocculation processes. The small magnet is placed on the bottom of the glass jar and generates a certain 'shear stress region' at each RPM setting. Based on experience, the jar test approach ensures the correct reproducibility of floc populations.

A modified pipette is vertically connected to the jar to take a subsample from the jar (volume of about 2000 mm^3 with a height of 50 mm in the pipette). The pipette mouth is put into the settling column so that the flocs can simply pass (settle) from the 50mm high fluid volume in the pipette and into the settling column with no actual fluid transfer from the pipette. This results in a control sample volume nominally of 400 mm^3 (1 mm image depth and 8 mm nominal video image width, with a nominal 50 mm high suspension in the pipette).

The camera views through an aperture in the settling column wall at a depth of 230 mm below the column water surface. It records all settling flocs/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 nominally 6 mm high and 8 mm wide.

The controlled volume of 400 mm^3 with flocculated sediments permits LABSFLOC2 calculated floc mass to be compared and calibrated directly to ambient concentration.

All flocs observed from within the control volume are measured and the dry mass of the flocs can be calculated. SSC of 50 mg/l usually means a few 100 flocs measures, and SSC of 500 mg/l means over 1000 flocs measured, so statistically a good representation of each suspension population is obtained

(N_{floc}=SSC x $V_{control}$/(π/6 x D_{floc}^3 x ρ_{floc})=number of flocs=400 with SSC=500 mg/l=0.5 kg/m^3; $V_{control}$=400 10^{-9} m^3; D_{floc}=100 10^{-6} m and ρ_{floc} =1000 kg/m^3).

Having each population equilibrate to the pre-determined SSC, permits a direct inter-comparison between sediment samples.

Extensive testing of this sampling protocol during earlier projects revealed that this technique created minimal floc disruption during acquisition. The complete laboratory setup of the LABSFLOC2-configuration is illustrated in Figure 3.2.1.

Figure 3.2.1 *Laboratory setup of settling tube and video camera system (LABSFLOC2-instrument)*

3.2.2 Settling velocities and floc characteristics

The analysis results are stored in separate excel sheets with the following data:

- total suspended sediment concentration [mg/l] and shear rate range;
- floc size [microns];
- floc effective density [kg/m^3];
- floc settling velocity [mm/s];
- floc fractal dimension [dimensionless];
- floc height/width ratio [floc shape];
- floc porosity [%].

The populations of the settling data are used to make plots of settling velocity versus floc size. A typical plot for sample WAW1 from the Western Scheldt Estuary is shown in Figure 3.2.2. The diagonal lines on each plot represent contours of Stokes equivalent effective density:

- purple line= 1600 kg/m^3 (pure sediment); settling velocity=0.35 mm/s for d_{50}=20 μm and 42 mm/s for d_{50}=220 μm;
- green line= 160 kg/m^3; settling velocity=0.03 mm/s for d_{50}=20 μm and 76.4 mm/s for d_{50}=880 μm;
- red line = 16 kg/m^3 (very watery flocs); settling velocity=0.02 mm/s for d_{50}=20 μm and 6.6 mm/s for d_{50}=880 μm.

Samples	Initial concentration (mg/l) of base/stock suspension;	Initial concentration (mg/l) of base/stock suspension;
	Low concentration range (C1)	High concentration range (C2)
S01_wp = WS-WAW1; p_{sand} = 37%	570	2609
S02_wp = NPZ-H2; p_{sand} = 12%	367	1436
S03_wp = WS-GR1; p_{sand} = 5%	198	3039
S04_wp = WS-HU1; p_{sand} = 88%	196	5268
S05_wp = WS-SA1; p_{sand} = 9%	138	1655
S06_wp = WS-BH1; p_{sand} = 55%	195	1386
S07_wp = WS-ZW2; p_{sand} = 10%	155	1623
S08_wp = NPZ-B8; p_{sand} = 53%	237	1790
S09_wp= BB2G; p_{sand} = 83%	438	3293
S10_wp= BB3; p_{sand} = 6%	411	1897
S11_wp= WS-SO3; p_{sand} = 57%	285	2028
S04_P= Plymouth-muddy; p_{sand} = 10%	198	1788
S05_P= Plymouth-coarse; p_{sand} = 72% (65-80)	497	3261

Table 3.2.1 *Initial concentrations of laboratory base/stock suspensions (WS=Western Scheldt Estuary; NPZ=Noordpolderzijl tidal channel; BB=Bengal Bay, Bangladesh)*

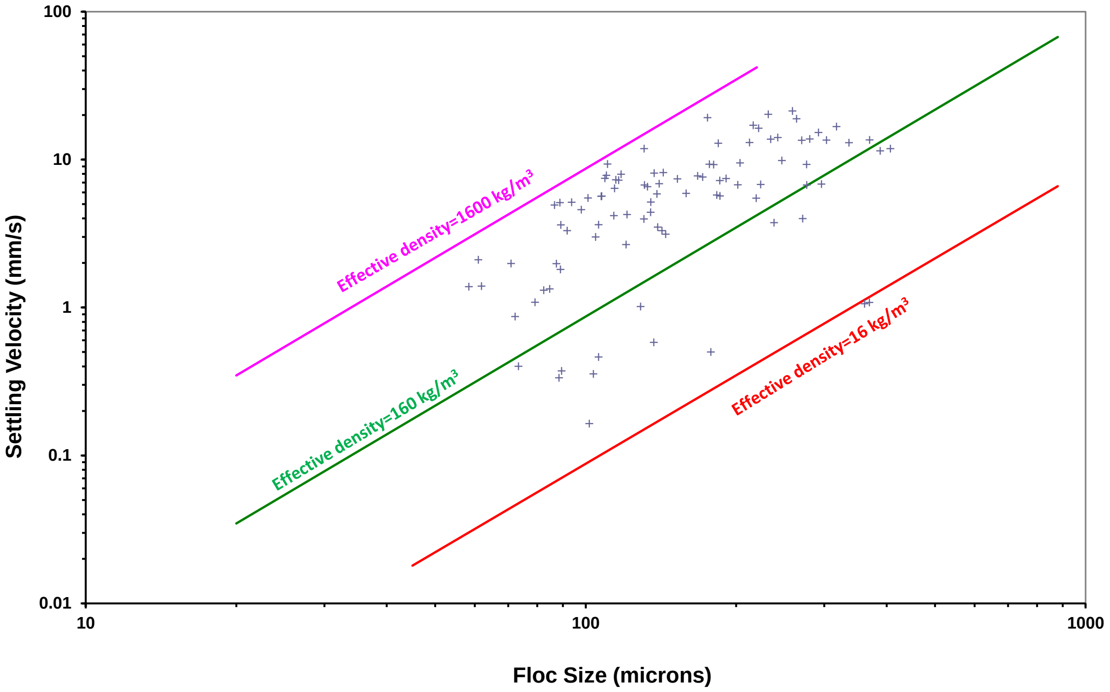


Figure 3.2.2 *Settling velocity as function of floc size of sample S01(WS-WAW1) at initial concentration of 570 mg/l*

To determine the mass percentage within predefined settling velocity values and the associated cumulative settling velocity curve (settling velocity as function of mass percentage), the effective density, the porosity and the dry mass of the flocs have to be determined. The effective floc density can be simply derived from the measured floc size and measured settling velocity using the settling law of Stokes. The derivation of the porosity of flocs and dry mass of the flocs is explained in Appendix A.1. The formulations involved are slightly different from those used by Manning et al. (2017)

Some examples of the effective submerged floc density (ρ_{floc}-ρ_w) as function of the measured floc size (from spreadsheet results provided by Prof. A. Manning) are shown in Figure 3.2.3. The values vary in the range of 200 to 2500 kg/m^3. Thus, the effective density of the flocs varies in the range of 1200 to 3700 kg/m^3 after adding of the fluid density. Floc density values (ρ_{floc}) higher than 2000 kg/m^3 are not realistic. The value of 2000 kg/m^3 is the density of a 'virtual' floc consisting of 60% of sediment and 40% of water, settling as an individual floc-object with a virtual thin plastic skin around it.

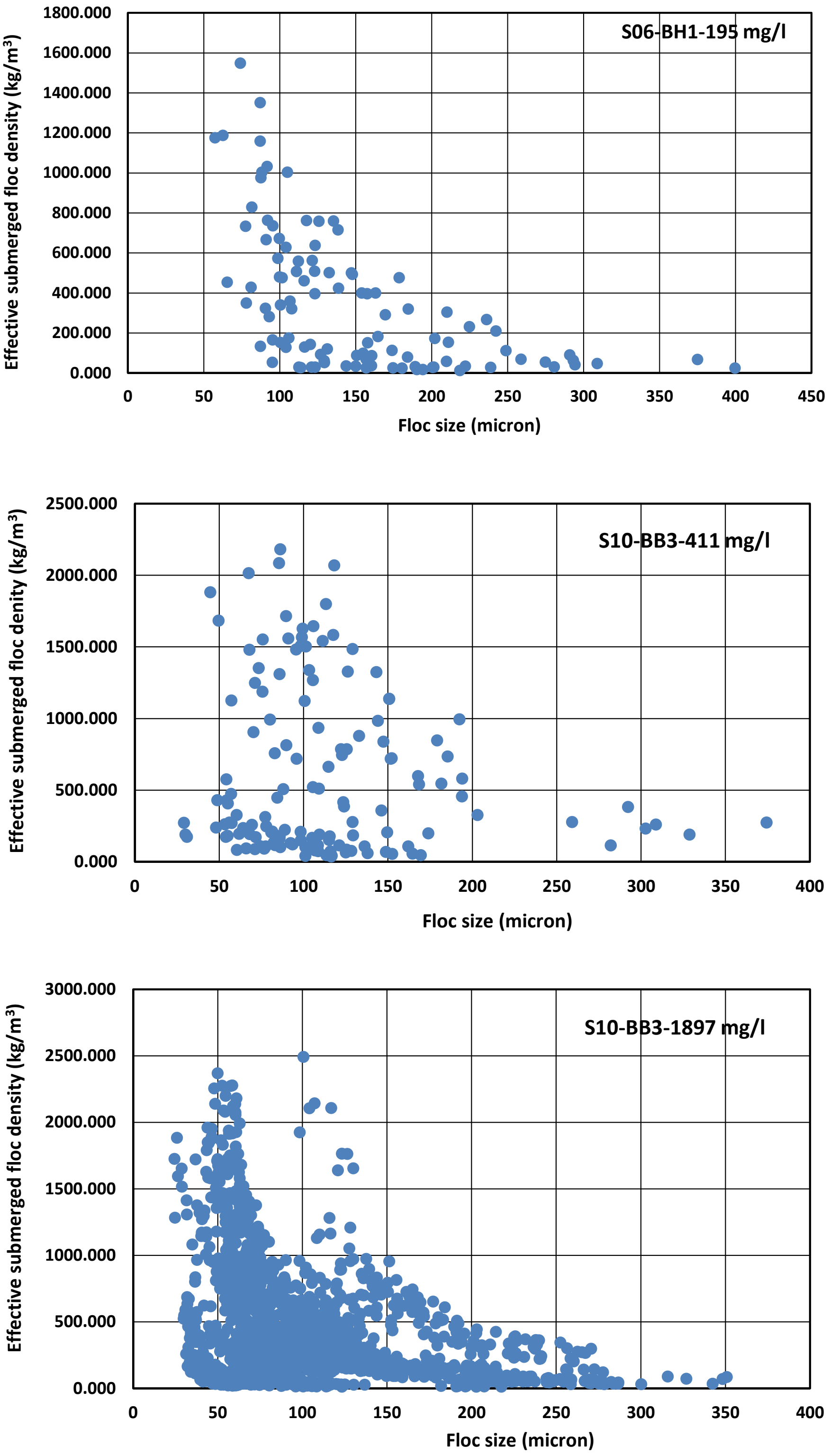


Figure 3.2.3 *Effective submerged floc density as function of floc size for 3 laboratory tests; LABSFLOC2-data*

Figure 3.2.4 shows the settling velocity as a function of the mass percentage smaller for sample S01-WAW1 with initial concentration of 570 mg/l. The dry mass of each floc is computed and summed over all flocs (i.e. 93 flocs) to obtain the total dry mass based on the spreadsheet results (red curve) of Prof. A. Manning. Based on this, the mass within two successive settling velocity values and the cumulative values are computed and plotted. Van Rijn has repeated this procedure (black curve) with a different porosity factor (see Appendix A1). The two curves of Figure 3.2.4 representing the porosity values of Manning et al. (2017) and of Van Rijn (Appendix A.1) show rather good agreement. Hence, both types of formulations for the floc porosity are reliable.

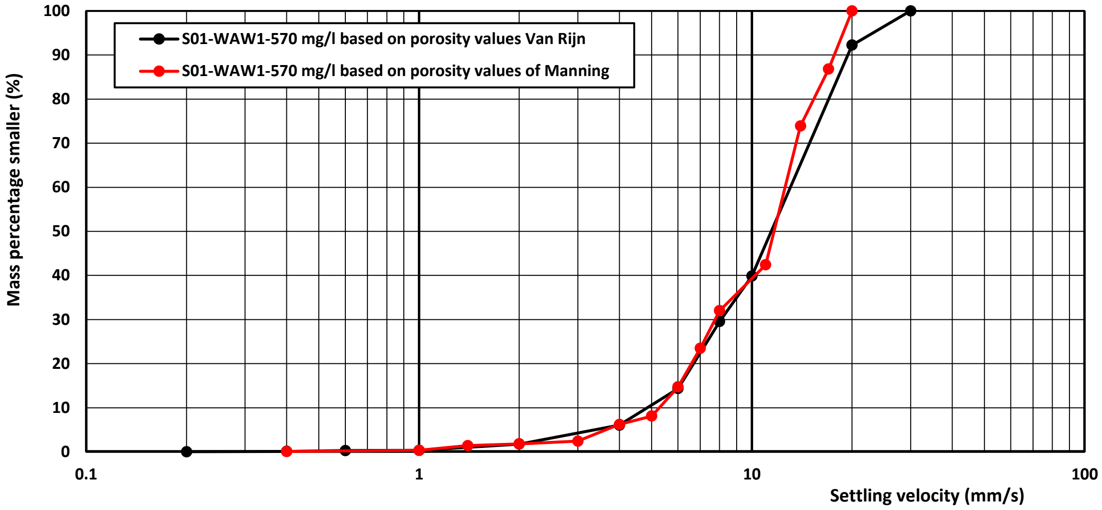


Figure 3.2.4 *Settling velocity distributions of sample S01 (WS-WAW1); initial concentration=570 mg/l*

Figures 3.2.5 and 3.2.6 shows the settling velocity distributions of all samples with low and high initial concentrations. All results are summarized in Table 3.2.2. The percentage of sand (> 63 μm) is included. The values $w_{s,10}$, $w_{s,50}$, $w_{s,90}$ are interpolated from the settling velocity distribution curves (Figure 3.2.5 and 3.2.6). The settling velocities are in the range of 0.5 to 30 mm/s; most values are in the range of 1 to 10 mm/s. The median settling velocity of all samples of the laboratory tests are in the range of 8 ± 6 mm/s, see Figures 3.2.5 and 3.2.6. The percentage of fines < 35 μm with a settling velocity < 1 mm/s is relatively small (< 15%). The floc sizes d_{10}, d_{50}, d_{90} are estimated from similar curves for the floc size (not shown). The floc sizes are in the range of 50 to 350 μm, see Table 3.2.2. The median floc size of all samples is about 150 ± 50 μm.

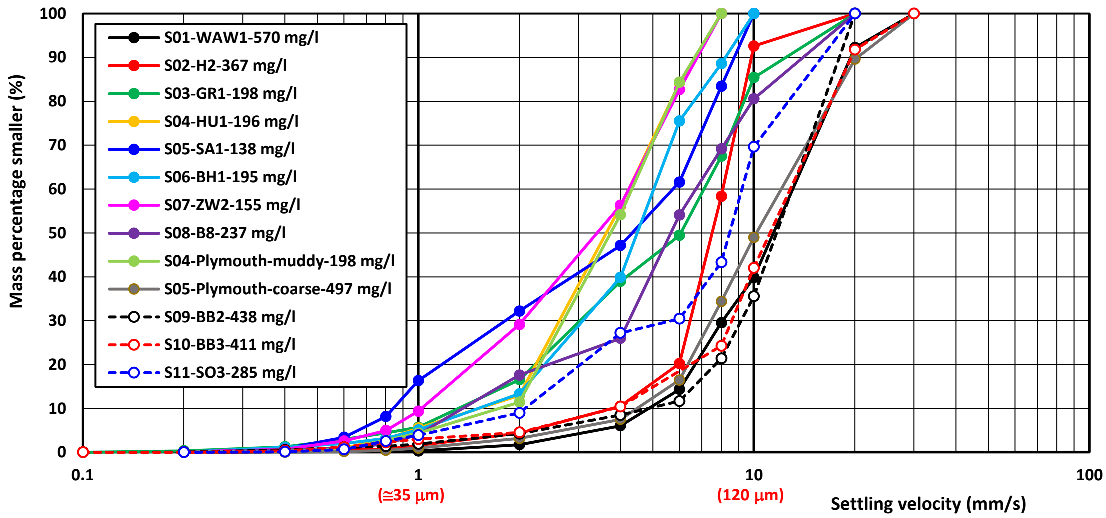


Figure 3.2.5 *Settling velocity distributions of all MUSA-samples; low initial concentration < 500 mg/l*

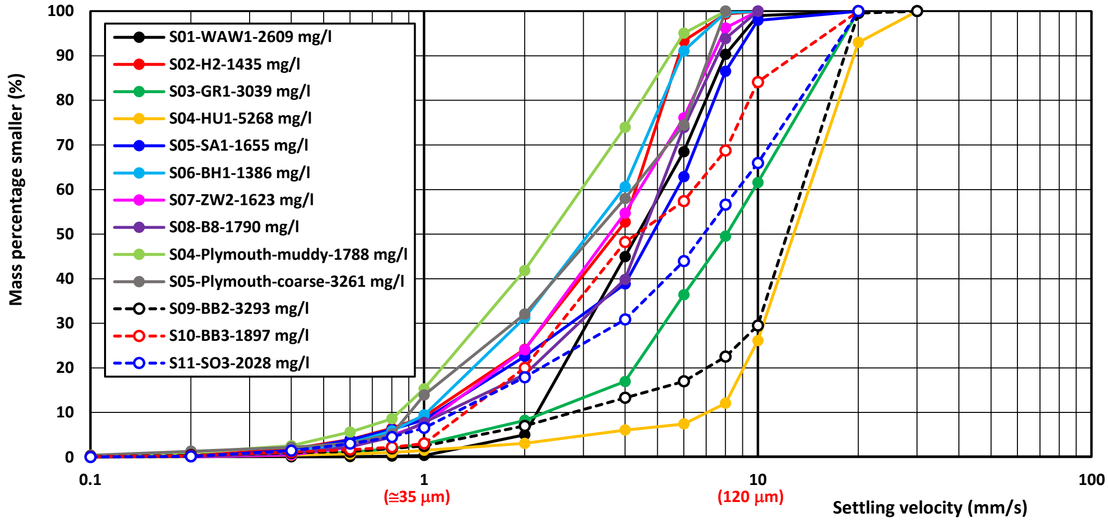


Figure 3.2.6 *Settling velocity distributions of all MUSA-samples; high initial concentration > 1500 mg/l*

The effect of the initial concentration (low of high concentration) on the median settling velocity is shown in Figure 3.2.7. The settling velocity increases strongly with concentration in the low concentration range (< 500 mg/l), most likely caused by flocculation processes. The median settling velocities are relatively low for initial concentrations >1500 mg/l with exception of the two values of very sandy samples. The reduction of the settling velocity for higher concentrations may be caused by hindered settling processes affecting the macro-flocs. However, the onset of the hindered settling processes is generally believed to occur for concentrations higher than about 5000 to 10000 mg/l (Van Rijn 1993).

Figure 3.2.8 shows the measured median settling velocity ($w_{s,50}$) as function of the percentage sand in the sample. The settling velocity is, on average, higher in a suspension with low initial concentrations (< 500 mg/l) than in a suspension with high initial concentrations (> 1000 mg/l), which is most likely related to flocculation and hindered settling effects. The variability may also be related to the sampling and test procedure.

Three samples (WesternScheldt-HU1; Plymouth-coarse and Bengal Bay-BB2G) are very sandy with percentage of sand >70%, see Table 3.2.1. The median settling velocity of these samples is most likely of the order of 10 mm/s given the high sand content (median diameter of the order of 100 μm). Each of these very sandy samples is tested at a low and a high initial concentration resulting in 6 test results. Four test results show median settling velocities > 10 mm/s, but two test results show relatively low values in the range of 3 to 3.5 mm/s. Sample HU1 has a relatively low settling velocity of 3.5 mm/s at a low initial concentration and sample Plymouth-coarse shows the opposite behaviour with a low settling velocity of 3.3 mm/s at a high initial concentration, see Table 3.2.1. Thus, these very sandy samples show a rather high variability range of 3 to 14 mm/s, which is difficult to explain for sandy samples. This high variability may be partly related to imperfections of the sample preparation procedure which involves the preparation of a base suspension with very small amounts of sand and mud. Under-sampling of the coarse fraction of a sample leads to underestimation of the median settling velocity.

Although there is considerable scatter (variability), the trendlines in Figure 3.2.8 show a weak increase of the median settling velocity for increasing percentage of sand; the settling velocity increases from about 2 tot 8 mm/s for very muddy samples to about 4 to 14 mm/s for very sandy samples. The settling range of 2 to 8 mm/s for muddy samples is rather high in comparison to the settling results of the traditional sedimentation methods (hydrometer) giving $w_{s,50}$-values in the range of 0.1 to 2 mm/s for muddy samples. Analysis of measured mud concentration profiles at the Holwerd-site indicate the presence of mud settling velocities in the range of 0.1 to 4 mm/s (see MUSA Report: Results of field measurement campaigns at Holwerd, The Netherlands).

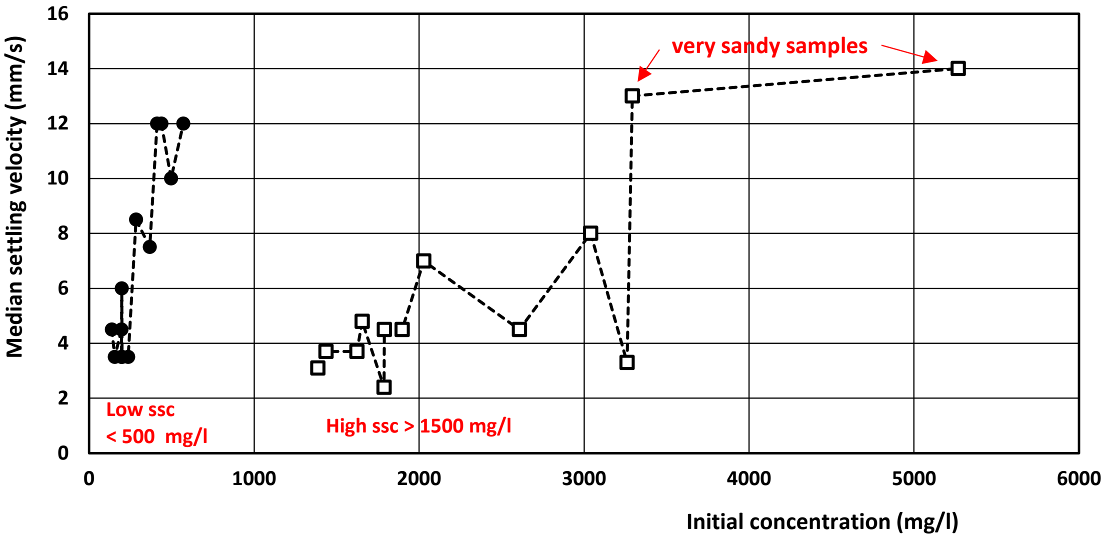


Figure 3.2.7 *Median settling velocity as function of initial concentration*

The present results with relatively large floc sizes and settling velocities raise the question whether the video-camera results (LABSFLOC2-instrument) have a bias towards the better visible macro-flocs with higher settling velocities. To evaluate the overall inaccuracy of the LABSFLOC2-instrument, two additional parameters are studied:

- the number of data points with particle and/or floc sizes < 30 μm and < 50 μm;
- the total dry sediment mass of the flocs of a sample.

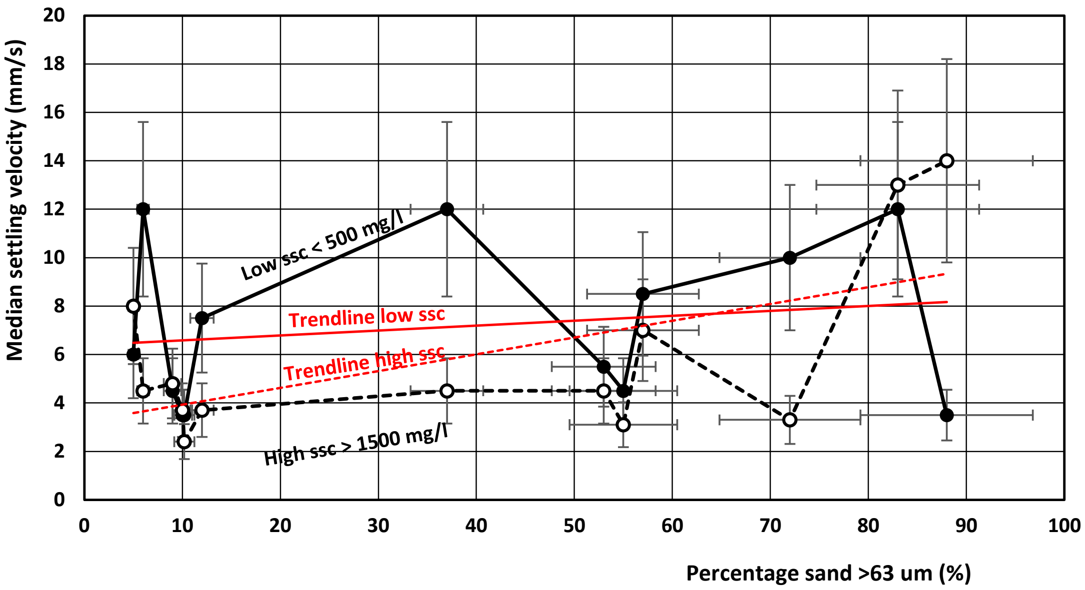


Figure 3.2.8 *Median settling velocity as function of the percentage of sand (at low and high initial concentration)*

Information of the number of data points with particle and/or floc sizes < 30 μm and < 50 μm (spreadsheet data provided by Prof. A. Manning) is given in Table 3.2.3. The amount of data in each population with floc sizes < 30 μm is extremely small: often zero and up to 4% in some cases. Based on this, two conclusions are possible: particles/flocs < 30 um are not present in the MUSA-samples or the LABSFLOC2-system (camera and software) is not capable to observe particles/flocs smaller than 30 μm. In the latter case, the median floc size and the corresponding median settling velocity are overestimated.

Another parameter which may give an indication of the overall inaccuracy involved is the total dry sediment mass of all particles/flocs of each sample measured by the LABSFLOC2-sysem. As the sample volume is approximately known (≅ 400 mm^3, see Section 2.2.2), the total dry mass can be used to compute the initial concentration, which can be directly compared to the initial concentration of the base suspension.

The test results (floc size, floc settling velocity) have been used to compute the floc density (ρ_{floc}) of each individual floc from the Stokes settling velocity equation which includes the floc density, see Appendix A.1.

Van Rijn has derived equations for the computation of the floc porosity and dry sediment floc mass, see Appendix A.1. These equations have been used to compute the floc porosity and dry sediment mass of each floc based on the measured floc size and measured settling velocity (spreadsheet data of Prof. A. Manning). The floc density (ρ_{floc}) is computed from the Stokes settling equation for saline water (1030 kg/m^3) and a water temperature of 20 °C. The porosity equation of Van Rijn Is slightly different from that used by Prof. A. Manning (see also Section 3.3.3).

Some of the data show floc porosity values < 0.3 and even < 0; these values are set to a minimum porosity of 0.3.

The total suspended sediment concentration (SSC) in each sample is computed from $\sum M_{floc,dry}/V_{sample}$ with $V_{sample} \cong 400$ mm^3 (based on information from Prof. A. Manning).

The results for six samples are shown in Table 3.2.4. The computed mud concentration (SSC) values from the LABSFLOC2-data are somewhat smaller (maximum 15%) than the original initial concentration values, which seems realistic as some of the micro-flocs may not have been observed by the video camera system, plus there could also be some overlapping of flocs during settling.

Samples	Floc size at low concentration < 500 mg/l (um)			Floc size at high concentration > 1500 mg/l (um)			Settling velocity at concentration < 500 mg/l (mm/s)			Settling velocity at concentration >1500 mg/l (mm/s)		
	d_{10}	d_{50}	d_{90}	d_{10}	d_{50}	d_{90}	$w_{s,10}$	$w_{s,50}$	$w_{s,90}$	$w_{s,10}$	$w_{s,50}$	$w_{s,90}$
S01_wp = WS-WAW1; p_{sand} = 37%	55	180	245	50	130	250	5	12	20	2.2	4.5	8
S02_wp = NPZ-H2; p_{sand} = 12%	70	140	360	70	150	360	4	7.5	10	1.2	3.7	5.9
S03_wp = WS-GR1; p_{sand} = 5%	55	110	310	50	115	300	1.5	6	14	2.2	8	17
S04_wp = WS-HU1; p_{sand} = 88%	65	210	250	65	135	240	1.5	3.5	7	7	14	19
S05_wp = WS-SA1; p_{sand} = 9%	70	110	230	70	120	225	0.9	4.5	9	1.2	4.8	8.5
S06_wp = WS-BH1; p_{sand} = 55%	75	135	260	70	135	260	1.5	4.5	8	1.1	3.1	6
S07_wp = WS-ZW2; p_{sand} = 10%	70	130	250	70	140	250	1	3.5	7	1.1	3.7	7.5
S08_wp = NPZ-B8; p_{sand} = 53%	50	125	180	45	80	180	1.5	3.5	15	1.1	4.5	7.7
S09_wp= BB2G; p_{sand} = 83%	50	160	260	35	95	210	4	12	18	2.8	13	18
S10_wp= BB3; p_{sand} = 6%	55	100	230	40	90	220	3	12	20	1.5	4.5	15
S11_wp= SO3; p_{sand} = 57%	65	170	280	65	150	290	2	8.5	17	1.3	7	17
S04_P= Plym-muddy; p_{sand} = 10%	65	220	250	65	130	255	1.7	3.5	7	0.85	2.4	5.5
S05_P= Plym-coarse; p_{sand} = 72%	75	180	250	70	125	260	3.5	10	20	0.9	3.3	7.1

Table 3.2.2 *Settling velocity; low and high ssc; mid-shear range*

Samples	Settling tests performed at initial concentration <500 mg/l			Settling tests performed at initial concentration >1500 mg/l		
	Total number of data points	Number of data points with floc size < 30 μm	Number of data points with floc size < 50 μm	Total number of data points	Number of data points with floc size < 30 μm	Number of data points with floc size< 50 μm
S01_wp = WS-WAW1; p_{sand} = 37%	90	0	0	1232	6 (0.5%)	39 (3%)
S02_wp = NPZ-H2; p_{sand} = 12%	110	0	<5	1014	0	35 (4%)
S03_wp = WS-GR1; p_{sand} = 5%	130	0	0	1287	6 (0.4%)	133 (10%)
S04_wp = WS-HU1; p_{sand} = 88%	85	0	<3	1165	0	41 (3.5%)
S05_wp = WS-SA1; p_{sand} = 9%	155	0	<10	1240	0	61 (5%)
S06_wp = WS-BH1; p_{sand} = 55%	105	0	0	1112	0	21 (2%)
S07_wp = WS-ZW2; p_{sand} = 10%	110	0	<3	1105	0	21 (2%)
S08_wp = NPZ-B8; p_{sand} = 53%	120	0	<10	1739	7 (0.4%)	277 (16%)
S09_wp=BB2G; p_{sand} = 83%	125	0	<10	1681	63 (4%)	393 (23%)
S10_wp=BB3; p_{sand} = 6%	140	2 (1.5%)	<10	1574	8 (0.5%)	186 (12%)
S11_wp=SO3; p_{sand} = 57%	100	3 (3%)	<10	1181	6 (0.5%)	64 (5%
S04_P=Plymouth-muddy; p_{sand} = 10%	80	0	<5	1198	0	20 (2%)
S05_P=Plymouth-coarse; p_{sand}=72%	90	0	0	1120	3 (0.3%)	43 (4%)

Table 3.2.3 *Floc size data points of LABSFLOC2-laboratory data*

Samples	Suspended sediment concentration (in mg/l) for test results with low concentrations		Suspended sediment concentration (in mg/l) for test results with high concentrations	
	Initial concentration (base/stock suspension)	Computed concentration	Initial concentration (base/stock suspension)	Computed concentration
S01_wp = WS-WAW1; p_{sand}=37%	570	520	2609	2340
S03_wp = WS-GR1; p_{sand}=5%	198	180	3039	2760
S06_wp = WS-BH1; p_{sand}=55%	195	175	1386	1260
S09_wp= BB2G; p_{sand}=83%	438	396	3293	2950
S10_wp= BB3; p_{sand}=6%	411	374	1897	1680
S11_wp= SO3; p_{sand}=57%	285	259	2028	1810

Table 3.2.4 *Computed suspended sediment concentration (SSC) from LABSFLOC2-laboratory data*

3.3 Field data

3.3.1 Background data

Water depths and current velocity were measured by instruments on the frame (Figure 2.3.6) deployed on the bed. Water depth was also measured using a rope with lead weight operated from the survey vessel. Water samples were taken regularly to determine the background mud concentrations. Water level, current velocity and mud concentration data at the site are given in Table 3.3.1.

It is noted that the mud concentrations of column 6 of Table 3.3.1 are those of the water samples taken by the Van Dorn water sampler. These values deviate somewhat from the mud concentrations measured by the PIRANHA sampler and the pump sampler due to local mud concentration variations in the water column at the Holwerd site (NL).

Time (hrs)	Water depth (m)		Water level (m to NAP)	Current velocity near bed (m/s)	Mud concentration (mg/l)	Type of measurements P= PIRANHA water-mud sampler and settling tube W= Water sampler (Van Dorn sampler)
	A	B				
6.00			0.6 HW			
10.15	2.3	1.3		0.05	432	Start of measurements (round 1); Bed fish into water P-instrument used to take water-mud sample transferred to settling tube (c_o=430 mg/l) Water-mud sample by pumping from intake attached to P-instrument into settling tube (c_o=313 mg/l) P-instrument used to take water-mud sample and also used as settling tube (placed vertical; c_o=400 mg/l) position); small subsample for settling analysis A.M. (S01)
11.00	2.5	1.5		<0.1	≅500	Bed sample taken using VV-grab wet density≅1400 kg/m^3; dry density=650 kg/m^3 Very soft mud; wooden stick (diameter=30 mm) can easily be pushed in bed over 1 m (resistance≅ 1 kg/cm^2)
11.30	2.3	1.3		0.4	1035 (ferry)	W-sample for settling analysis A.M. (S02) Ferry in port; ferry jets generate high mud conc.
12.15	2	1	-1.08 LW	0.15	465	W-sample for concentration and settling analysis A.M.
13.10	2.1	1.1		0.15	429	W-sample for settling analysis A.M. (S03)
13.45	2.2	1.2		0.55	2088 (ferry in port; ferry jets)	Start of measurements (round 2) P-instrument used to take water-mud sample transferred to settling tube (c_o=4142 mg/l) Water-mud sample by pumping from intake attached to P-instrument into settling tube (c_o=3264 mg/l) P-instrument used to take water-mud sample and also used as settling tube (placed vertical; c_o=2618 mg/l) position); small subsample for settling analysis A.M (S04)
15.15	2.5	1.5		0.15	492	W-samples for settling analysis A.M. (S05)
15.55	3	2.0		0.8	800 (ferry)	W-samples for settling analysis A.M. (S06)
16.30	3.5	2.5		0.7	385	W-samples for settling analysis A.M. (S07)
17.00	4	3		0.5	350	W-sample for concentration and settling analysis A.M. Bed-fish out of water (instruments were partly into soft mud bed over 0.3 m) with Aquadopp for acoustic velocity; OBS for concentration; Lisst-100x for particle size
18.15			-1.02 HW			

Table 3.3.1 *Summary of background data and type of measurements (A.M.= by Prof. A. Manning)*

3.3.2 Settling velocity derived from settling tube results derived from PIRANHA-instrument

Settling tests were performed using water-sediment samples from the Holwerd site on 24 May 2022.Three methods were used to take water samples for the settling tests, as follows:

1. peristaltic pump; water-sediment sample of about 2 liters was taken in the water column and transferred to a (laboratory) settling column at the field site laboratory to perform a settling test (LST-PUMP samples);
2. tube-type sampler with valves on both ends (PIRANHA sampler); water-sediment sample of about 2 liter was taken in the water column and transferred to a settling column at the field site laboratory to perform a settling test (LST-PIRANHA samples);
3. tube-type sampler with valves on both ends (PIRANHA sampler) was put in vertical position after sampling for a direct in situ settling test (IST-PIRANHA samples); small subsamples (50 to 100 ml) were taken at successive times by opening a small tap.

The water samples were taken around 10:15 hours during conditions with low concentrations and around 13:45 hours with high concentrations. In all, six samples were tested: 3 samples of low concentrations and 3 samples of high concentrations. The basic settling data are given in Appendix A.2. The precise method to compute the settling velocity from the data is given in Table A.2

A summary of the results is given in Table 3.3.2. The percentage of sand is an estimate based on the settling tube results. The sample volumes were too small for sieve analysis. The sampling location is a small harbour close to the ferry landing point where the suspended samples are muddy with minor amounts of fine sand (<5% and up to 15% during ferry boat arrival).

Figures 3.3.1 and 3.3.2 and Table 3.3.2 show the results for low and high concentrations. It is assumed that 100% of the sediments have a settling velocity lower than 10 mm/s (sand of about 120 μm). The maximum settling velocities based on the first measurements after 60 sec are in the range of 4 to 5 mm/s representing the settling velocities of fine sand and macroflocs. Sieve analysis of the sand fraction of suspended samples in the ferry channel of Holwerd shows the presence of fine sand in the range of 63 to 100 μm (WaterProof 2019). Coarser sand is not present in the samples in the ferry channel where flow velocities may go up to 1 m/s. The settling tests in May 2022 were done in a small harbour area near ferry landing point, where there is no flow at all. So, suspended sand will hardly be present in the samples and mostly in the range of 63 to 100 micron (not coarser).

Another approach (proposed by J. Spearman of HR Wallingford) is to use the exponential distribution $c=c_o \exp(-w_s t/h)$ of Section 2.3.2. If the data of the first measurement after 60 seconds are used, the average mass-weighted settling velocities of the population as a whole are in the range of 0.15 to 0.77 mm/s (A2: 0.25 mm/s; A3: 0.25 mm/s; A3: 0.15 mm/s; A4: 0.76 mm/s; A6: 0.2 mm/s and A7: 0.77 mm/s, see Appendix A2). These values (between brackets in Table 3.3.2) are mostly smaller than the median settling velocities of settling tube data. Using this approach, the gap between the settling tube results and the LABSFLOC2-results is also large (Table 3.3.3).It is noted that the exponential decrease of the concentrations in a settling column is only valid for a homogenous (well-mixed) suspension of uniform particles/flocs (mono-dispersed suspension), but less valid for a poly-dispersed suspension with a wide range of particles/flocs resulting in a different settling process with distinct zones with smaller and larger particles /flocs.

The most important conclusions are:

- For low concentrations, the LST-pump produces a much higher fraction of fines, which may be caused by the destruction of the flocs in the pump;
- For high concentrations, all curves are fairly close together; results of the IST-method show more variations.
- The median settling velocity is much higher (factor 3 to 5) for high concentrations (flocculation effect).
- The maximum settling velocities are in the range of 4 to 5 mm/s.

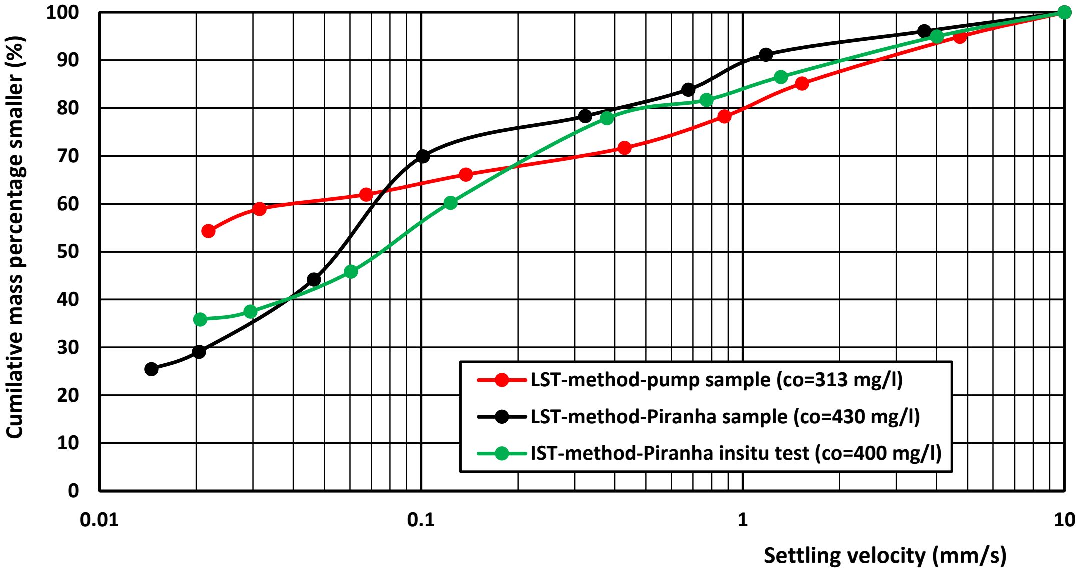


Figure 3.3.1 *Settling velocity curves derived from settling tube tests; low concentrations 300 to 400 mg/l*

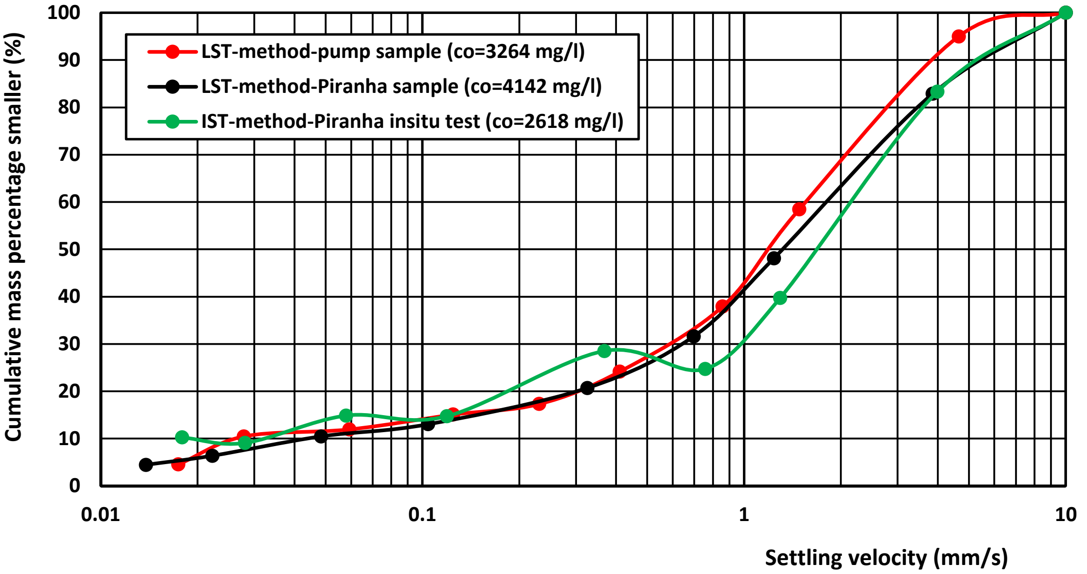


Figure 3.3.2 *Settling velocity curves derived from settling tube tests; high concentrations 2500 to 4000 mg/l*

Sampling method	Settling velocity (mm/s) Low concentrations 300-400 mg/l				Settling velocity (mm/s) Low concentrations 2500-4000 mg/l			
	$w_{s,10}$	$w_{s,50}$	$w_{s,90}$	$w_{s,max}$	$w_{s,10}$	$w_{s,50}$	$w_{s,90}$	$w_{s,max}$
Laboratory Settling (2 tests) (LST-PUMP samples) A2:c_o-low=313 mg/l, $p_{sand}\cong$5% A3:c_o-high=3264 mg/l, $p_{sand}\cong$15%	<0.01	0.02 (0.02)	2.5	4.7	0.02	1 (0.25)	3.8	4.7
Laboratory Settling (2 tests) (LST-PIRANHA samples) A4:c_o-low=430 mg/l, $p_{sand}\cong$5% A5: c_o-high=4142 mg/l, $p_{sand}\cong$15%	<0.01	0.055 (0.15)	1	3.7	0.05	1.5 (0.76)	5.5	3.9
Insitu Settling (2 tests) (IST-PIRANHA samples) A6: c_o-low=400 mg/l, $p_{sand}\cong$5% A7: c_o-high=2618 mg/l, $p_{sand}\cong$15%	<0.01	0.075 (0.2)	2	4.0	0.035	1.8 (0.77)	5.5	4.0

Table 3.3.2 *Characteristic settling velocity data for low and high initial concentrations; settling tube results (average mass-weighted settling velocity based on exponential distribution between brackets)*

3.3.3 Settling velocity, floc size and floc density derived from LABSFLOC2-instrument

The settling tests including video camera registrations of the LABSFLOC2-instrument (University of Plymouth, UK) were done during the field test day on 24 May 2022. Later in the period of June to October 2022, the camera data were analysed by Prof. A. Manning to determine the settling velocities and the corresponding floc sizes. The basic data are given in Appendix A.3.

Figures 3.3.3 and 3.3.4 show typical settling velocity results (sample S02 and S07 from Holwerd site). The particle and floc sizes are in the range of 20 to 400 μm. The bulk of the data points are in the range of 50 to 250 μm; the number of data points with particle and floc sizes < 30 μm is rather small (mostly < 2% and maximum 4% for test S01; Table 3.3.4).

The analysis results of all samples based on the LABSFLOC2-method are presented in Table 3.3.3 and in Figure 3.3.5. The median floc size is in the range of 80 to 160 μm (120±40 μm). The median settling velocity ($w_{s,50}$) is in the range of 2 to 12 mm/s (7±5 mm/s), see Figure 3.3.5. This variation may be due to variations in the sand content in the samples.

Figure A3b (Appendix A3) shows the distribution of the suspended mass over the settling velocity classes for test S06. Most of the suspended mass is in the three highest velocity classes 10 to 30 mm/s, although only 15% of the data points has a settling velocity > 10 mm/s. As a result, the median settling velocity ($w_{s,50}$) is quite high (12 mm/s) for test S06. The mean settling velocity of all data points (259) is 3.5 mm/s. Thus, the median settling velocity based on mass-related percentages is strongly related to the (largest, heaviest) flocs with the highest settling velocities.

The effect of the initial sediment concentration on the median ($w_{s,50}$) settling velocity is shown in Figure 3.3.6. Except for test S07-385 mg/l and S01-400 mg/l, the settling velocity increases for initial concentrations < 800 mg/l and decreases for initial concentrations > 800 mg/l.

The results of Figure 3.3.6 and also Figure 3.2.8 are remarkable in the sense that relatively low settling velocities are measured by LABSFLOC2-instrument for relatively high mud concentrations.

The results of Figure 3.3.6 show scatter which may partly be related to the extremely small subsample of 2.5 ml taken from the PIRANHA-sample for the LABSFLOC2-setling test. The mud concentration of one single subsample of 2.5 ml may not be representative for the mud concentration of the larger water-sediment sample (about 1 liter). The PIRANHA-sample may not have been fully homogenous.

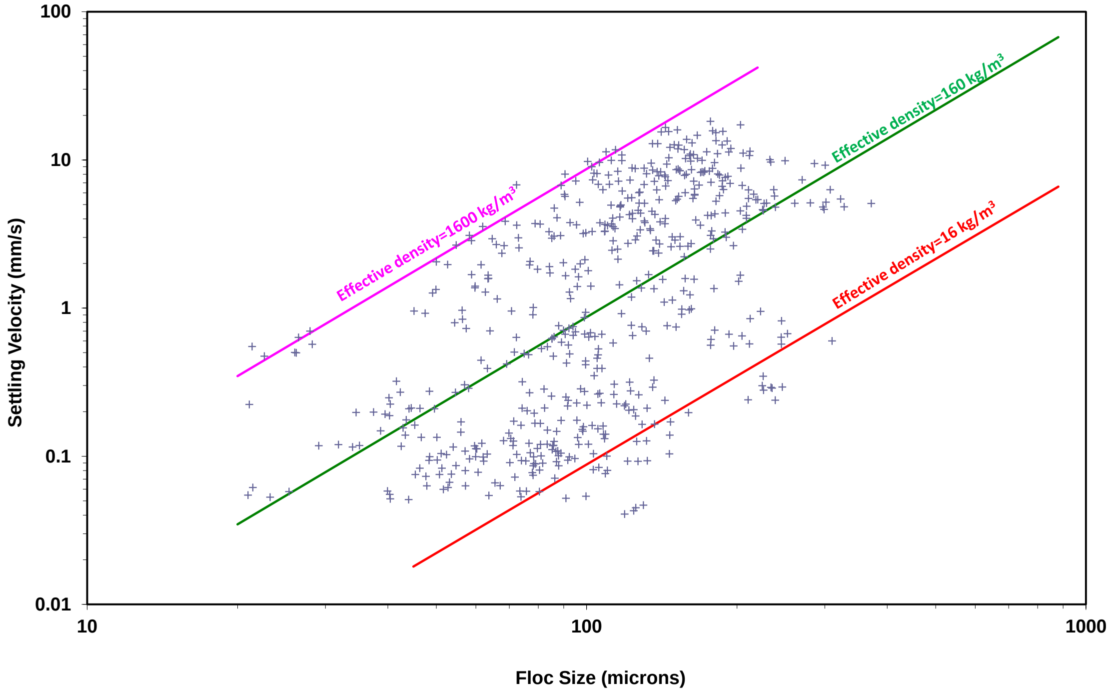


Figure 3.3.3 *Settling velocity versus floc size of sample S02 (c_o=1035 mg/l)*

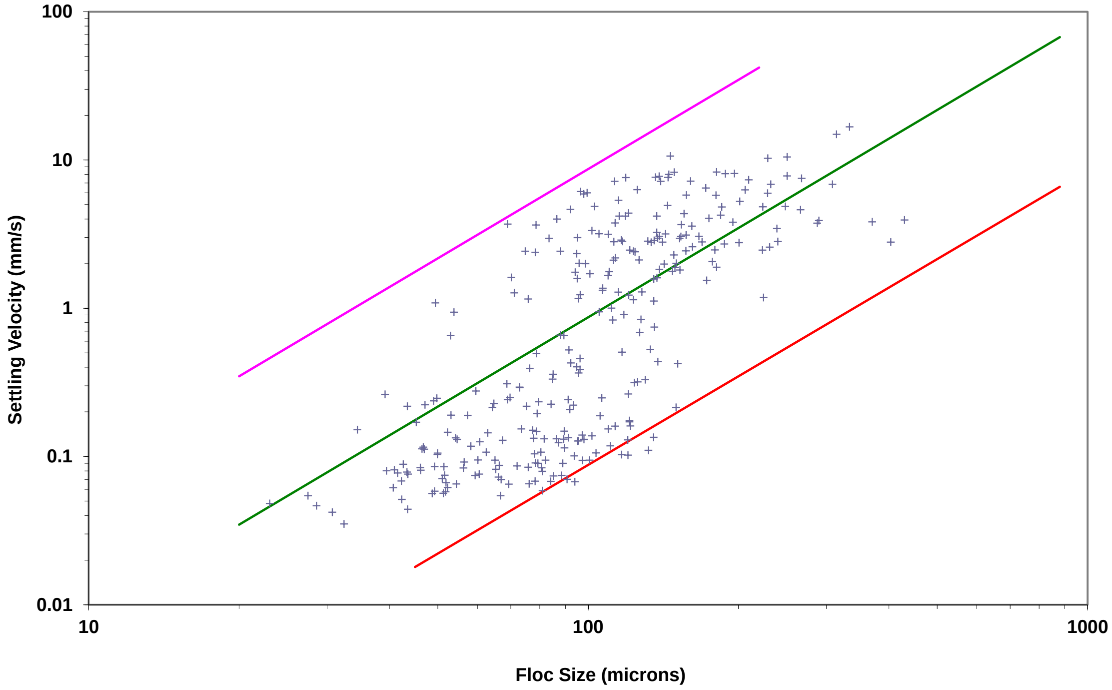


Figure 3.3.4 *Settling velocity versus floc size of sample S07 (c_o=385 mg/l); Holwerd site (NL)*

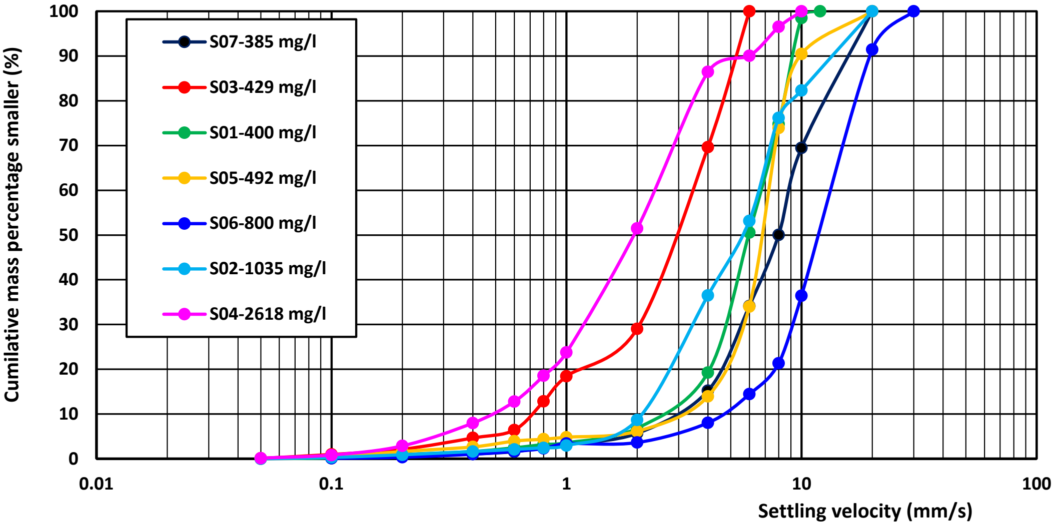


Figure 3.3.5 *Settling velocity distributions of all samples derived from LABSFLOC2-instrument; Holwerd site (NL)*

Samples	Floc size (um)			Settling velocity (mm/s)		
	d_{10}	d_{50}	d_{90}	$w_{s,10}$	$w_{s,50}$	$w_{s,90}$
S07= sample with concentration of 385 mg/l (1043 data points)	50	120	280	3	8	17
S03= sample with concentration of 429 mg/l (1408 data points)	45	80	160	0.7	3	5.5
S01= sample with concentration of 400 mg/l (1339 data points)	40	100	300	2.7	6	9
S05= sample with concentration of 492 mg/l (1470 data points)	45	110	220	3	7	10
S06= sample with concentration of 800 mg/l (1774 data points)	65	160	280	4.8	12	20
S02= sample with concentration of 1035 mg/l (2757 data points)	55	130	240	2.2	5.8	14
S04= sample with concentration of 2618 mg/l (5726 data points)	50	120	220	0.5	2	6

Table 3.3.3 *Settling velocity and floc size data of LABSFLOC2-instrument; Holwerd site (NL)*

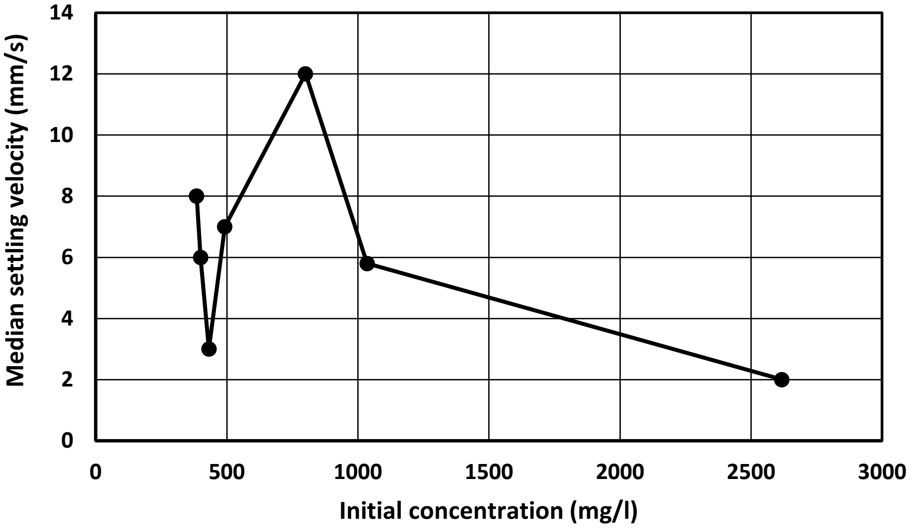


Figure 3.3.6 *Effect of initial concentration on median settling velocity*

Figure 3.3.7 shows the computed effective submerged floc density (ρ_{floc}-ρ_w) as function of the measured floc size for 2 field tests (from spreadsheet results provided by Prof. A. Manning). The values vary in the range of 10 to 1000 kg/m^3. Thus, the effective density of the flocs varies in the range of 1000 to 2000 kg/m^3 after including of the fluid density, which is a realistic range.

The total suspended sediment concentration (SSC) in each sample is computed from $\sum M_{floc,dry}/V_{sample}$ with $V_{sample} \cong 400$ mm^3 (based on information from Prof. A. Manning). The porosity equation of Van Rijn (Appendix A.1) and that of Manning et al. (2017) have been used to compute the mass of the flocs. The results for all samples are shown in Table 3.3.4. Using the porosity values of Van Rijn, the computed initial concentration is generally somewhat smaller (except for Test S02) than the original initial concentration. Using the porosity values of Manning, the computed concentration values are generally higher (20%) than the original values.

Samples	**Total number of data points**	**Number of data points with floc size < 30 μm**	**Number of data points with floc size < 50 μm**	**Computed initial SSC from LABSFLOC2-data (mg/l)**	
				Porosity Van Rijn	**Porosity Manning**
S07= sample with initial concentration of 385 mg/l	290	3 (1%)	33 (10%)	374	483
S03= sample with initial concentration of 429 mg/l	840	0 (0%)	65 (8%)	401	518
S01= sample with initial concentration of 400 mg/l	321	13 (4%)	79 (25%)	387	503
S05= sample with initial concentration of 492 mg/l	420	6 (1.5%)	60 (14%)	470	608
S06= sample with initial concentration of 800 mg/l	259	5 (2%)	24 (10%)	778	1009
S02= sample with initial concentration of 1035 mg/l	569	13 (2%)	50 (9%)	1048	1385
S04= sample with initial concentration of 2618 mg/l	4169	69 (1.5%)	529 (13%)	1793	2312

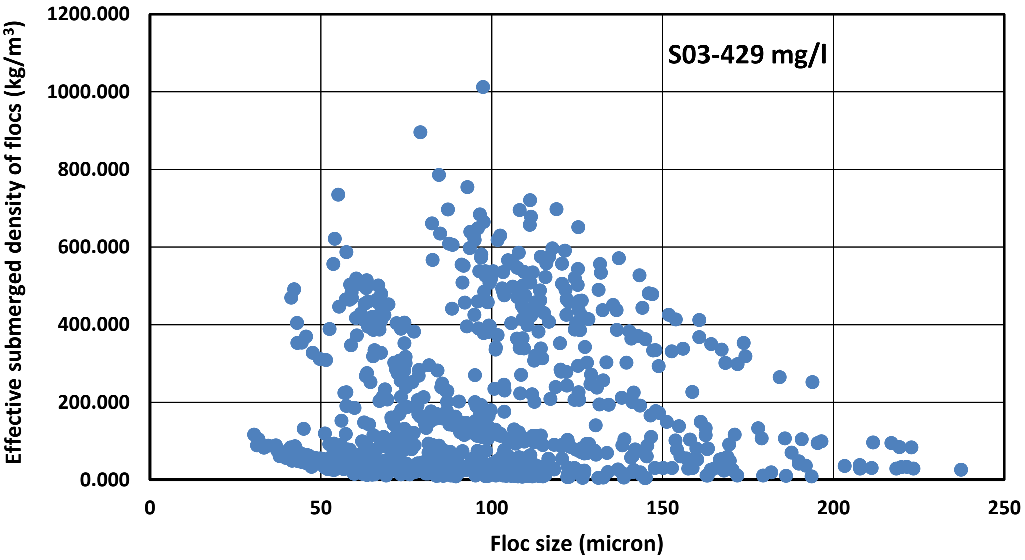
Table 3.3.4 *Computed suspended sediment concentrations from LABSFLOC2-data; Holwerd site*

The amount of smaller flocs is further illustrated by the following example of Test S03 (initial concentration of 429 mg/l) with a relatively low median settling velocity of 3 mm/s. The floc data are as follows:

- total number of flocs: 840 with total mass of $1.6\ 10^{-7}$ kg;
- fraction 20-30 μm: 0 flocs with settling velocity in range 0.03-0.08 mm/s;
- fraction 30-63 μm: 169 flocs (20% of total population) with settling velocity in range 0.04-2 mm/s;
- fraction 63-125 μm: 509 flocs (60% of total population) with settling velocity in range 0.06-6 mm/s;
- fraction 125-250 μm: 162 flocs (20% of total population) with settling velocity in range 0.1-11 mm/s;
- fraction >250 μm: 0 flocs with settling velocity in range 1.2-17 mm/s;
- micro-flocs defined as flocs < 160 μm: 781 flocs (93 % of total population);
- macro-flocs defined as flocs >160 μm: 59 flocs (7% of total population);
- fraction < 63 μm: 169 flocs with total mass of $2.7\ 10^{-9}$ kg (1.5% of total mass of $1.6\ 10^{-7}$ kg).

The number of flocs of the fine fraction < 63 um is < 20% of the total number of flocs; the fine silt and clay fraction < 30 um is absent (0%) in the total population.

The mass percentage of the fraction < 63 μm is only 1.5% of the total mass based on the LABSFLOC2-instrument. Thus, a minor error (say 10% to 20%) in the computation of the initial concentration by summation of the mass of all flocs (Table 3.3.4) may represent a rather high amount of fine flocs < 63 um which are missing.



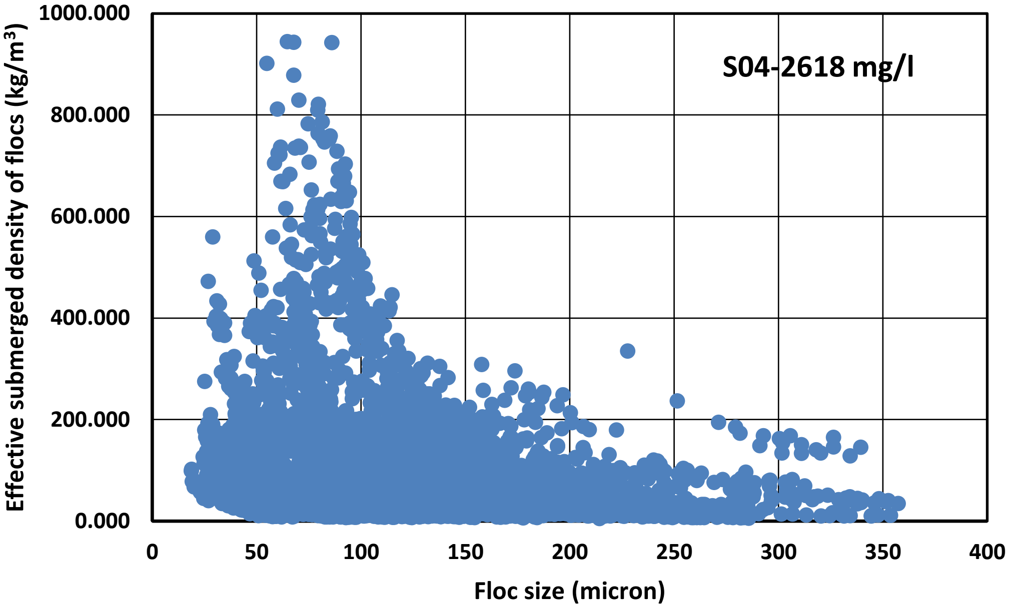


Figure 3.3.7 *Effective submerged floc density as function of floc size for 2 field tests; Holwerd site (NL)*

3.3.4 Comparison of settling velocities

The settling velocity distributions of samples with low and high initial concentrations as measured by the PIRANHA-instrument and the LABSFLOC2-instrument are compared in Figure 3.3.8.

The median settling velocity of both methods (LABSFLOC2-instrument and P-instrument) are reasonably similar for high initial concentrations > 2000 mg/l; the median settling velocity is in the range of 1.5 to 2 mm/s. The results are different for the fine sediment range; the P-instrument measures a much larger fraction with low settling velocity (15% with settling velocity < 0.1 mm/s for P-instrument and 2% for LABSFLOC2-instrument).

The results of both methods deviate significantly for low initial concentrations of about 400 mg/l. The PIRANHA-settling tube produces a median settling velocity of the order of 0.1 mm/s for an initial concentration of about 400 mg/l, whereas the LABSFLOC2-method gives a median settling velocity of the order of 2.5 mm/s. Based on the PIRANHA-results, about 80% of the settling particles/flocs data have a settling velocity < 0.5 mm/s and maximum 20% < 0.5 mm/s for the LABSFLOC2-instrument.

The main causes for these deviations, particularly at low initial concentrations, are:

- the observation/presence of the larger macro-flocs is underestimated by the mechanical PIRANHA settling tube, as the fragile flocs may have been broken upon or during sampling/observation (bias towards smaller sizes);
- the observation/presence of the individual particles and micro-flocs (< 30 μm) is underestimated by the LABSFLOC2-video camera instrument (bias towards larger sizes); sizes smaller than about 30 μm are less frequently measured, see Table 3.3.4.

It is concluded that the LABSFLOC2-instrument may substantially underestimate the fine silt and clay fraction < 30 μm. This fraction generally is relatively high in conditions with relatively low concentrations < 500 mg/l when flocculation processes are not so strong. Consequently, the median settling velocity of the LABSFLOC2-instrument for low concentration conditions may be systematically on the high side (values >1 mm/s). However, as the average (mass-weighted) settling velocity is much more affected by the larger flocs, these smaller flocs have only a small effect on the overall settling velocity.

More research on this topic is highly recommended. For future field measurements, it is proposed to use a Laser-Diffraction (LD) instrument for determination of the volume fraction of micro- and macro-flocs of small subsamples taken from field samples (from P-tube, or Van Dorn-tube). The floc distributions of the LD-method can be compared to those of the LABSFLOC2-method. This requires the setup of a field laboratory close to the field sampling site.

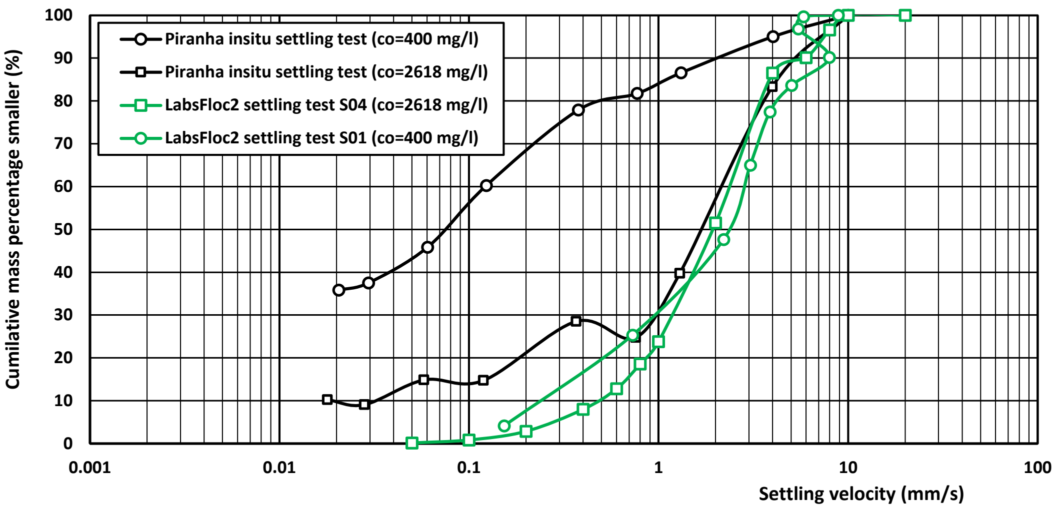


Figure 3.3.8 *Settling velocity distributions of samples measured by PIRANHA- and LABSFLOC2-instruments (subsample of LABSFLOC2 is from same PIRANHA-sample)*

4 Summary, conclusions, discussions and recommendations

4.1 Summary and conclusions

Two types of studies on settling velocities and floc size have been performed in the MUSA-Project:

- Measurement of settling velocities and floc sizes in laboratory conditions;
- Measurements of settling velocities and floc sizes in field conditions (at Holwerd, Wadden Sea, The Netherlands).

The laboratory study involved has been done by Prof. A. Manning of HR Wallingford (UK) and University of Plymouth (UK) using the LABSFLOC2-instrument.

For the measurements of settling velocities and floc sizes in the field, the following methods and instruments are used:

- In situ settling test (IST): the sampling instrument (bottom-withdrawal tube or side-withdrawal tube; Van Rijn 2012) is used to take a water-suspended sediment sample and is afterwards used as a settling tube;
- Laboratory settling test (LST): water-suspended sediment samples are taken by a cylinder-type of sampler (Van Dorn sampler) with valves on both ends or by a pump sampler; the samples are returned to the laboratory (sometimes on site) for a settling tube test;
- Settling velocities derived from moving particles and flocs recorded by a camera system (LABSFLOC2-instrument): two options are possible:
  a. camera can be lowered into the water column or
  b. water samples are taken and immediately analyzed by camera recordings in on site laboratory.

Prof. A. Manning from the University of Plymouth and HR Wallingford took part in the field measurements on 23, 24 and 25 May 2022. He operated and analyzed the results of the LABSFLOC2-instrument.

Instruments

The video-based LABSFLOC2 (Laboratory Spectral Flocculation Characteristics) is a portable laboratory instrument utilizing a low-intrusive, high resolution video camera to observe flocs as they settle in a settling column constructed of Perspex**.** A subsample is extracted from field water-sediment samples or laboratory jar/bottle/flume samples and is immediately transferred to the camera-connected column using a modified pipette (maximum 50 ml). The Perspex settling column has a square cross-section of 100x100 mm^2 and a vertical length of 350 mm. The video camera, the center of which is positioned 75 mm above the base of the column, views all particles in the center sheet (1 mm depth; 45 mm from the camera lens) of the column with as they settle from within a predetermined sampling volume. The total image volume is nominally 6 mm high, 8 mm wide and 1 mm deep (volume 48 mm^3). The digital floc images are captured at a frame rate of 25 Hz (one frame is 0.04 s), at a resolution of 1600 × 1200 pixels, with an individual pixel nominally representing 5 μm.

The Stokes settling velocity law is used to compute the effective floc density. Based on image-analysis algorithms, the floc porosity, fractal dimensions, floc dry mass and the mass settling flux of a floc population are computed. The computed dry mass of the measured particles and flocs can be compared with the total mass in the settling column (i.e. a mass-balanced referenced floc population), thus providing an estimate of the efficiency and reliability of each sampling procedure.

The PIRANHA-instrument (P-instrument) is a combination of a water-sediment sampler and a settling tube (IST-method) by placing it in upright position standing on its tail fin. The P-instrument has valves on both ends and is lowered in horizontal position with open valves to the sampling point in the water column. The valves are closed by pulling a rope and the instrument is raised in horizontal position and transferred to the on-site laboratory where it is gently turned over a few times to create a homogeneous suspension and then placed in vertical position to start the settling process (t=0). Small subsamples of water sand sediments are taken by opening a small tap at the side of the tube at preset times over a period of 3 hours. The volume of each sample is noted; the sediment is removed from the sample by filtration, the sediment sample is dried and weighed to determine the sediment concentration of the subsample. The settling velocity curve can be derived from the decrease of the sediment concentration over time.

Both instruments have different types of errors. Van Kessel (Deltares, 2003) gives a detailed discussion of all possible errors related to the determination of settling velocity, particularly for settling tube measurements.

Laboratory tests

Various sediment samples collected in the MUSA-Project were used to study the flocculation process and corresponding parameters (floc size, settling velocity and floc density) in a laboratory setup of the LABSFLOC2-instrument in Plymouth, UK.

The sediment samples of MUSA were used to make uniform suspension (concentrations in the range of 100 to 5000 mg/l) in saline water (salinity of 35 ppt). A reasonable amount from the original sediment sample was taken to make a 'stock slurry'. The stock slurry was stirred and a subsample was taken to determine the base suspended sediment concentration (SSC) of this stock. A smaller amount from the stock SSC was transferred to a jar and diluted to get concentrations in the range of 150 to 5000 mg/l. The suspension in the jar was stirred by an accurately controlled magnetic stirrer to enhance flocculation processes (mid-shear turbulence range).

A modified pipette was vertically connected to the jar to take a subsample from the jar (volume of about 2000 mm^3 with a height of 50 mm in the pipette). The pipette mouth was put into the settling column so that the flocs can simply pass (settle) from the 50 mm high fluid volume in the pipette and into the settling column where they are observed by the video camera.

The observed floc sizes are in the range of 50 to 350 μm. The characteristic settling velocities are in the range of 0.5 to 15 mm/s; most values are in the range of 1 to 10 mm/s.

The effective density of the flocs is found to vary in the range of 1200 to 3700 kg/m^3. Floc density values higher than 2000 kg/m^3 are not realistic. This is the density of a virtual floc consisting of 60% of sediment and 40% of water, settling as an individual floc-object with a virtual thin plastic skin around it.

The settling velocity increases strongly with concentration in the low concentration range (< 500 mg/l), most likely caused by flocculation processes. The median settling velocities are relatively low for initial concentrations > 1500 mg/l (except for very sandy samples). The reduction (variability) of the settling velocity for higher concentrations may be caused by hindered settling processes affecting the macro-flocs, but it may also partly be related to imperfections of the sampling and test procedures which involves the preparation of base suspensions with very small amounts of mud and sand.

Although there is considerable scatter, the settling velocities show a weak increase of the median settling velocity for increasing percentage of sand; the settling velocity increases from about 2 tot 8 mm/s for very muddy samples to about 4 to 14 mm/s for very sandy samples. The settling velocity range of 2 to 8 mm/s for muddy samples is rather high in comparison to the settling results of the traditional sedimentation methods (hydrometer) giving $w_{s,50}$-values in the range of 0.1 to 2 mm/s for muddy samples.

Analysis of the basic data of the floc populations shows that the amount of data with floc sizes < 30 μm is extremely small: often zero and up to 4% in some cases. Based on this, two conclusions are possible: particles/flocs < 30 μm are not present in the MUSA-samples or the LABSFLOC2-instrument is not capable to observe particles/flocs smaller than 30 μm. In the latter case, the median floc size and the corresponding median settling velocity are overestimated.

Another method to evaluate the overall inaccuracy involved is the determination of the total dry sediment mass of all particles/flocs of each sample measured by the LABSFLOC2-instrument and to compare this directly to the initial concentration of the sample. The results for six samples show that the computed SSC-values from the LABSFLOC2-data are somewhat smaller (maximum 15%) than the original initial concentration values, which is a rather good result.

Field experiments

Both instruments (LABSFLOC2-instrument and in-situ PIRANHA settling tube) were used to study the settling velocities in field water-sediment samples at the tidal site of Holwerd in The Netherlands on 24 May 2022.

Three methods were used to take water samples for the settling tests, as follows:

- peristaltic pump; water-sediment sample of about 2 liters was taken in the water column and transferred to a (laboratory) settling column at the field site laboratory to perform a settling test (LST-pump);
- tube-type sampler with valves on both ends (PIRANHA sampler); water-sediment sample of about 2 liter was taken in the water column and transferred to a settling column at the field site laboratory to perform a settling test (LST-PIRANHA);
- tube-type sampler with valves on both ends (PIRANHA sampler) was put in vertical position after sampling for a direct in-situ settling test (IST-PIRANHA); small subsamples (50 to 100 ml) were taken at successive times by opening a small tap.

The water samples were taken around 10:15 hours during conditions with low concentrations and around 13:45 hours with high concentrations. The most important conclusions of the settling velocity results of the PIRANHA instrument are:

- For low concentrations, the LST-pump produces a much higher fraction of fines, which may be caused by the destruction of the flocs in the pump;
- For high concentrations, all curves are fairly close together; results of the IST-method show more variations.
- The median settling velocity is much higher (factor 3 to 5) for high concentrations (flocculation effect).

The settling tests results of the LABSFLOC2-instrument (HR Wallingford, UK) show the presence of particles and flocs with sizes in the range of 20 to 400 μm. The bulk of the data points are in the range of 50 to 250 μm; the number of data points with particle and floc sizes < 30 μm is rather small (mostly < 2% and maximum 4% for test S01). The median floc size is in the range of 80 to 160 μm (120±40 μm). The median settling velocity is in the range of 2 to 12 mm/s. Except for test S07-385 mg/l and S01-400 mg/l, the settling velocity increases for initial concentrations < 800 mg/l and decreases for initial concentrations > 800 mg/l. Analysis of the results show that the median settling velocity based on mass-related percentages is strongly related to the (largest, heaviest) flocs with the highest settling velocities.

The initial concentration can also be computed by summation of the mass of all observed flocs. Using the porosity values of Van Rijn (Appendix A.1), the computed initial concentration is generally somewhat smaller (about 15%, except for test S02) than the original initial concentration. Using the porosity values of Manning, the computed concentration values are mostly higher (20%) than the original values.

Comparison of the settling velocity distributions of samples shows that the results of both instruments are reasonably similar for high initial concentrations > 2000 mg/l; the median settling velocity is in the range of 1.5 to 2 mm/s. The results of both methods deviate significantly for low initial concentrations. The PIRANHA-settling tube produces a median settling velocity of the order of 0.05-0.1 mm/s for an initial concentration of about 400 to 500 mg/l, whereas the LABSFLOC2-method gives a median settling velocity of the order of 3 to 7 mm/s. The main causes for these deviations at low initial concentrations are:

- the observation/presence of the larger macro-flocs > 160 μm is underestimated by the mechanical PIRANHA settling tube, as the fragile flocs may have been broken upon or during sampling/observation (bias towards smaller sizes);
- the observation/presence of the individual particles and micro-flocs (< 30 μm) is severely underestimated by the LABSFLOC2-video camera instrument (bias towards larger sizes); sizes smaller than about 30 μm are less frequently measured.

Analysis of the floc data measured by the LABSFLOC2-instrument shows that the total mass of sediments in the samples is underestimated by maximum 20%, which may seem a low value but it represents a rather high amount of fine flocs not observed by the LABSFLOC2 -instrument.

It is concluded that the LABSFLOC2-instrument may substantially underestimate the fine silt and clay fraction < 30 μm. This fraction generally is relatively high in conditions with relatively low concentrations

< 500 mg/l when flocculation processes are not so strong. Consequently, the median settling velocity of the LABSFLOC2-instrument for low concentration conditions may be systematically on the high side (values > 1 mm/s).

4.2 Discussions: settling velocity used in sedimentation models

Settling velocities are of prime importance for the engineering question: how much sediment will deposit in a navigation channel in muddy conditions?

So far, two methods are generally used to determine the settling velocity at a field site:

- in-situ settling tubes and video-camera systems;
- fitting of measured velocity profiles to the logarithmic velocity profile (to find the bed-shear velocity u_*) and the measured mud concentration profile to the theoretical Rouse-concentration profile (to find the settling velocity (w_s), see Figure 4.1.; this approach requires a major field effort with a bed frame for measuring velocities and concentration in at least 7 points in the lowest 1 to 2 m of the depth.

The results of the settling tube and the LABSFLOC2-instrument may be quite different in some cases, as found in the present study. Overall, the settling velocities derived from the LABSFLOC2-instrument are in the range of 2 to 10 mm/s, whereas those of the insitu PIRANHA-settling tube are in the range of 0.1 to 2 mm/s.

How can we use these results in sedimentation modelling studies?

If the engineering question is how much sediment will deposit in a dredged channel, it is the total mass sediment flux to the bed which matters, which may not be very well represented by the median settling velocity. Larger floc have larger mass and therefore dominate the deposition. Thus, if a minor percentage of the smaller flocs are missed, it may not contribute much to the total deposition.

Using a modelling approach, generally three sediment fractions are required for accurate modelling of the fines with a wide settling velocity range of 0.1 to 10 mm/s. Available settling velocity curves can be used to estimate the most relevant settling velocity ranges (fine clay-silt: 0.1-0.5 mm/s; coarse silt: 0.5-2 mm/s and macroflocs of mud and fine sand: 2-10 mm/s). In a mixed sediment environment, normally the mud equations are applied to fine sediment and sand equations to sandy sediment. However, it may be so that much of the sediment settling is in the form of flocs made of sand and mud combined resulting in a relatively high settling velocities as derived from video registrations of settling velocities. If so, the standard models may over-simplify the physics involved. Some evidence for this is given by Spearman et al. (2011), who found that the predicted concentration variations at the sandy mud flat Foulness in the Outer Thames are much better represented by using a mud-sand floc algorithm in a 1DV-model.

Up to now, the fraction 0.5-2 mm/s is the dominant fraction in most standard mud modelling studies resulting in very reasonable deposition estimates in comparison to dredged volumes (Van Rijn, 2015).

The LABSFLOC2-results indicate that the macroflocs with effective settling velocities in the range of 2 to 10 mm/s may be the dominant fraction. If this is true, our mud sedimentation models may substantially overestimate the deposition in a dredged channel. For example, the mud sedimentation model of Deltares operated with 2 fractions and settling velocity of 0.4 and 1.5 mm/s produced reasonable results for the annual deposition in the Holwerd ferry channel (Grasmeijer et al., 2021).

Finally, the modelling consequences of high settling velocities due to macroflocs in mixed mud-sand conditions are demonstrated by a simple practical example.

Let us assume that a measured load of sediment (mud and fine sand) with uniform concentration of 1000 mg/l over the depth is passing across a dredged channel. Mud is dominant with 800 mg/l and settling velocity of 1 mm/s and fine sand of 200 mg/l and settling velocity of 10 mm/s. Most likely, the effective settling velocity is $(800 \times 1+200 \times 10)/1000 \cong 2.8$ mm/s

The trapping depends on the incoming load and on the trapping efficiency which strongly depends on the settling velocity.

The trapping efficiency can be computed for both fractions separately. Generally, our models can predict the measured deposition quite well. If only one fraction of 1000 mg/l is used with an effective settling velocity of 2.8 mm/s, our models will also work reasonably well. If we assume that for mixed mud and sand the settling velocity is substantially higher (true or not), the trapping of this mixture will be much higher but the incoming load remains the same. Thus, the predicted deposition will go up and our models will highly overpredict.

4.3 Recommendations

At present stage of research, we do not have conclusive proof that both instruments (P-instrument and L-instrument) are measuring correct settling velocities for mixed mud-sand suspensions. More laboratory and field work is required to answer the following questions:

1. is the L-instrument correctly identifying the settling velocities of micro- and macroflocs and are the settling velocities of very small subsamples transferred to a laboratory setup representative of what happens in nature?
2. why is the relatively high settling velocity of macroflocs so dominant in the results of the L-instrument and why are these high settling velocities so different from the values of the P-instrument and from the values used in present day standard sedimentation models to obtain decent deposition results?
3. what is the effect of sand particles on the settling behaviour of macroflocs measured by the L-instrument?
4. what is the effect of vibrations generated by the closure of the valves of the P-instrument on the breakup of flocs?
5. what is the effect of the length of the P-instrument on the measured settling velocities of fine sand and macroflocs (use P-instrument with length of 0.75 m and analyse the deposited mass of sediment on the bottom of the tube)?
6. perform velocity and concentration measurements with a detailed bed frame (at least 7 points simultaneously) for analysis of settling velocities by fitting of profiles and measure settling velocities using the P- and L-instruments at the same site for comparison.

Finally, it is recommended to use a Laser-Diffraction instrument and underwater sedimentation balance instrument in future studies for determination of the volume fraction of micro- and macro-flocs of small subsamples taken from field samples (from P-tube, or Van Dorn-tube). The floc and settling velocity distributions of these instruments can be compared to those of the Labsfloc2-method. This requires the setup of a field laboratory close to the field sampling site.

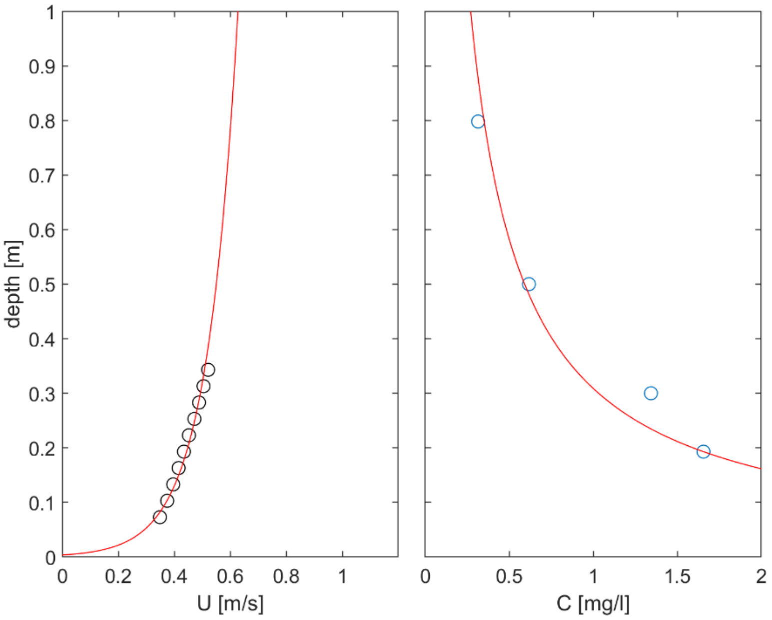


Figure 4.1 *Example of fitting a velocity profile (left) and mud concentration profile (right) to derive bed-shear velocity and settling velocity*

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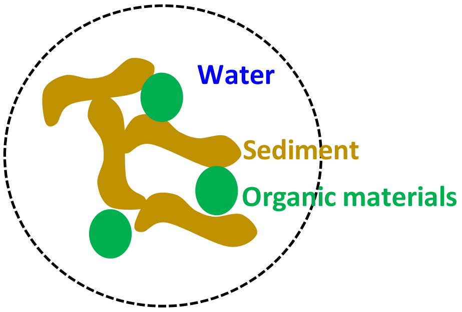
A Appendices

A.1 Derivation of equations for porosity and dry sediment mass of flocs

Flocs consist of sediment, organic materials and interstitial water, see the sketch below.



Definitions and assumptions:

V_{floc}	volume of floc (measured)
V_s	sediment volume in floc = $V_{floc} - V_{or} - V_{iw} = V_{floc} - \alpha_1 V_s - V_{iw}$
	giving: $(1+\alpha_1)V_s = V_{floc} - V_{iw}$ or $V_s = (V_{floc} - V_{iw})/(1+\alpha_1) = (1-p)V_{floc}/(1+\alpha_1)$
V_{iw}	volume of interstitial water in floc;
V_{or}	volume of organic materials in floc=$\alpha_1 V_s$ with $\alpha_1 \cong 0.1$;
p	porosity factor $=V_{iw}/V_{floc}$;
ρ_w	fluid density of saline water$\cong$ 1030 kg/m^3;
ρ_s	sediment density= 2650 kg/m^3;
ρ_{or}	density or organic materials ($\cong$400 kg/m^3)=$\alpha_2 \rho_s$ with $\alpha_2 \cong 0.15$-0.2;
ρ_{floc}	density of floc (including water, sediment and organic materials; range$\cong$ 1000 to 2000 kg/m^3)

Floc volume: $V_{floc}=V_s + V_{or} + V_{iw}$

Floc mass: $M_{floc}= V_s \rho_s + V_{or} \rho_{or} + V_{iw} \rho_w$

Floc density: $\rho_{floc}=M_{floc} / V_{floc}= V_s \rho_s / V_{floc} + V_{or} \rho_{or} / V_{floc} + V_{iw} \rho_w / V_{floc}$

$$\rho_{floc}= (1 - p) \rho_s / (1 + \alpha_1) + \alpha_1 V_s \alpha_2 \rho_s / V_{floc} + p \rho_w$$

$$\rho_{floc}= (1 - p) \rho_s / (1 + \alpha_1) + \alpha_1 \alpha_2 (1 - p) \rho_s / (1 + \alpha_1) + p \rho_w$$

$$\rho_{floc}= \gamma (1 - p) \rho_s + p \rho_w \quad \text{with } \gamma = (1 + \alpha_1 \alpha_2) / (1 + \alpha_1)$$

$$p = (\gamma \rho_s - \rho_{floc}) / (\gamma \rho_s - \rho_w)$$

1) no organic materials: $\alpha_1 = 0$ and $\gamma = 1$

2) organic materials assumed to be about 10%: $\alpha_1 \cong 0.1$; $\alpha_2 \cong 0.2$ and $\gamma = 1.02 / 1.1 \cong 0.9$

3) $\rho_{floc} = 2000$ kg/m^3 (sand floc with water): p = (2650-2000) / (2650-1030) $\cong$ 0.4 (40%)

If the settling velocity (w_s) and floc size (D_{floc}) are measured based on video-camera recordings, the floc density can be computed from the Stokes settling equation: $w_s = (\rho_{floc} / \rho_w - 1)\ g\ D_{floc}^2 / (18\nu)$ with ν the kinematic viscosity coefficient.

Dry sediment mass of floc: $M_{dry,floc} = V_s\ \rho_s = (1 - p)\ \rho_s\ V_{floc} = (1 - p)\ \rho_s\ (\pi / 6\ D_{floc}^3)$

Example calculation are included in Table A.1 and in Figure A.1. The porosity factor varies in the range of 0.4 to 1.

Floc density (ρ_{floc}; kg/m^3) (submerged floc density between brackets)	**Porosity factor**	
	No organic materials (γ = 1)	**Organic materials (γ = 0.9)**
1050 (20)	0.99	0.985
1100 (70)	0.956	0.948
1150 (120)	0.925	0.91
1200 (170)	0.895	0.874
1250 (220)	0.864	0.837
1300 (270)	0.83	0.801
1400 (370)	0.771	0.726
1500 (470)	0.71	0.653
1600 (570)	0.65	0.580
1800 (770)	0.525	0.432
2000 (970)	0.4	0.284

Table A.1 *Porosity factor of flocs*

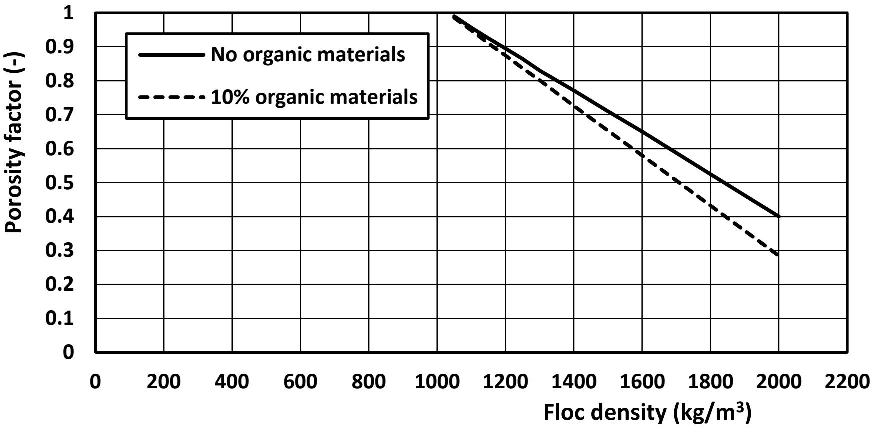


Figure A.1 *Porosity factor of flocs*

A.2 Basic data of field settling tests of settling tubes, Holwerd site, Wadden Sea, 24 May 2022 (NL)

Volume (ml)	Mass filter without mud (gram)	Mass filter with mud (gram)	Time (minutes)	Dry Mass mud (gram)	Concentration (mg/L)	Settling height (cm)	Settling velocity (mm/s)	Cumulative mass percentage smaller (%)
47.8	0.1178	0.1328	0	0.0150	313.81	29.2	10	100.00
48	0.1202	0.1345	1	0.0143	297.92	28.35	4.7250	94.94
61	0.1187	0.1350	3	0.0163	267.21	27.5	1.5278	85.15
48.5	0.1184	0.1303	5	0.0119	245.57	26.3	0.8767	78.25
52	0.1188	0.1305	10	0.0117	225.00	25.7	0.4283	71.70
27	0.1188	0.1244	30	0.0056	207.41	24.75	0.1375	66.09
72	0.1194	0.1334	60	0.0140	194.44	24.25	0.0674	61.96
53	0.1195	0.1293	120	0.0098	184.91	22.6	0.0314	58.92
68	0.1202	0.1318	160	0.0116	170.59	20.9	0.0218	54.36

Settling velocity of row 2 = 28.35 x 10 (mm)/(1 x 60 s) = 4.725 mm/s and so on

Cumulative percentage smaller=(concentration 297.9 mg/l / initial concentration 313.8 mg/l) x 100%=95% and so on

Table A.2 Basic settling data of Laboratory Settling test; LST-Pump sample 1; c_o=313 mg/l

Volume (ml)	Mass filter without mud (gram)	Mass filter with mud (gram)	Time (minutes)	Dry Mass mud (gram)	Concentration (mg/L)	Settling height (cm)	Settling velocity (mm/s)	Cumulative mass percentage smaller (%)
56	0.1197	0.3025	0	0.1828	3264.29	29.3	10	100.00
53.5	0.1183	0.2842	1	0.1659	3100.93	27.9	4.6500	95.00
53	0.1178	0.2189	3	0.1011	1907.55	26.7	1.4833	58.44
53	0.1210	0.1866	5	0.0656	1237.74	25.7	0.8567	37.92
53	0.1179	0.1597	10	0.0418	788.68	24.6	0.4100	24.16
52	0.1252	0.1546	17	0.0294	565.38	23.5	0.2304	17.32
48.7	0.1175	0.1415	30	0.0240	492.81	22.4	0.1244	15.10
53	0.1187	0.1394	60	0.0207	390.57	21.3	0.0592	11.96
55	0.1200	0.1388	120	0.0188	341.82	20	0.0278	10.47
57	0.1210	0.1295	180	0.0085	149.12	18.8	0.0174	4.57

Table A.3 Basic settling data of Laboratory Settling test; LST-Pump sample 2; c_o=3264 mg/l

Volume (ml)	Mass filter without mud (gram)	Mass filter with mud (gram)	Time (minutes)	Dry mss mud (gram)	Concentration (mg/L)	Settling height (cm)	Settling velocity (mm/s)	Cumulative mass percentage smaller (%)
47.5	0.1194	0.1399	0	0.0205	431.58	22.9	10	100.00
48	0.1187	0.1386	1	0.0199	414.58	22	3.6667	96.06
48.8	0.1183	0.1375	3	0.0192	393.44	21.2	1.1778	91.16
50	0.1185	0.1366	5	0.0181	362.00	20.3	0.6767	83.88
71	0.1220	0.1460	10	0.0240	338.03	19.4	0.3233	78.32
54	0.1198	0.1361	30	0.0163	301.85	18.2	0.1011	69.94
76	0.1200	0.1345	60	0.0145	190.79	16.7	0.0464	44.21
59	0.1200	0.1274	120	0.0074	125.42	14.65	0.0203	29.06
60	0.1208	0.1274	160	0.0066	110.00	13.9	0.0145	25.49

Table A.4 Basic settling data of Laboratory Settling test; LST-Piranha sample 1; c_o=431 mg/l

Volume (ml)	Mass filter without mud (gram)	Mass filter with mud (gram)	Time (minutes)	Dry mss mud (gram)	Concentration (mg/L)	Settling height (cm)	Settling velocity (mm/s)	Cumulative mass percentage smaller (%)
50	0.1212	0.3283	0	0.2071	4142.00	24.3	10	100.00
50	0.1248	0.2964	1	0.1716	3432.00	23.1	3.8500	82.86
53	0.1271	0.2327	3	0.1056	1992.45	22.25	1.2361	48.10
50	0.1274	0.1929	5	0.0655	1310.00	20.9	0.6967	31.63
52	0.1203	0.1649	10	0.0446	857.69	19.5	0.3250	20.71
50	0.1184	0.1454	30	0.0270	540.00	18.7	0.1039	13.04
53	0.1190	0.1420	60	0.0230	433.96	17.4	0.0483	10.48
54	0.1181	0.1324	120	0.0143	264.81	15.95	0.0222	6.39
55	0.1192	0.1294	180	0.0102	185.45	14.85	0.0138	4.48

Table A.5 Basic settling data of Laboratory Settling test; LST-PIRANHA sample 2; c_o=4142 mg/l

Volume (ml)	Mass filter without mud (gram)	Mass filter with mud (gram)	Time (minutes)	Dry mass mud (gram)	Concentration (mg/L)	Settling height (cm)	Settling velocity (mm/s)	Cumulative mass percentage smaller (%)
26	0.1201	0.1539	0	0.0338	400.00	24.5	10	100.00
26	NA	NA	1	NA	NA	24.1	4.0139	95.00
26	0.1201	0.1291	3	0.0090	346.15	23.6	1.3117	86.54
26	0.1218	0.1303	5	0.0085	326.92	23.1	0.7713	81.73
26	0.1209	0.1290	10	0.0081	311.54	22.7	0.3778	77.88
24.9	0.1209	0.1269	30	0.0060	240.96	22.2	0.1233	60.24
30	0.1214	0.1269	60	0.0055	183.33	21.7	0.0604	45.83
30	0.1209	0.1254	120	0.0045	150.00	21.2	0.0294	37.50
30	0.1209	0.1252	180	0.0043	143.33	22.2	0.0206	35.83

Table A.6 Basic settling data of InSitu Settling test; IST-PIRANHA sample 1 ; c_o=400 mg/l

Volume (ml)	Mass filter without mud (gram)	Mass filter with mud (gram)	Time (minutes)	Dry mass mud (gram)	Concentration (mg/L)	Settling height (cm)	Settling velocity (mm/s)	Cumulative mass percentage smaller (%)
30.9	0.1191	0.2000	0	0.0809	2618.12	24.5	10	100.00
30	0.1185	0.1835	1	0.0650	2166.67	23.9	3.9865	82.76
30	0.1203	0.1513	3	0.0310	1033.33	23.3	1.2943	39.47
30	0.1220	0.1413	5	0.0193	643.33	22.7	0.7559	24.57
31	0.1179	0.1409	10	0.0230	741.94	22.1	0.3676	28.34
30	0.1212	0.1327	30	0.0115	383.33	21.4	0.1190	14.64
30	0.1198	0.1314	60	0.0116	386.67	20.8	0.0578	14.77
44	0.1204	0.1308	120	0.0104	236.36	20.2	0.0280	9.03
30	0.1186	0.1266	180	0.0080	266.67	19.3	0.0179	10.19

Table A.7 Basic settling data of InSitu Settling test; IST-PIRANHA sample 2; c_o=2618 mg/l

A.3 Basic data of field settling tests of LABSFLOC2-instrument, Holwerd site, Wadden Sea, 24 May 2022 (NL)

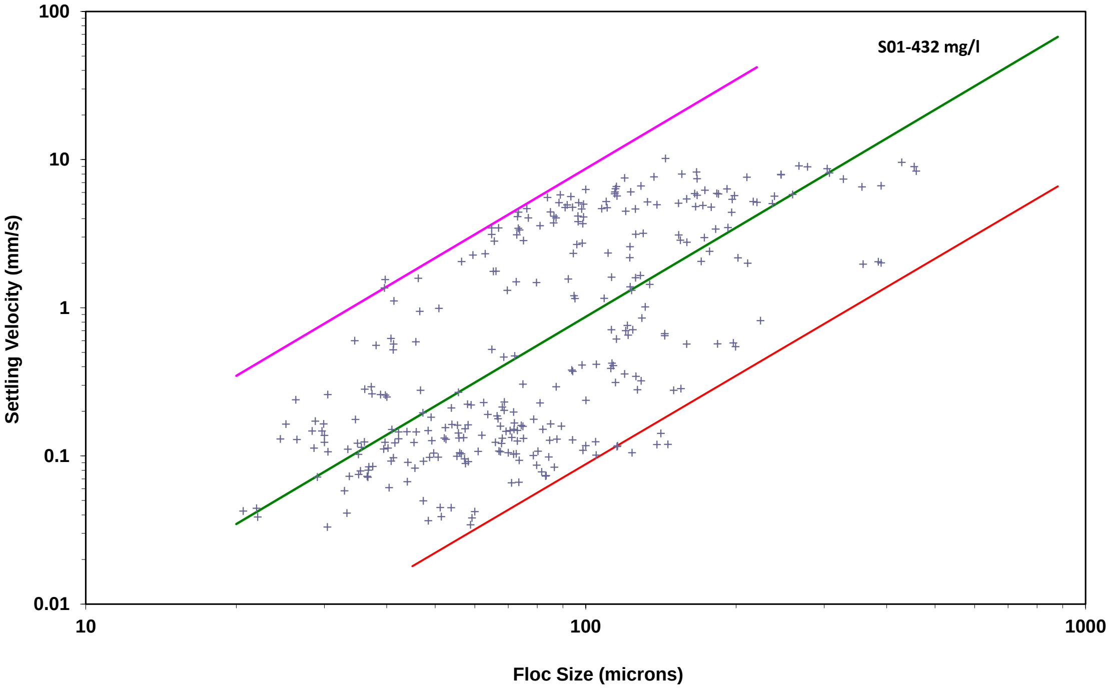


Figure A.2 *Settling velocity versus floc size of sample S01 (c_o = 432 mg/l)*

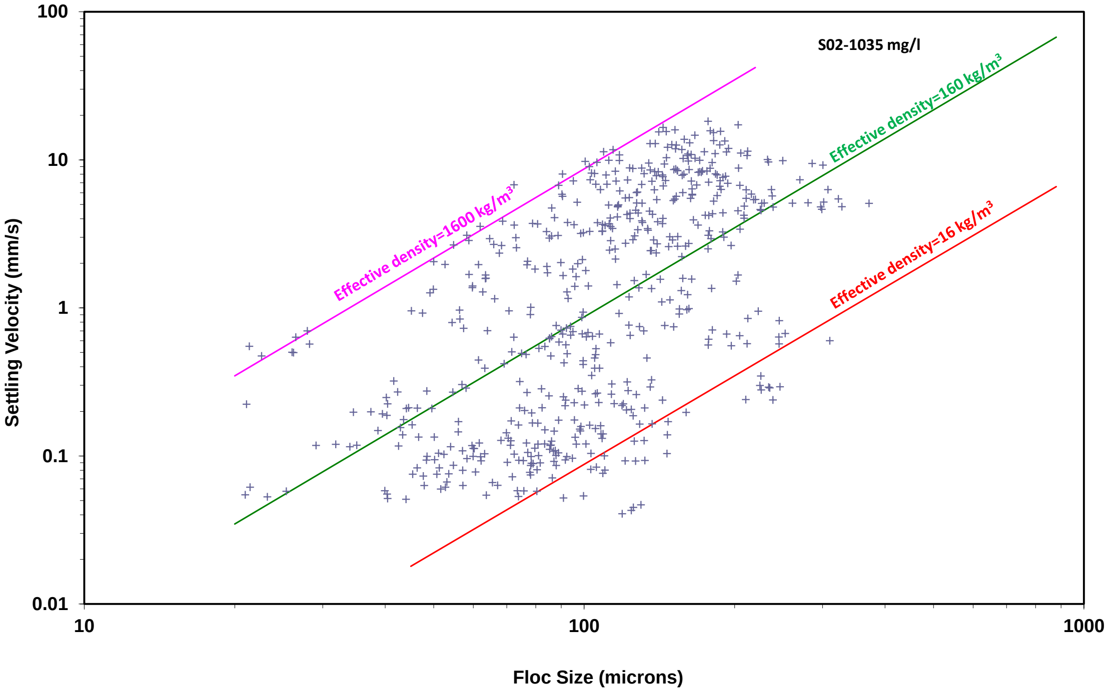


Figure A.3 *Settling velocity versus floc size of sample S02 (c_o = 1035 mg/l)*

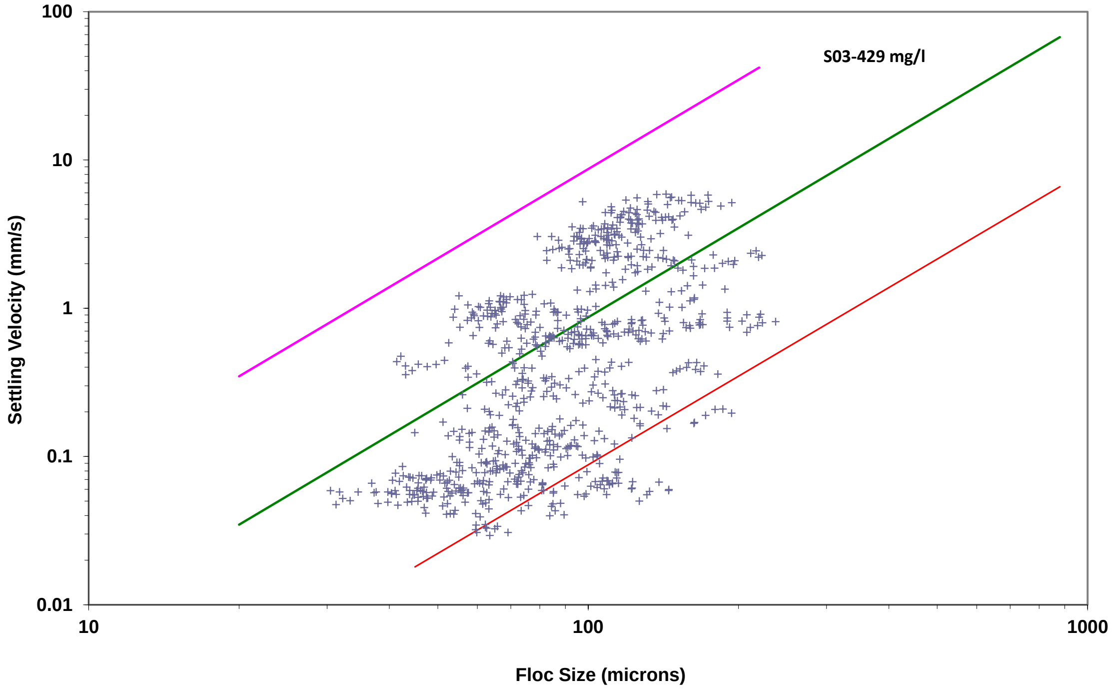


Figure A.4 *Settling velocity versus floc size of sample S03 (c_o = 429 mg/l)*

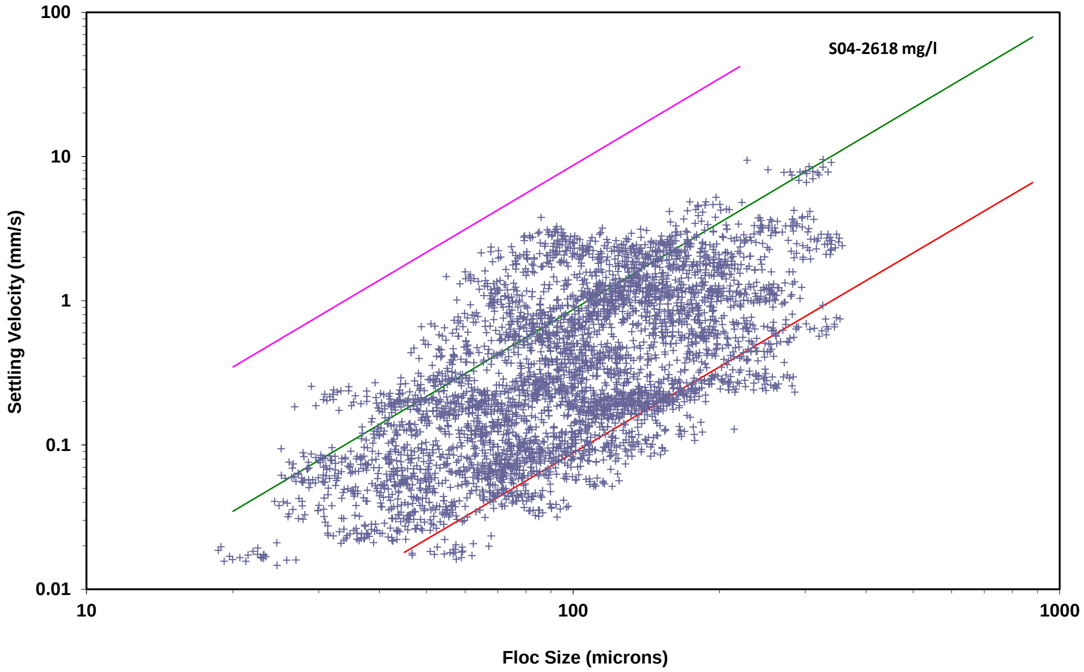


Figure A.5 *Settling velocity versus floc size of sample S04 (c_o = 2088 mg/l)*

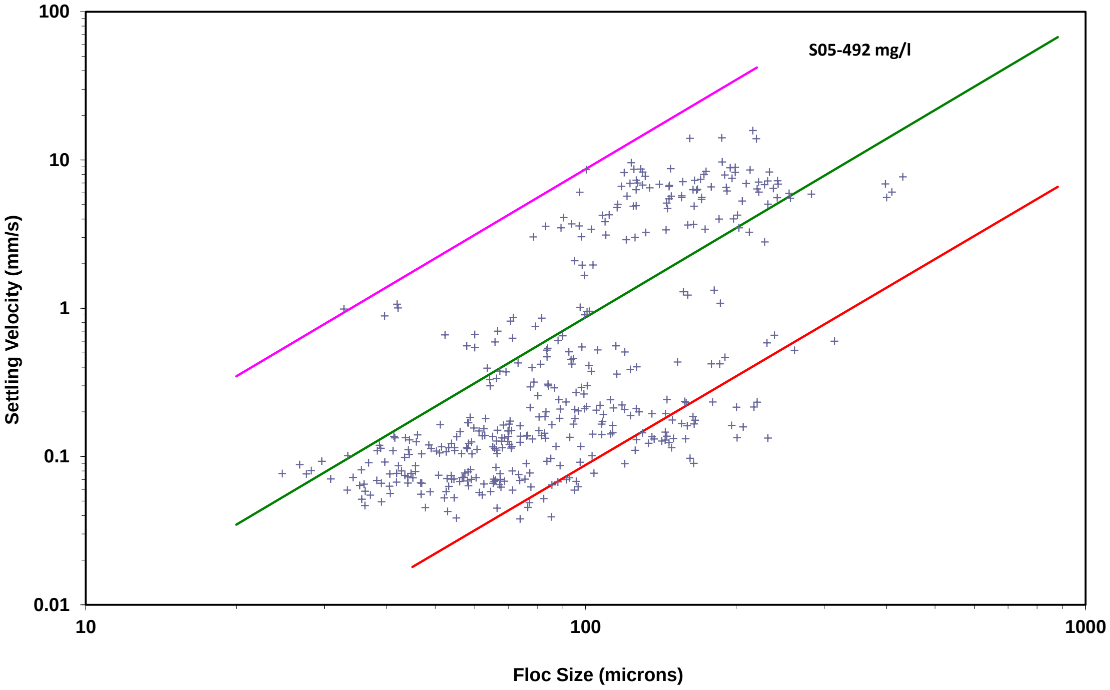


Figure A.6 *Settling velocity versus floc size of sample S05 (c_o = 492 mg/l)*

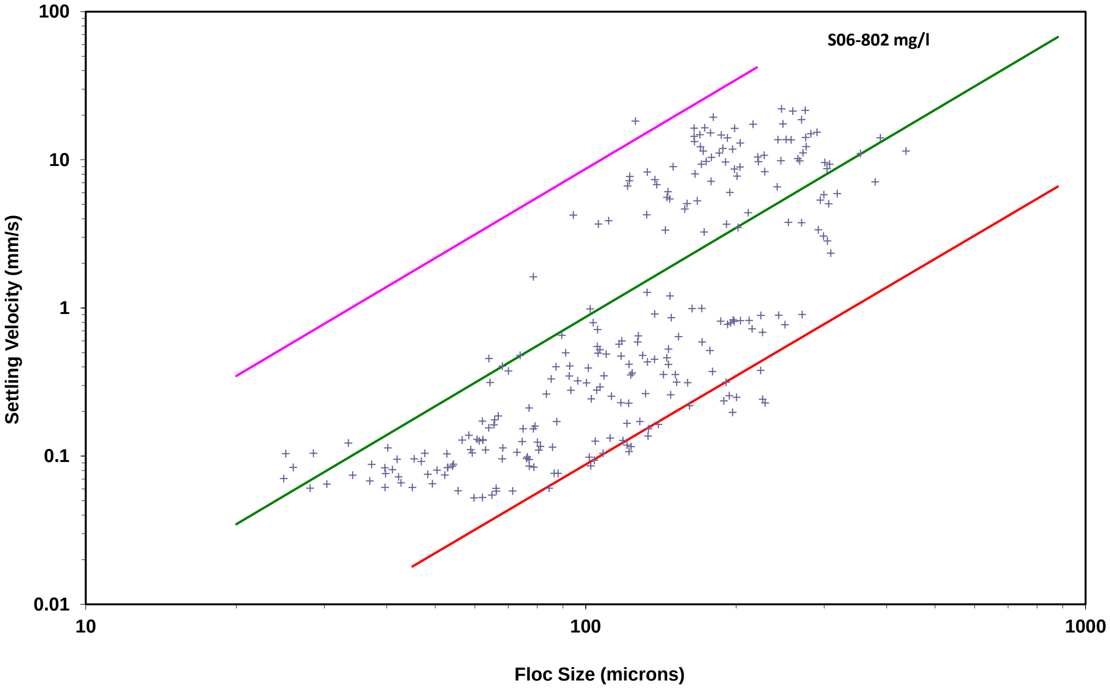


Figure A.3a *Settling velocity versus floc size of sample S06 (c_o = 802 mg/l)*

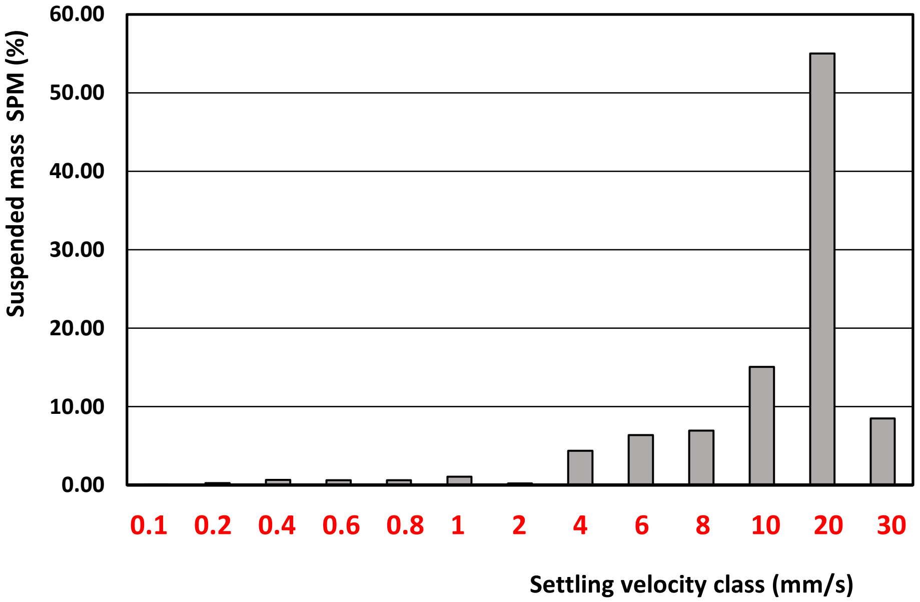


Figure A.3b *Distribution of suspended mass over settling velocity classes of sample S06 (c_o = 802 mg/l)*

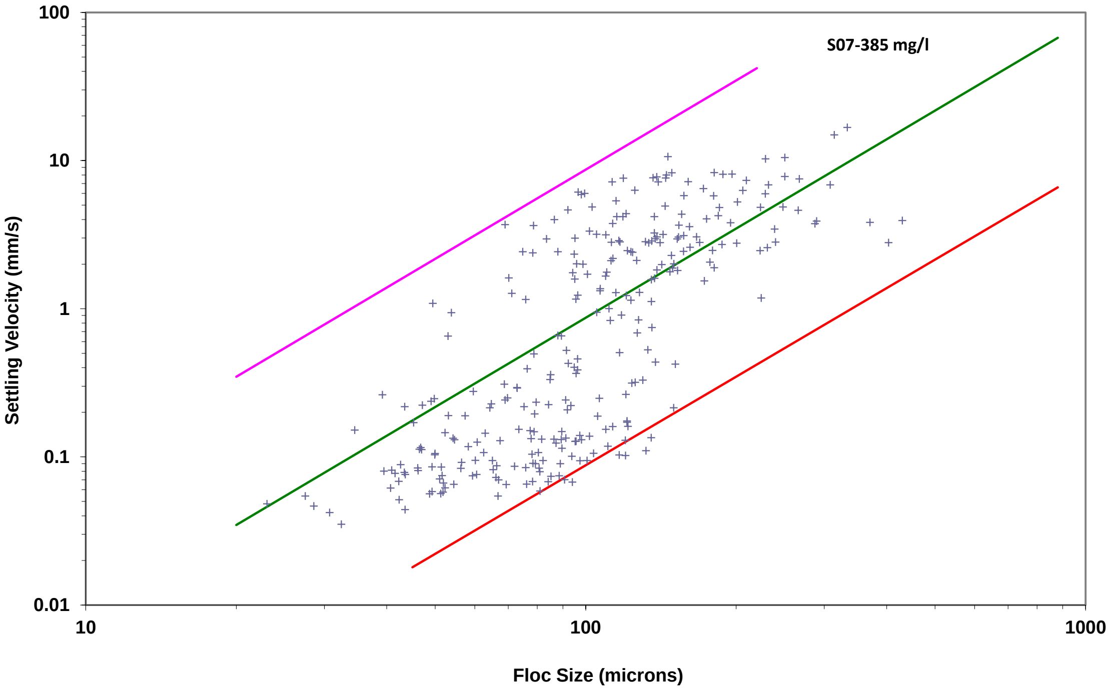


Figure A.3 *Settling velocity versus floc size of sample S07 (c_o = 385 mg/l)*