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Analysis of sedimentation and resuspension processes of aquaculture biosolids using an oscillating grid

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Abstract

Sedimentation and resuspension processes of aquaculture biosolids (non-ingested feed and faeces) are analysed using vertically oscillating grids as a source of turbulence in fluid tanks. An oscillating grid system consists of a container in which a grid is stirred vertically generating a well-known turbulent field that is function of amplitude and frequency of oscillation, distance between grid and measurement point, and mesh spacing of the grid. The grid used in this study had a mesh spacing of 1.2 cm, and was calibrated using different amplitudes (1, 1.5 and 2 cm), frequencies (from 1 to 6 Hz) and distances (2.4, 2.7 and 3 cm). After calibration, the turbulence needed to resuspend biosolids and to maintain them in the water column following different times of consolidation, and with biosolids of different origin, was analysed. It was observed that the turbulence needed to resuspend aquaculture biosolids increased with the time of consolidation. When the turbulence was decreased after a resuspension process, the next sedimentation of biosolids showed a hysteretic behaviour: turbulence needed to resuspend a fixed percent of biosolids from the tank bottom is substantially higher than that needed to maintain the same percentage suspended in the water column. Differences in resuspension behaviour of biosolids originated in different tanks were also observed.

The method provides useful information that can be compared with turbulence generated by fish swimming activity, in order to determine the culture conditions, which can promote self-cleaning conditions in a particular tank.

Keywords: Turbulence; Fish faeces; Solid waste; Resuspension; Oscillating grid

1. Introduction

Sedimentation and resuspension processes of aquaculture biosolids (fish faeces and non-ingested feed) are very important in aquaculture systems since they affect environmental conditions. Their accumulation in the tank bottom can lead to hypoxic conditions (Sumagaysay-Chavoso and San Diego-McGlone, 2003) that affect fish welfare and growth (Thetmeyer et al., 1999; Buentello et al., 2000). Nevertheless, if biosolids are maintained in the water column, or resuspended from the bottom, they may be removed from rearing areas with recirculation water, and can be separated by filtration or sedimentation processes (Cripps and Bergheim, 2000). Their maintenance in the water column will be determined by the turbulence level in the tank. Fish swimming activity and tank design (geometry and water inlet conditions, Oca et al., 2004) are the primary factors determining turbulence levels in the tank.

The study of resuspension and sedimentation processes of biosolids is especially complex, due to the cohesive properties of these materials. Biosolids are,

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mainly, aggregates of particles and/or microflocs subjected to aggregation and disaggregation processes, which modify their physical characteristics over time.

The density of aquaculture biosolids is very low, presenting a specific gravity (ratio of the density of a substance to that of a standard substance, water in this case) in the range of 1.005–1.250 (Chen et al., 1993; Patterson et al., 2003; True et al., 2004; Johnson and Chen, 2005; Droppo et al., 2007).

Turbulence generated by fish swimming activity has a great importance in aquaculture tank hydrodynamics, especially in intensive farming systems, where high fish densities are common. The higher the fish density, the higher the turbulence generated, and this turbulence can be enough to maintain biosolids in suspension or promote their resuspension from the tank bottom, even with low current velocity or a zero mean velocity. Chen et al. (1993), working in a recirculating system with brook trout (*Salvelinus fontinalis*) weighing 50 g and rainbow trout (*Oncorhynchus mykiss*) weighing 100 and 500 g, determined that more than 95% of the suspended particles in an aquaculture tank have a diameter less than 20 μm.

If biosolids are left undisturbed, they increase the resistance to resuspension as a result of consolidation of the bed (Mehta et al., 1989; Zreik et al., 1998; Orlins and Gulliver, 2003), or by sediment layer biostabilization (Droppo et al., 2007). The cause of biosolids consolidation at the bottom is the gradual compression and collapse of the particles and/or aggregates, when water that is in the pores is driven out. Mucus presence in aquaculture biosolids also increases this resistance to resuspension (Nowell et al., 1981).

In natural or artificial water streams, the transport of cohesive sediments is determined by the critical bed shear stress for erosion (perpendicular force needed to resuspend sediments) and for deposition (perpendicular force above which sediments are maintained in suspension) (Van Rijn, 1993). Flumes or tanks where the introduced bed shear stress is known are used to measure this erosion rate (Nowell et al., 1981; Portela and Reis, 2004; Droppo et al., 2007) or deposition rate (Neumeier et al., 2007).

Under low or zero mean vertical velocity, oscillating grids are a useful alternative tool for evaluating the dynamics of sedimentation and resuspension, and may be particularly useful in aquaculture tanks to study the effects of fish-generated turbulence.

Oscillating grids have already been used in the study of various environmental processes such as the initiation of sediment motion (Sánchez and Redondo, 1998; Medina et al., 2001), mixing in coastal waters (Carrillo et al., 2001), and turbulent mixing across density interfaces (Hopfinger and Toly, 1976; McDougall, 1979). Other authors (Tsai and Lick, 1986; Orlins and Gulliver, 2003) have used oscillating grids to study the resistance to resuspension of cohesive sediments originated in lakes with a high percentage of clay and silt. The method gives a quick and easy assessment of the turbulence levels characteristic of biosolids sedimentation and resuspension dynamics.

The purpose of this study is to evaluate the turbulence, generated by means of vertically oscillating grids, needed to resuspend aquaculture biosolids and to evaluate the minimum turbulence that allows biosolids to remain suspended in the water column. The effect of consolidation time and biosolids origin in the above mentioned processes would be analysed.

2. Material and methods

An oscillating grid consists of a grid, with a mesh size M (cm) (distance between the centers of two neighbouring openings), that oscillates around a mean position with an amplitude S (stroke in cm) at a known frequency f (Hz) (Fig. 1). In the fluid closer to the grid, there are large gradients in the turbulence level in the direction of grid oscillation. Beyond a distance 2 mesh sizes (M) from the grid, the movement of the oscillating grid generates isotropic turbulence with a zero mean flow in the container (Thompson and Turner, 1975; Hopfinger and Toly, 1976; Atkinson et al., 1987).

Turbulence can be expressed as the root mean square of the velocity (RMS). RMS is a statistical measure of the velocity fluctuation (Eq. (1)).

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{n} (v_i - v_{\mathrm{ave}})^2}{n}} \tag{1}$$

where v_i is the instantaneous velocity measurement, v_{ave} is the mean velocity of the flow, and n is the number of instantaneous velocity measurements. RMS is expressed in terms of velocity units.

Thompson and Turner (1975) found a linear relation between RMS and the grid oscillation frequency (f), and Hopfinger and Toly (1976) described an empirical equation that relates the RMS with oscillation frequency (f), stroke length (S), mesh spacing of the grid (M) and distance between the mid-point of the grid and the measurement point (z) (Eq. (2)).

$$\mathrm{RMS} = C \times M^{0.5} \times S^{1.5} \times f \times z^{-1} \tag{2}$$

C is a constant that must be experimentally obtained because depends on the grid characteristics, which are

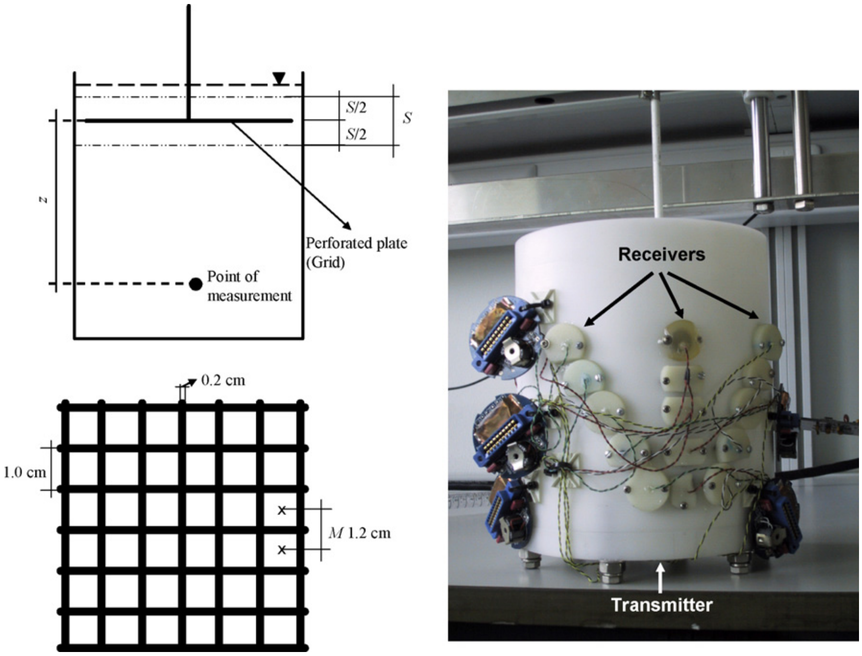

Fig. 1. Experimental setup (above, S is the stroke or amplitude of oscillations, and z the distance between the point of measurement and the grid), and characteristics of the perforated plate used in the present work (bottom, M is the mesh size). Right: acoustic transducers mounted in the custom made cylindrical container.

mesh spacing M and solidity (perpendicular area to the flow direction that is blocked by the grid bars). Hopfinger and Toly (1976) found a value of 0.25 for all three velocity components in a square tank (M of 5 and 10 cm, and solidity <40%), and De Silva and Fernando (1992) found values of 0.22 and 0.26 for the X–Y and Z axis, respectively (M of 4.76 cm and solidity of 36%). Solidity has to be less than 40%, allowing to obtain nearly isotropic turbulence with zero mean flow at distances greater than 2 M, and to avoid secondary circulations (Hopfinger and Toly, 1976; De Silva and Fernando, 1992).

We performed experiments to evaluate the feasibility of using oscillating grids for studies of resuspension and sedimentation processes with aquaculture biosolids. These experiments included, (a) the definition of the experimental device in order to be able to change the parameters S, f and z, (b) the calibration of the grid to find the relationships between S, f, z, and the RMS values, and (c) the experimental procedure to measure the suspended fraction of biosolids in the water column and the fraction settled in the tank bottom.

2.1. Experimental grid device

The experimental device consisted in a horizontal grid that moved vertically inside a container with a slightly larger horizontal section than the grid. A variable velocity gear head motor (K50 640, Kelvin, Madrid, Spain) connected to an eccentric arm, powered the vertically oscillating grid in a stainless steel structure. The motor had a nominal rotational velocity of 374 rpm and could be reduced to 1/20.

The grid was a perforated plate (stainless steel of 0.15 cm thickness) with 1 cm × 1 cm square orifices with a center-to-center spacing of 1.2 cm (M) (Fig. 1), presenting 30.5% solidity.

2.2. Grid calibration

In order to calibrate the flow introduced by the oscillating grid, we did velocity measurements under different oscillation conditions. Several types of sensors have been used to measure velocity in oscillating grid systems: hot-film probes (e.g. Thompson and Turner, 1975; Hopfinger and Toly, 1976), Laser Doppler Velocimeters (LDV, e.g. McDougall, 1979; De Silva and Fernando, 1992), Digital Particle Image Velocimetry (DPIV, e.g. Cheng and Law, 2001), acoustic Doppler velocimeters (ADV, e.g. Brunk et al., 1996; McKenna and McGillis, 2004). In this study we have used an ADV system, which allows measuring 3-dimensional velocities with a high frequency.

A custom made cylindrical container (made of Delrin, inner Ø 12.9 cm) was used to mount acoustic transducers flush to the inner wall (Nortek AS, Sandvika, Norway) (Fig. 1). Arrays of one acoustic transmitter and 3 acoustic receivers were aligned to measure 3-dimensional particle velocities using the Doppler effect at specific points inside the container. The system had 5 sets of transducers with measurement points at 23, 43, 64, 83 and 103 mm of height, and 23, 43, 64, 46 and 25 mm distance to the nearest wall, respectively. Data were acquired at 25 Hz for 1 min. Water was seeded with hollow glass spheres with a density close to that of water and a size around 11 μm (Spherical Hollow Glass Spheres, Potters Industries Inc.) to increase the strength of the signal and reduce noise. Measurements were conducted using sea water at approximately 22 °C.

In order to ensure steady state conditions inside the container, the oscillation of the grid was maintained at a constant stroke (S) and frequency (f) for 20 min before each measurement (Cheng and Law, 2001).

Three strokes ($S = 1$, 1.5 and 2 cm), three distances from the grid to the point of measurement ($z = 2.4$, 2.7 and 3 cm), and frequencies (f) from 1 to 6 Hz were used during calibration. All the distances (z) were above two mesh spaces ($z \geq 2$ M) ensuring isotropic turbulent conditions were achieved. The maximum frequency used was 6 Hz following McDougall (1979), who recommended the oscillation frequency to be smaller than 7 Hz in order to maintain horizontal mean velocities close to zero.

2.3. Grid measurement procedure

The study of resuspension and sedimentation processes required (1) the collection of biosolids and their placement with minimal disturbance in a container, (2) the progressive variation of the turbulence, and finally (3) the measurement of the percent of biosolids present in the water column at each turbulence level.

Biosolids were collected in a flow-through system from three 0.7 m^3 cylindrical fish tanks (tanks 0, 1 and 2) containing Sea bass (*Dicentrarchus labrax*, L.), with constant water temperature and salinity 37‰. Tank 0 contained an undetermined number of fish with different sizes. Tank 1 contained 11 fish weighting 129.45 ± 15.24 g and with a length 19.69 ± 1.99 cm, and tank 2 contained 69 fish weighting 79.54 ± 20.12 g and with a length 15.79 ± 1.69 cm. In all tanks, fish were manually fed *ad libitum* with commercial extruded pellets (Mistral 21, 49–52% protein, 33–41% fat and 10–15% lipids, ProAqua, S.L.).

Biosolids collection was made with a 300 ml glass jar through an outlet pipe in the false floor at the bottom of the fish tank. The jar was completely filled with water and biosolids, and immediately closed. Once in the laboratory, the jar was opened and the experimental containers were filled with the water and biosolids collected. We were extremely gentle during the whole procedure to minimize biosolids disturbance. Approximately a 0.5 cm layer of biosolids was placed in the bottom of the container. Then the experimental containers were slowly topped with water from the same fish tank, up to 12 cm in height.

Experimental containers were made of 1 cm thick transparent methacrylate. They were 25 cm high and had an 11 cm × 11 cm internal horizontal square section to minimize secondary circulation (Peters and Redondo, 1997).

For the assessment of biosolids resuspension (resuspension events), biosolids were left for 1 h and then the turbulence level was gradually increased every twenty minutes until all the biosolids were in the water column (no biosolids in the container bottom). For the assessment of aquaculture biosolids sedimentation (sedimentation events), when all the biosolids were in the water column the turbulence level was gradually decreased every thirty minutes. The final level was with still-water (RMS of 0 cm s^{-1}) during 30 min.

At each turbulence level, during resuspension and sedimentation events, water samples were withdrawn for analysis to quantify the presence of biosolids in the water column. Water (5 ml) was withdrawn from a point placed 5 cm below the free surface.

In order to measure the percent of biosolids suspended in the water column, two kinds of measurements were made: (1) turbidity was determined for all the samples after its dilution 1/5 with distilled water, using a spectrophotometer (Hach, model DR/2000) measuring FTU units (Formazin Turbidity Unit), and (2) total organic carbon (TOC) was also determined simultaneously with turbidity in some resuspension and sedimentation events. These samples were pressure-filtered through precombusted glass fibre filters (Whatman GF/F 0.7 μm) and the solid residue was analysed for total organic carbon with a TOC-Analyser (Shimadzu, TOC-V_{CSN}), connected to a Solid Sample Module (Shimadzu, Model SSM-5000A).

The percent of suspended biosolids was calculated from FTU values as:

$$\frac{\mathrm{FTU}_i - \mathrm{FTU}_{\mathrm{min}}}{\mathrm{FTU}_{\mathrm{max}} - \mathrm{FTU}_{\mathrm{min}}} \times 100 \qquad (3)$$

where FTU_i is the turbidity measurement at a fixed RMS value, $\mathrm{FTU}_{\mathrm{min}}$ is the measurement when all the biosolids are in the bottom of the container (RMS of 0 cm s^{-1}), and FTU_{max} is the measurement when all the biosolids are in water column (maximum RMS).

Similarly, the percent of suspended biosolids was calculated from TOC values as:

$$\frac{TOC_i - TOC_{min}}{TOC_{max} - TOC_{min}} \times 100 \qquad (4)$$

where TOC_i is the organic carbon measurement at a fixed RMS value, TOC_{min} is the measurement when all the biosolids are in the bottom of the container (RMS of 0 cm s^{-1}), and TOC_{max} is the measurement when all the biosolids are in water column (maximum RMS).

Both values (percent of biosolids calculated from FTU or TOC) where practically identical in those samples belonging to the series analysed using both methods. The relationship between TOC and FTU was strongly linear, with r^2 from 0.852 to 0.955 and $p < 0.001$, showing the turbidity as a good indirect measurement of the biosolids suspended.

2.4. Experimental procedure

Four set of experiments were done (Table 1):

1. Evaluation of the resistance to resuspension as a function of consolidation time;
2. study of a sedimentation process after resuspension using a gradual decrease of turbulence;
3. study of two consecutive processes of resuspension and sedimentation using a gradual increase in turbulence, followed by a gradual decrease in turbulence;
4. differences in resuspension and sedimentation processes of aquaculture biosolids originated in different tanks.

2.4.1. Evaluation of the resistance to resuspension as a function of consolidation time

Biosolids were collected in tank 0, and immediately placed in two different containers. With the first container, after 1 h of biosolids placement, the turbulence was progressively increased every 20 min (resuspension 1, 1 h of consolidation: R1CT1) until all the biosolids were in the water column (no biosolids in container's bottom). The experiment was repeated with the second container, after 48 h of biosolids placement (resuspension 1, 48 h of consolidation: R1CT48). At each turbulence level the percent of suspended biosolids was determined.

2.4.2. Study of a sedimentation process after resuspension

Biosolids were collected in tank 1. After 48 h of biosolids placement in the container the resuspension event began (resuspension 1, 48 h of consolidation: R1CT48) and the turbulence was increased gradually with steps of 0.17–0.18 cm s^{-1}. Each turbulence level was maintained during 20 min.

After total resuspension of biosolids, the sedimentation event was started (S1CT48), decreasing turbulence gradually (steps of 0.17–0.18 cm s^{-1}) every 30 min. The final turbulence level was with still-water (RMS of 0 cm s^{-1}) during 30 min. At each turbulence level the percentage of suspended biosolids was determined.

2.4.3. Study of two consecutive processes of resuspension and sedimentation

After the previous experiments (R1CT48 and S1CT48) this was repeated with a consolidation time of 48 h after the biosolids first resuspension event (resuspension 2, 48 + 48 h of consolidation: R2CT48 + 48 and S1CT48 + 48). Also, at each turbulence level the percent of suspended biosolids was determined.

2.4.4. Resuspension and sedimentation processes of aquaculture biosolids originated in different tanks

Experiments R1CT48 and S1CT48 (see Section 2.4.2) with biosolids collected in tank 1, were repeated with biosolids collected in tank 2 (R1CT48 and S1CT48) in order to evaluate the effect of resuspension and sedimentation events on biosolids with different origin. Also, at each turbulence level the percent of suspended biosolids was determined.

3. Results and discussion

3.1. Grid calibration

The constant C from Eq. (2) (Hopfinger and Toly, 1976) for the X and Y-axes, and for the Z-axis was determined. These calibration constants, obtained by linear regression between RMS (experimental values) and $M^{0.5} S^{1.5} f z^{-1}$ (Fig. 2), were 0.253 ($r^2 = 0.841$) for X and Y-axes (C_{x-y}) and 0.377 ($r^2 = 0.957$) for Z-axes (C_z) (Fig. 2). Both constants are slightly higher than those obtained by Hopfinger and Toly (1976) ($C = 0.25$) and De Silva and Fernando (1992) ($C_{x-y} = 0.22$, $C_z = 0.26$). These authors used larger containers, and also bigger center-to-center mesh spacing ($M = 5$ and 10 cm; and $M = 4.76$ cm). Thus, some differences in C values were expected.

Table 1
Summary of experiments

Experiment	Tank	Event	Number of resuspension/ sedimentation event	Consolidation time (h)
Evaluation of the resistance to resuspension as a function of consolidation time				
R1CT1	Tank 0	Resuspension	1	1
R1CT48	Tank 0	Resuspension	1	48
Study of a sedimentation process after resuspension				
R1CT48	Tank 1	Resuspension	1	48
S1CT48	Tank 1	Sedimentation	1	48
Study of two consecutive processes of resuspension and sedimentation				
R1CT48	Tank 1	Resuspension	1	48
S1CT48	Tank 1	Sedimentation	1	48
R2CT48 + 48	Tank 1	Resuspension	2	48 + 48
S2CT48 + 48	Tank 1	Sedimentation	2	48 + 48
Differences in resuspension and sedimentation processes of aquaculture biosolids originated in different tanks				
R1CT48	Tank 1, 2	Resuspension	1	48
S1CT48	Tank 1, 2	Sedimentation	1	48

3.2. Experimental procedure

3.2.1. Evaluation of the resistance to resuspension as a function of consolidation time

The resistance to resuspension was lower immediately after their collection (R1CT1) than after 48 h of consolidation in the tank bottom (R1CT48) (Fig. 3). For example, to resuspend 50% of biosolids in the water column after their collection an RMS_{x-y} of 0.60 cm s^{-1} was needed, while an RMS_{x-y} of 0.90 cm s^{-1} was needed to resuspend the same proportion when biosolids were left consolidating for 48 h.

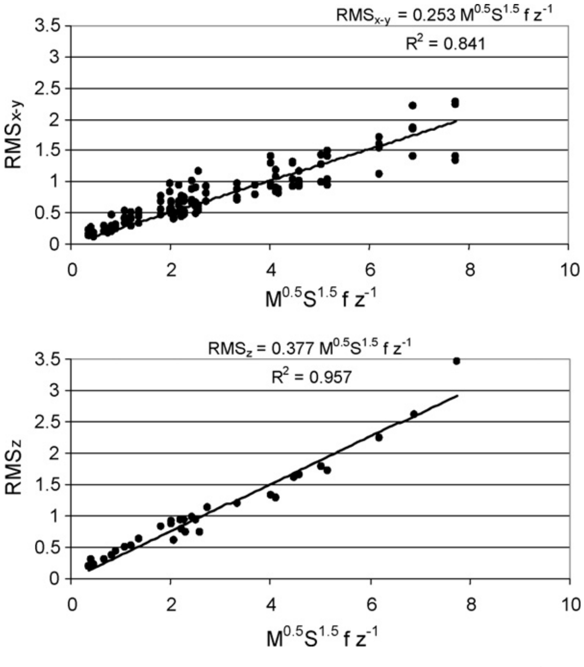

Fig. 2. Relationship between RMS experimental values (cm s^{-1}) and $M^{0.5}\,S^{1.5}\,f\,z^{-1}$ obtained in calibration experiments for X–Y (above) and Z (bottom) axis.

Our results demonstrate that resistance to resuspension increases with consolidation time. Similar results were found by Orlins and Gulliver (2003) for cohesive sediments in lakes. The increase in resistance to resuspension is a function of particle size, consolidation time and cohesiveness (Medina et al., 2001). Cohesiveness is enhanced by high fine particle content and a high organic matter ratio (Otsubo and Muraoka, 1988), and aquaculture biosolids present both characteristics.

Droppo et al. (2007) showed that consolidation time enhanced resistance in resuspension of biosolids accumulated under a rainbow trout (*O. mykiss*) cage, but they believed this increase was influenced strongly by biofilm integration on and within the surface sediment layer than by consolidation and dewatering effects. In our case the increase in the resistance to resuspension has been demonstrated. However, further experiments are necessary to study the presence of biofilm, and to separate the effects of consolidation and of biofilm integration.

Present results could be compared with turbulence generated in a tank with fish, in order to determine biosolids placement in the tank bottom. Masaló et al. (2008) determined the turbulence generated by fish swimming activity in a tank with a current velocity of 13 cm s^{-1} (approx.). With sea bass of 48 g and 35.5 kg m^{-3}, RMS_x in the tank was between 2.428 and 3.632 cm s^{-1}, and working with sea bass of 11.7 g and 11.8 kg m^{-3}, RMS_x was between 1.419 and 1.728 cm s^{-1}.

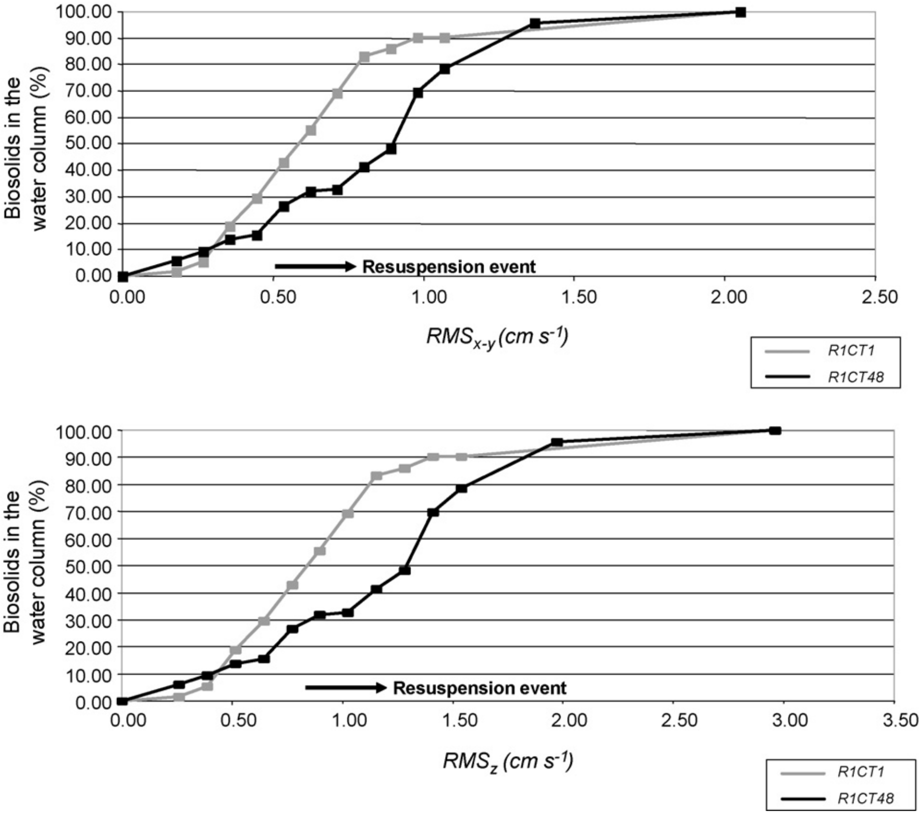

Fig. 3. Fraction of biosolids in the column as a function of the turbulence (RMS$_{x-y}$ above, and RMS$_z$ bottom) applied after collection (R1CT1, light grey line) and after 48 h of consolidation (R1CT48, black line).

3.2.2. Study of a sedimentation process after resuspension

After a total resuspension of biosolids when the turbulence was decreased gradually (sedimentation event), the percent of suspended biosolids, for the same turbulence level, was much higher than for the resuspension event (Fig. 4). For example, at an RMS$_{x-y}$ of 0.35 cm s^{-1} more than 80% of the biosolids were still

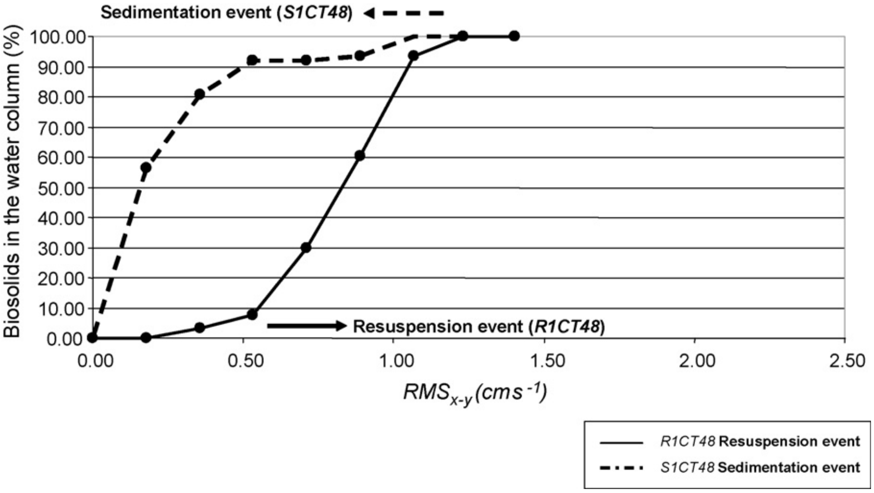

Fig. 4. Fraction of biosolids in the column during resuspension (filled line) and sedimentation (dashed line) as a function of the turbulence (RMS$_{x-y}$) applied after 48 h of consolidation (R1CT48 and S1CT48).

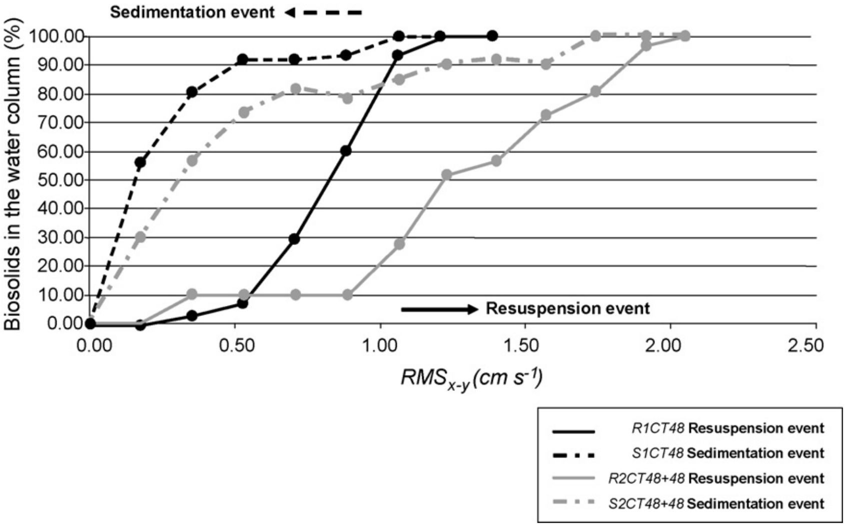

Fig. 5. Fraction of biosolids in the column during resuspension (filled line) and sedimentation (dashed line) event as a function of the turbulence (RMS$_{x-y}$) applied after 48 h of consolidation (R1CT48 and S1CT48, black line) and after 48 h of first resuspension event (R2CT48 + 48 and S2CT48 + 48, light grey line).

in the water column during the sedimentation event S1CT48, while during the resuspension event R1CT48, only about 3% of the biosolids were in the water column. This fact showed that the presence of biosolids in the water column greatly depends on the initial state, resulting in a hysteresis loop classified as counter clockwise. In this study the minimum RMS$_{x-y}$ that allows maintaining 50% of the biosolids in the water column after their resuspension was around 0.20 cm s^{-1}, whereas the RMS$_{x-y}$ needed to resuspend 50% of the biosolids placed in the bottom of the container was higher than 0.70 cm s^{-1}.

This hysteresis behaviour has also been found in cohesive sediments originated in estuaries (Portela and Reis, 2004), and in the sediment dynamics of snowmelt runoff streams (Langlois et al., 2005).

3.2.3. Study of two consecutive processes of resuspension and sedimentation

In experiments carried out following 48 h of consolidation time after the first resuspension (R2CT48 + 48, Fig. 5), the behaviour of the biosolids was similar to the R1CT48 experimental series. The curve showed again a hysteresis loop, with a higher fraction of biosolids in the water column for the same level of turbulence when their origin was the water column than when the origin was the bottom of the container.

During the second resuspension event the turbulence needed to resuspend the same amount of biosolids was higher than in the first resuspension event. For example, to resuspend 50% of the biosolids in the water column during the first resuspension event R1CT48 the RMS$_{x-y}$ needed was lower than 0.90 cm s^{-1}, while in the second resuspension event R2CT48 + 48 it was higher (around 1.20 cm s^{-1}). A similar behaviour can be observed during the sedimentation event, were a higher turbulence was needed to maintain the same percent of sediments suspended during the second sediment event than during the first. For example to maintain 50% of the biosolids in the water column during sedimentation event the RMS$_{x-y}$ needed were higher (around 0.36 cm s^{-1}) during the second sedimentation event, S2CT48 + 48, than during the first one, S1CT48, (around 0.20 cm s^{-1}). These differences suggest that during each consolidation biosolids particles aggregate, and as they become bigger and denser, their net sedimentation rates increase.

3.2.4. Resuspension and sedimentation processes of aquaculture biosolids originated in different tanks

As before in tank 1 (R1CT48), resuspension followed by a sedimentation event in tank 2 (R1CT48) also presented a hysteresis behaviour (Fig. 6). In experiments carried out after 48 h of consolidation time (R1CT48 and S1CT48), biosolids resuspension began in tank 1 when RMS$_{x-y}$ was about 0.35 cm s^{-1}, and all the biosolids were in the water column at a RMS$_{x-y}$ of 1.20 cm s^{-1}. In tank 2, biosolids resuspension began earlier, RMS$_{x-y}$ about 0.20 cm s^{-1}, and all the biosolids were in the water column at a RMS$_{x-y}$ of 0.90 cm s^{-1}, again, a lower turbulence than in tank 1.

The differences observed between biosolids collected in tanks 1 and 2 during the resuspension event

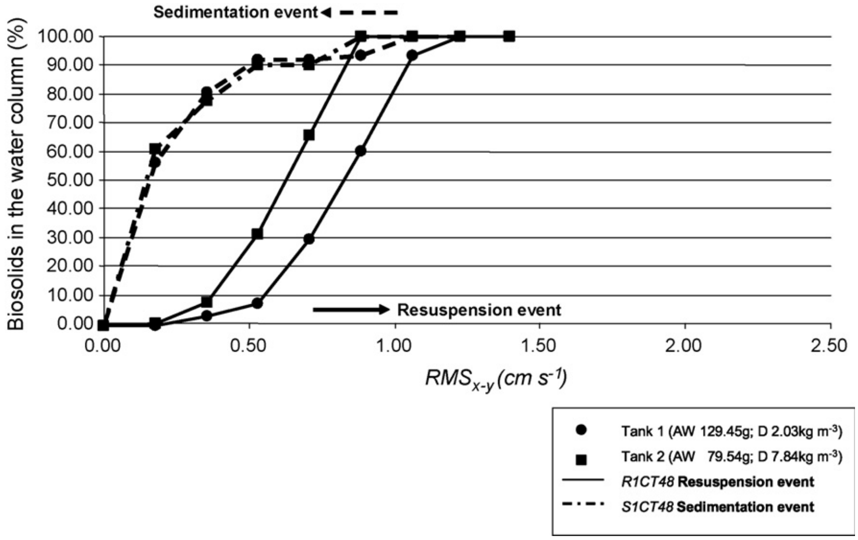

Fig. 6. Fraction of biosolids in the column during resuspension (filled line) and sedimentation (dashed line) events as a function of the turbulence (RMS$_{x-y}$) applied after 48 h of consolidation (R1CT48 and S1CT48 tanks 1 and 2). Tank 1 – circles – (D: 2.03 kg m^{-3}; AW: 129.45 ± 15.24 g), and tank 2 – squares – (D: 7.84 kg m^{-3}; AW: 79.54 ± 20.12 g): D: density, AW: average weight.

were not observed during the sedimentation event, where the behaviour of the curve was very similar in spite of the differences in the biosolids origin.

Differences observed in resuspension of biosolids originated in different tanks could be due to fish size. It has been observed that turbulence needed to resuspend biosolids originated in a tank with smaller fish (tank 2), is lower than turbulence needed to resuspend biosolids generated in tanks with bigger fish (tank 1). Magill et al. (2006) studied the settling velocity of faecal pellets working with Sea bream (*Sparus aurata*, L.) of 60, 240 and 380 g, and Sea bass (*D. labrax*, L.) of 50, 80 and 280 g, and pointed out that smaller fish produced smaller faecal particles. So, the smaller the particles, the lower the turbulence needed to resuspend them.

4. Conclusions

The oscillating grid method has proven adequate and logistically simple to determine the resistance of aquaculture biosolids to be resuspended by turbulence in the tank bottom, and to determine the minimum turbulence that allows biosolids to remain suspended in the water column. An increase in resistance to resuspension with consolidation time has been observed.

An hysteresis behaviour was observed in cycles of resuspension–sedimentation of biosolids. Their presence in the water column, at a fixed turbulence level, was higher during sedimentation events than during resuspension events. Thus, biosolids presence in the water column depends on the initial state.

When biosolids have been subjected to two consecutive consolidation and resuspension processes, the turbulence level needed to resuspend them in the second resuspension was higher, and the second sedimentation process occur under a higher turbulence level than the first one.

We have observed differences in resuspension behaviour of biosolids originated in tanks containing different fish sizes. Lower turbulence was needed to resuspend biosolids originated by smaller fish. Thus, the method allowed the detection of differences in the resuspension of biosolids of different origin.

Among the many applications of the method here described, we could point to the determination of the optimal self-cleaning conditions in fish tanks under specific culture conditions, knowing the turbulence generated by fish swimming activity that can be measured using ADV techniques according to the method described by Masaló et al. (2008). It can also be applied to investigate the effects of different binders added to feeds in the resistantance to resuspension of biosolids, and also to investigate the effect of different fish species and sizes on the resuspension, again as a means of optimizing fish tank culture conditions.

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