Sludge accumulation pattern inside oxidation ditch case study

Moharram Fouad and Ahmed El-Morsy

ABSTRACT

The sludge accumulation pattern of an oxidation ditch (OD) plant treating municipal wastewater was observed under dry and wet weather conditions, during 3 years of operation. The accumulation patterns along the ditches and their rates were revealed. In addition, the composition of the accumulation was investigated. Finally, the ratio of sand and volatile particles, mixed liquor suspended solids (MLSS), and mixed liquor volatile suspended solids, as well as the removal efficiency were also observed against the accumulated sludge. Further, a laboratory-scale channel was used to investigate the settleability of grit after mixing with variable values of MLSS. The observed results indicated that the economical design and operation of ODs using a velocity value between 0.3–0.35 m/s is not recommended, to avoid the settling of all solids. High values of MLSS and sludge age need high horizontal velocity (more than 0.35 m/s) and more power to avoid settling problems and system failure. The influence of flow velocity on the sludge settleability was studied, enabling better planning of future ditch design and operation.

Key words | accumulation, grit, oxidation ditch, patterns, velocity, wastewater

Moharram Fouad (corresponding author)
Faculty of Engineering,
University of Mansoura,
Egypt
E-mail: *moharramf2001@yahoo.com*

Ahmed El-Morsy
Faculty of Engineering,
University of Tanta,
Egypt

INTRODUCTION

Oxidation ditches (ODs) are very popular wastewater treatment processes all over the world (Yang *et al.* 2009; Liu *et al.* 2010; Zhan *et al.* 2013). The development of ODs started in the Netherlands in the 1950s and the first report on their performance was presented by Pasveer (1959). Typical OD systems consist of a single or multi-channel configuration within a ring, oval or horseshoe-shaped basin (racetrack type). The main advantage of ODs is that they can produce a high quality effluent with minimum cost, because carbonaceous biochemical oxygen demand (BOD) removal, nitrification and denitrification can be accomplished within a single reactor (Stensel & Coleman 2000; Liu *et al.* 2010).

Generally, an OD is equipped with aeration rotors or brushes that provide aeration and mixing (Moulick *et al.* 2002; Thakre *et al.* 2008, 2009). Aeration and mixing are promoted by ensuring that horizontal velocity (HV) in the reactor is sufficient to create suitable turbulence. Thus, HV between 0.25 and 0.60 m/s with a typical value between 0.25 and 0.35 m/s is an important factor in an OD (Abusam *et al.* 2002; Metcalf and Eddy 2003). An HV more than 0.25 m/s is usually recommended to: (a) supply a sufficient quantity of dissolved oxygen (DO) to maintain aerobic conditions and avoid anaerobic zones; (b) prevent the settling of organic and solid particles; and (c) mix the wastewater with the suspended biomass, nutrients and DO uniformly (Gillot *et al.* 2000; Abusam *et al.* 2002; Gresch *et al.* 2010). However the HV is restricted to a maximum of 0.60 m/s to avoid excessive erosion, excessive aeration, excessive recirculation, hydraulic jump, or other undesirable non-uniform flow phenomena (Banasiak *et al.* 2005).

ODs can be operated under entirely aerobic conditions under a high value of HV to obtain reliable organic removal and nitrification. However, alternating aerobic and anoxic conditions are very necessary to achieve both nitrification and denitrification (Insel *et al.* 2005; Liu *et al.* 2010). Also, the value of HV is the key factor that influences the aerobic and anoxic zones which must occur inside the ODs (Edward *et al.* 1989). A high value of HV may result in loss of the anoxic zones upstream of the aerators, or reduce the detention time of the mixed liquor in each pass of the anoxic zones (Edward *et al.* 1989). The lengths of aerobic and anoxic zones involved in the ODs become more active under low velocity values. In addition, based on energy consumption, for an

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economical operation of ODs a low velocity value of 0.3–0.35 m/s is recommended (Simon *et al.* 2001).

Generally, several problems appear when operating ODs under the previous velocity values (Hartley 2008). Practically, wastewater is screened and pumped into the ODs directly, i.e. no sand or grit removal is provided prior to the ditches. Grit removal and primary settling prior to an OD are not typical in this design. Observations from existing ODs confirmed that HV between 0.3–0.35 m/s may result in poor mixing and sludge settling inside the OD. So, grit and sand particles may settle inside the OD, as the settling velocity limits of these particles are very close to the operational velocities (Teeter 2000; Wang *et al.* 2008). Further, grit settling can be maximized when large quantities of grit is received during wet weather conditions, especially in the case of a combined sewer, or from storm water with high solid content. Settling of grit and sand particles to the bottom of the OD forms a sludge layer along the ditch bottom. Accumulated sludge layers are greatest in ODs and can impact performance by altering the ditch's hydraulics due to a decrease in the ditch's effective volume. Unless frequent cleaning of the accumulated solid is carried out, several problems are expected with regard to removal efficiency, nitrification, denitrification, settling properties, etc.

This study provided a comprehensive evaluation of the mechanisms and performance of ODs with a combined sewer or under wet weather conditions. The main aim of this study was to investigate the effects of sludge accumulation in OD plants. The accumulation rates of sludge and its distribution along the OD were determined. The main objectives of this study were to: (a) observe the accumulation rate and pattern in the field; (b) investigate the physical properties of the accumulated sludge; (c) evaluate the performance of the OD during the accumulation of the sludge; and (d) investigate the effects of HV on the sludge accumulation experimentally.

EXPERIMENT AND METHODS

This study was developed based on two sets of data which were collected from the field and confirmed at the laboratory scale, as explained below.

Field data during cleaning of the ditches

Several field sites were selected and observed for this study. Preliminary results and observations were taken from four different OD plants with various capacities in north Egypt. It was found that most of the ODs exhibited similar behaviours for sludge accumulation under the same operational parameters irrespective of the efficiency of the grit removal chambers. Typical grit removal chambers for these plants are generally designed considering an HV of 0.3 m/s. Further, no dead zones were observed inside the ODs of these plants. One plant was chosen to be completely observed under specific conditions. This wastewater treatment plant is a small OD plant with a capacity of 3,000 m^3/day. The plant receives municipal sewage from a combined sewer from an urban area, which is located in north Egypt. The plant mainly has four parallel ODs followed by two final settlers. Each OD has a volume of 750 m^3 (50.0 m × 6.0 m × 2.5 m) and has four injection rotors (Figure 1(a)). The ditches have a design circulation velocity of 0.285 m/s, and a mixed liquor suspended solids (MLSS) of 3,000 mg/1. The ditches run under a retention time of 24 hours and sludge age of 20.0 days. Full details about this plant are presented by the authors elsewhere (Fouad & El-Morsy 2012). The raw wastewater of the plant has medium values of chemical oxygen demand (COD), BOD, ammonia nitrogen (NH_3-N), total suspended solids, and volatile suspended solids (VSS) of 765, 565, 22, 370–660, and 200–340 mg/L, respectively. This system is widely used in Egypt and in other Mediterranean countries, especially for small and medium communities. The observation of this plant was undertaken in two phases. The first phase was carried out when the plant was stopped, while all ditches were empty for cleaning and maintenance, while the second phase was undertaken after restarting this cleaned plant. The first phase observations were carried out over three months, while the second phase was extended to 36 months.

During the first phase (cleaning the ditches), observations included the measurements of sludge distribution and its thickness along the ditch, as well as the sludge characteristics. Sludge samples were extracted and some physical parameters were measured. In addition, a batch of sludge was stored in the laboratory and the concentration of coarse and fine particles was measured to gather more detailed data on the type of the accumulated soil (Paing *et al.* 2000; Saqqar & Pescod 1995). The particles collected from the ditch were characterized with a sieve size analyzer which measures the sand particles ranging from 0.75 to 2.0 mm (according to standard methods). The concentrations of sand and the volatile solids (VS) per mass (mg/kg) of sample were determined after drying and heating the samples at 105 °C and at 550 °C for 20 min, respectively. After full cleaning of the ditches and restarting the plant, the performance was completely observed for more than 36 months until full accumulation of sludge happened once more.

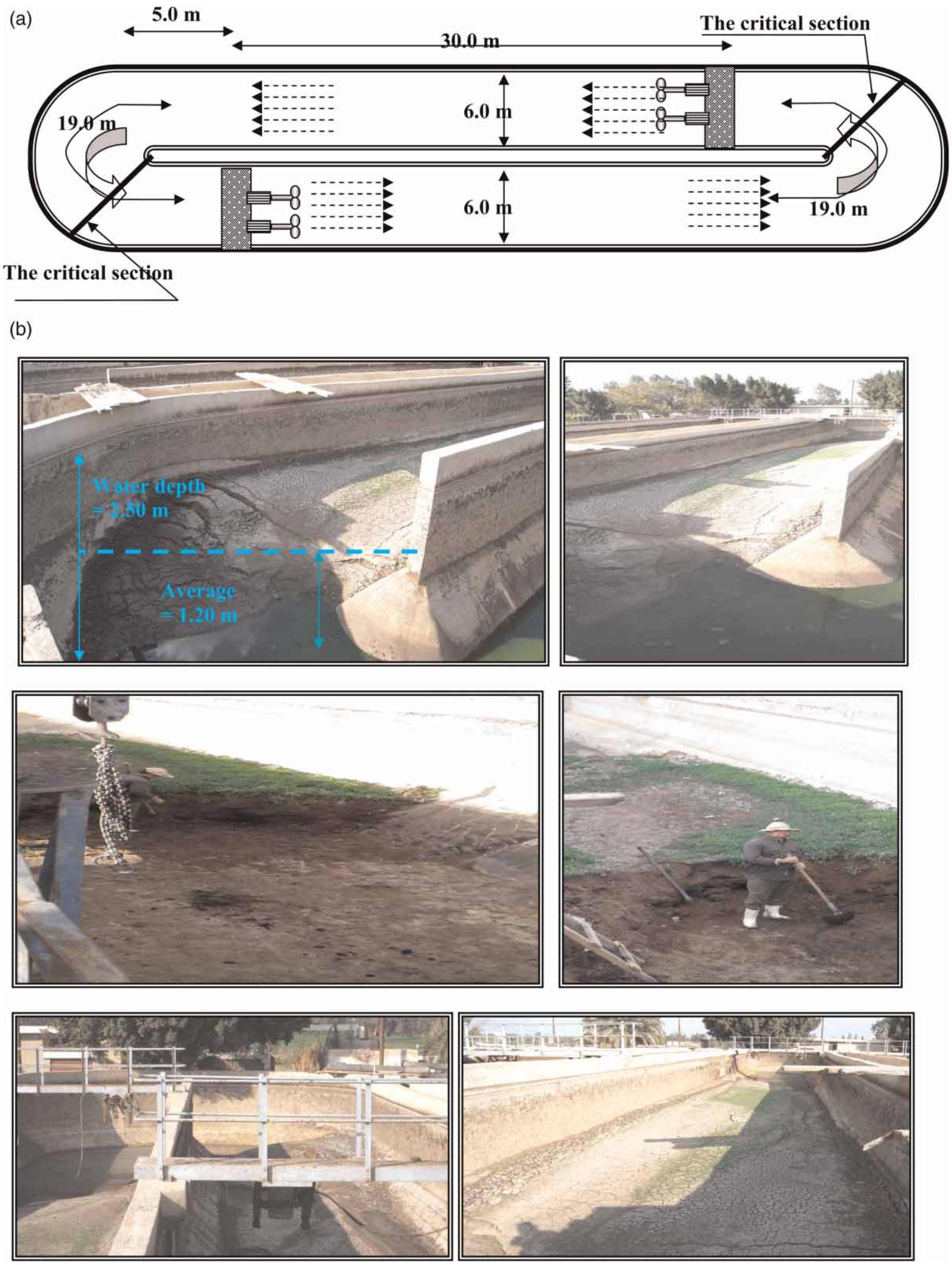

Figure 1 | (a) OD with the critical section. (b) Typical sludge accumulation pattern inside the OD.

Field data after operating the ditches

During the second phase (plant operation), periodical observations included the flow velocities and velocity profiles as a function of sludge accumulation depth. The flow velocities were observed and measured by using an acoustic Doppler velocimeter. Further, the removal efficiency of COD and suspended solids (SS) as well as DO values were observed against the sludge accumulation. Finally, the concentration of the MLSS and the mixed liquor volatile suspended solids (MLVSS) were also observed against the sludge accumulation and time too.

Laboratory verification

To reveal the effect of MLSS on the settling properties of the sand and silt particles, a laboratory experiment was carried out using a straight channel. The channel was made of perspex (manufactured by TecQuipment Ltd, UK, 1969), so that the movement of the suspended particles and sludge could be accurately observed. The flume was a rectangular channel 4.80 m long, 0.075 m wide and 0.17 m deep with adjustable slope, equipped with a submerged pump, constant head tank and an adjustable valve to control the discharge released down the flume. It was also equipped with various probes for velocity and volume measurements, and a timer. Full details of this flume are found in Fouad *et al.* (2014).

The laboratory tests were carried out using synthetic wastewater that had variable values of MLSS. The experiments were carried out to investigate the settleability of the sand and silt particles under a high value of MLSS. Tests covered a range of MLSS values with different ratios up to 4,000 mg/L (zero, 2,000, 3,000, and 4,000 mg/L) along with different values of flow velocity. A stock quantity of sand particles was prepared to create a fixed concentration of 400 mg/L which is a typical concentration in the natural wastewater. In each run, the channel content was cleaned and the bed slope was adjusted to the desired velocity.

During these experiments, seven initial velocities were adopted for the test (0.20, 0.25, 0.30, 0.35, 0.40, 0.45 and 0.50 m/s). The initial velocity of flow was measured after placing the MLSS and the sand particles. The flow velocities were observed and measured using an acoustic Doppler velocimeter. Flow water depth was measured manually by using screw/vernier depth gauges at different positions.

RESULTS AND DISCUSSION

Sludge accumulation pattern and characteristics

Figures 1(b) and 2 illustrate the accumulation pattern and the characteristics of the sludge. Figure 2(a) illustrates the height of the accumulated sludge along the centre line of the ditch. From Figures 1(b) and 2 it is clear that the two critical sections which have the maximum sludge height (1.2 m) are found directly upstream of the aerators.

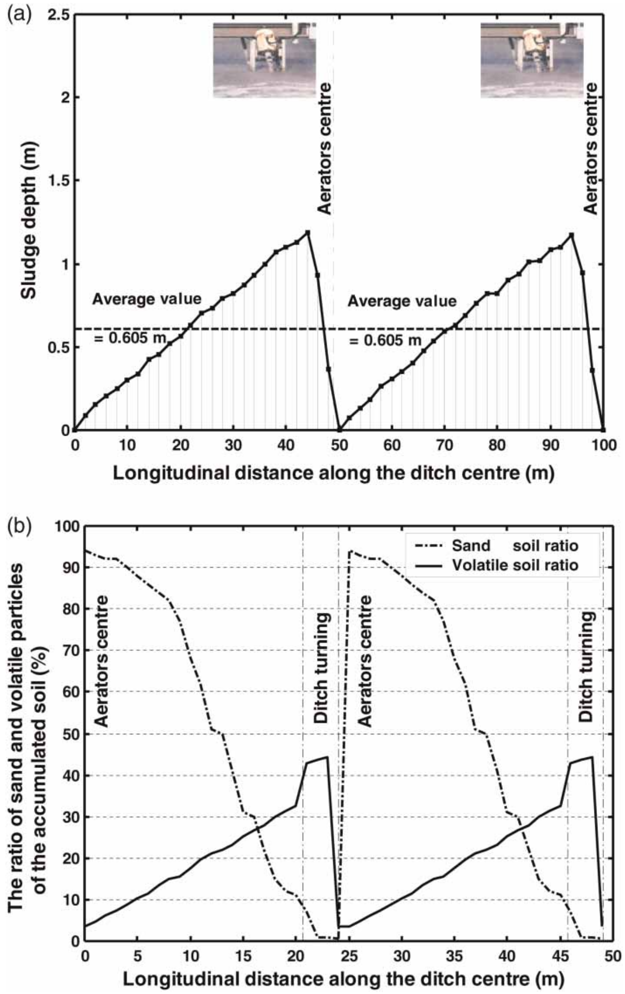

Figure 2 | (a) Profile of sludge depth along the ditch. (b) Ratio of sand and volatile particles of the accumulated soil along the ditch centre.

Conversely, the two critical sections which have no accumulation of sludge are found directly downstream of the aerators. So, the sludge height starts from zero after the aerators then increases gradually until reaching the maximum value directly before the next aerators.

Figure 2(b) illustrates the ratios of the sand and the volatile particles of the accumulated sludge along the centre line of the ditch. It can clearly be seen that the sand concentration decreases with distance from the aerators; however, the volatile concentration increases with distance from the aerators. The sand particles have a maximum value (93%) in front of the aerators then gradually decrease up to zero in the rotation area behind the aerators. Conversely, the volatile particles have a maximum value (44%) in the rotation area behind the aerator and have a minimum value (4%) in front of the aerators. Similar volatile ratios have been reported previously by Nelson *et al*. (2004) and Nelson & Jimenez (2000) for facultative ponds.

Treatment efficiency during sludge accumulation

Figures 3 and 4 reveal the performance of the ditches directly after cleaning the ditches until sludge accumulation once again. Figure 3(a) reveals the increasing rate of the sludge accumulation and its effect on ditch volume. It is clear that sludge has accumulated regularly inside the ditch during the 36 months (Figure 3(a)). However, some sludge was released from the ditches in the summer seasons (which have dry and hot weather) and much sludge was settled during the winter seasons (which have wet and cold weather). Figure 3(b) reveals the increase and decrease

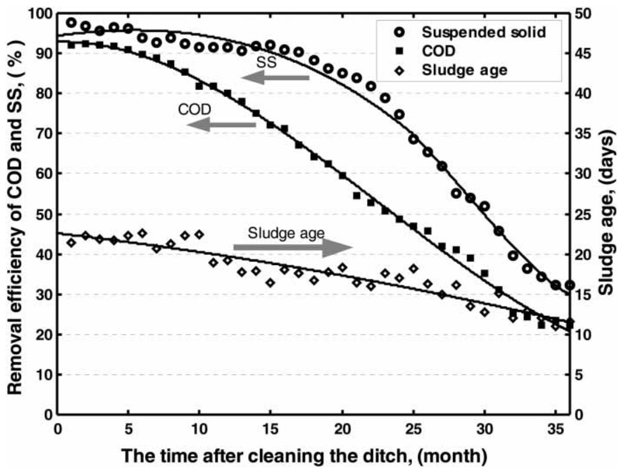

Figure 4 | Removal efficiency of COD and SS as well as sludge age against operation time after cleaning the ditch.

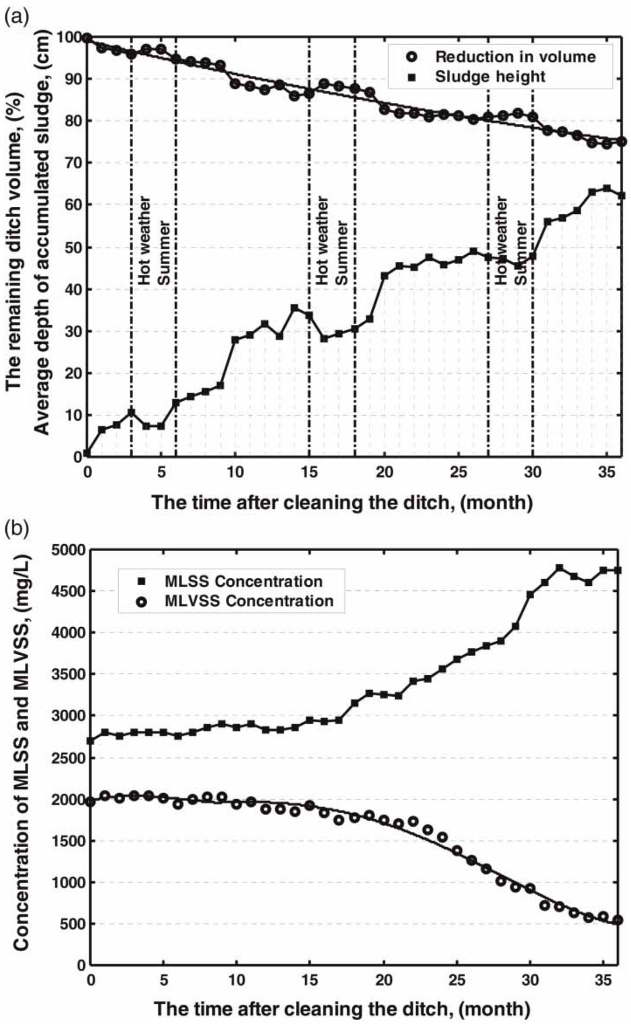

Figure 3 | (a) Accumulated sludge and volume reduction against operation time after cleaning the ditch. (b) Concentration of MLSS and MLVSS against operation time after cleaning the ditch.

rate of the MLSS and MLVSS, respectively. Due to the sludge accumulation, MLSS increased from 2,750 to 4,850 mg/L; however, MLVSS decreased from 2,000 to 500 mg/L under the same recirculation ratio (Figure 3(b)). Based on the previous conditions, the removal efficiency of the ditches decreased to 30% and 20% for COD and SS, respectively (Figure 4). Further, the sludge age of the system came down from 21 days to only 11 days (Figure 4). The sludge age was estimated according to Fouad & Bhargava (2005, 2012) after considering the suspended biomass only. So, the main reasons for the decreasing removal efficiency of COD against operation time after cleaning the ditch was the decrease of sludge age, retention time and MLVSS. The previous results can be interpreted easily based on Figure 5.

Figure 5 illustrates the performance of the ditches during the sludge accumulation period after classifying this period into four phases (I, II, III and IV). The sludge depth was observed by submerging a levelling staff in the critical sections which had the maximum sludge height (Figure 1(a)). During the first phase, the ditches were clean except for the movement of a thin layer of sand on the bottom, so normal values were observed for DO, HV and MLSS, with maximum removal efficiency for COD and SS (Figure 5-I). After a few months, a large quantity of sand particles had accumulated on the bed and a significant quantity of silt particles appeared in the liquid. So the velocity profile changed as shown in Figure (5-II), i.e. the velocity increased at the liquid surface, while it decreased at the liquid bottom. Due to the high velocity value addition, MLSS was increased to 3,100 mg/L with some increase in the DO value. With more accumulation of sludge, a fixed layer of sludge was settled on the ditch bottom, which resulted in a

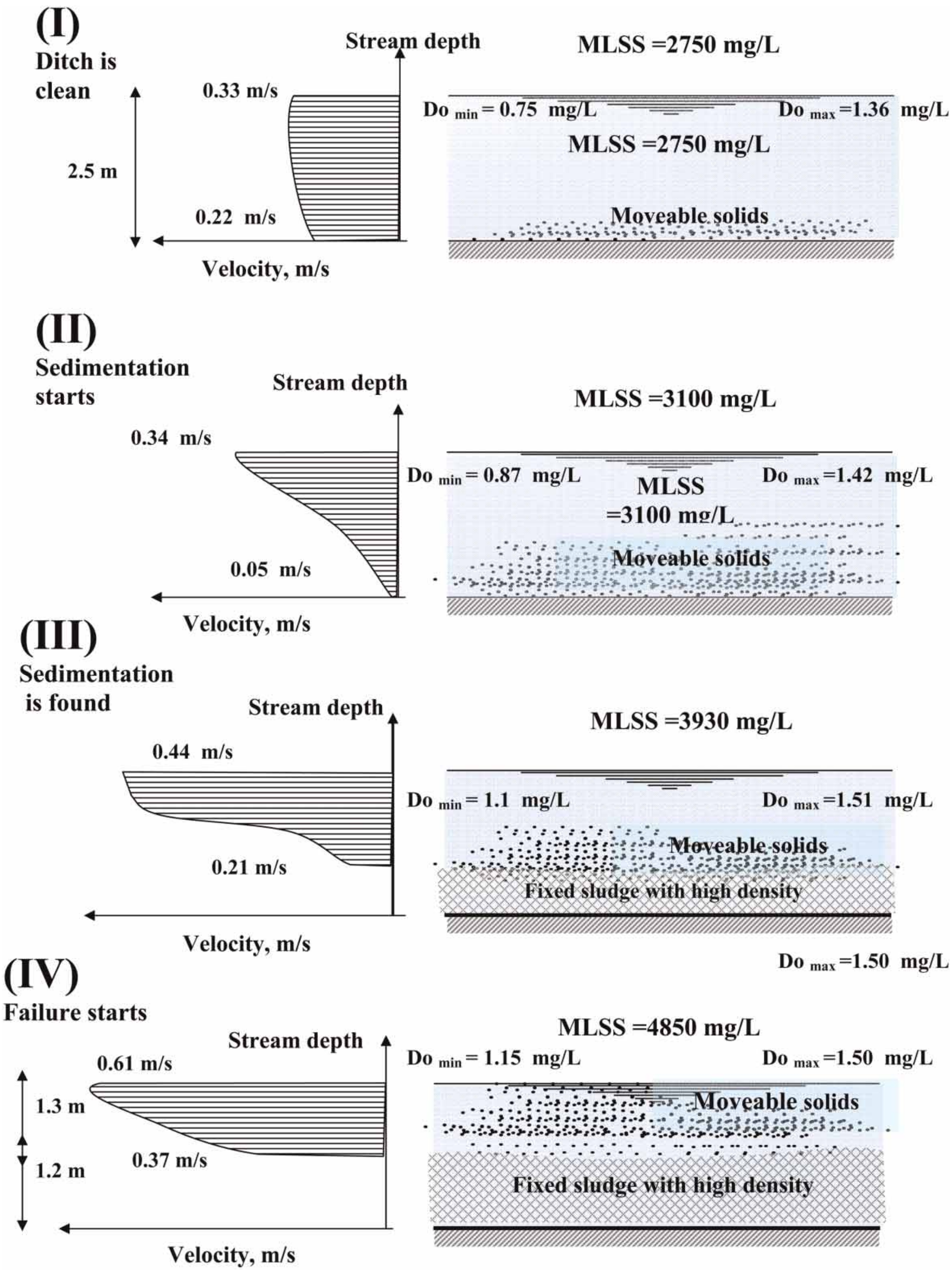

Figure 5 | Sludge accumulation phases in the OD at the critical sections. I – Ditch is clean, II – Sedimentation starts, III – Sedimentation is found, and IV – Failure starts.

decreased retention time and MLVSS as well as high velocity at the surface (Figure 5-III). The high velocity increased the values of MLSS (3,930 mg/L) which included a significant amount of suspended solids. The short retention time and the low value of MLVSS decrease the removal efficiency of the ditch (Figure 4). At the final stage the system has failed. During this phase, the high velocity brought a huge amount of suspended solids to the liquid. So the system failed mainly due to the significant decrease of MLVSS from 2,000 to 500 mg/L; however, the short retention time sped up the system failure. A minimum MLVSS value leads to reduced sludge age, system stability and safety factor (sludge age/minimum sludge age), which are the main reasons for system failure (Fouad & Bhargava 2012).

Laboratory verification of the results

It was clear to the authors that the concentration of MLSS might affect the settleability of the sand and silt particles, so Figure 6 was prepared using a laboratory channel. In fact, unclear results were obtained when adding the sand particles and MLSS to the channel; Figure 6(a) shows that MLSS has little effect on the settleability of the sand particles. However, at low velocity values less than 0.30 m/s, MLSS increases the settleability of the sand particles. This means that, in the case of sand particles, MLSS can act as a weak centre of nucleus for sedimentation.

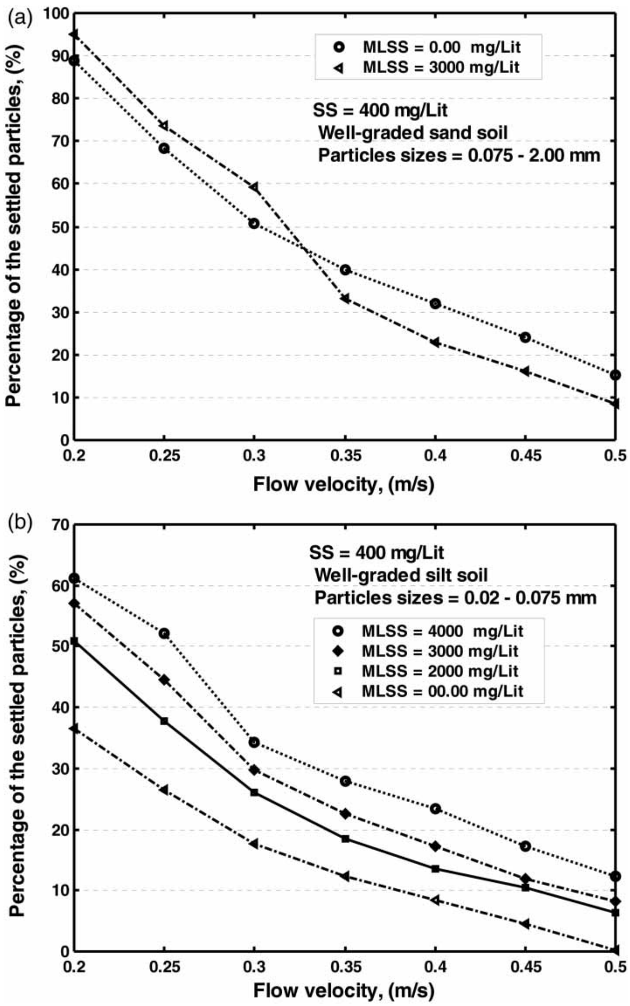

Figure 6 | (a) Settling of sand particles against flow velocity (laboratory verification). (b) Settling of silt particles against flow velocity (laboratory verification).

However, the effect of MLSS on the particle settleability was clear in the case of silt particles. Figure 6(b) confirms that the increase in the MLSS results in an increase in the settleability of the silt particles under the same velocity value. This means when ODs run at a high value of MLSS the settleability is increased, especially for fine solid particles.

The main reason for these results can be simply illustrated. It is well known that most microorganisms tend to attach to solid particles, especially under aerobic and anoxic conditions (Crump & Baross 1996; Waidner & Kirchman 2007). These microorganisms excrete chemicals and enzymes which are the origin for this attachment (Udaka 1976; Waidner & Kirchman 2007). In the ODs, high biomass concentration and long sludge age help the microorganisms to cover most solids with a thin biofilm layer, especially under low HV values. These covered solids come in to contact with each other and collect more colloidal particles. Subsequently, the stream velocity cannot overcome the increasing frictional forces between these covered solids, allowing sedimentation inside the ditch. So, conventional OD design must avoid biofilm formation inside the ditch by selection of appropriate values of MLSS and sludge age. The economical design and operation of ODs using velocity values between 0.3–0.35 m/s is not recommended, to avoid the settling of all solids. High values of MLSS and sludge age need high HV (more than 0.35 m/s) and more power to avoid settling problems and system failure.

CONCLUSION

The observed results indicated that a rotation velocity close to 0.3 m/s is inadequate to prevent particles settling in an OD, especially in the case of combined sewer, wet weather conditions, or under stormwater conditions with high solid content. The microorganisms increase the sludge settleability inside the ditches especially for fine soil (silt). Sludge settleability increases directly with the increase of microorganism concentration. There is a typical pattern for sludge accumulation inside an OD which has two critical zones, usually existing behind the rotor aerators. As sludge accumulates inside the ditches, new profiles are found for the rotation velocity, dissolved oxygen, MLSS, and MLVSS. As a result, the removal efficiency of ODs continuously comes down due to solid accumulation, the significant decrease of MLVSS and the short retention time. Finally, more solid accumulation inside ODs significantly reduces removal efficiency and leads to system failure.

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