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Deposition pattern, effect on nitrogen removal and component analysis of deposited sludge in a carrousel oxidation ditch

He Li[a], Ji Fang-ying[a,*], Zhou Wei-wei[a], Xu Xuan[a], Chen Rui-hong[b], Liu Na[a], He Xiao-ling[a]

[a]*Key Laboratory of Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing University, Chongqing 400045, China*
Tel. +86 023 65127537; Fax: +86 023 65127537; email: jfy@cqu.edu.cn
[b]*College of Environmental science and Engineering, Tongji University, Shanghai 200092, China*

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ABSTRACT

The impact of sludge deposition on nitrogen removal was studied in order to provide basic research data for alleviating the sludge deposition problem. The site was an emptied oxidation ditch at a wastewater treatment plant in Chongqing City (China). Actual tests and numerical simulations were used to analyze the distribution of deposited sludge. Organic substances and the X-ray fluorescence spectra and particle sizes of deposited sludge were also analyzed. The height of deposited sludge was 0.2–1.2 m, and the total volume of deposited sludge accounted for about 19% of the effective volume of the oxidation ditch. The sludge was mainly deposited in the anoxic zone, reducing the hydraulic retention time, and nitrogen removal rate by 57 and 20%, respectively. The volatile suspended solids (VSS)/suspended solids (SS) value of the deposited sludge ranged from 0.05 to 0.27, and the sludge's main component was sand. The median particle size (D50) range was 67.14–251.87 μm, and this had an obvious correlation with VSS/SS. Inorganic substances from influent precipitated in the bottom of the oxidation ditch together with sludge through attachment, capture, and entrapment.

Keywords: Deposited sludge; Inorganic solid; Sand; Oxidation ditch; Nitrogen removal

1. Introduction

The oxidation ditch (OD) has been widely used due to its good treatment performance, low sludge production and ability to function without a primary settling tank [1]. The typical OD is composed of straight and curved channels, with mechanical aerators and submerged propellers used jointly to realize plug-flow and supply oxygen in the OD. The special structure and flow pattern distribute dissolved oxygen heterogeneously in the OD and provide favorable conditions for nitrification and denitrification. However, they also make it easy for sludge to be deposited. In recent years, many researchers have focused on the influence of oxygen supply [2,3], sludge loading [4], and operational cycle-time length [5] on nitrogen removal performance, but the influence of sludge deposition on nitrogen removal has been ignored.

Most OD are aerated by a surface aerator with blades immersed 20–30 cm in the water, resulting in

*Corresponding author.

sludge deposition at the bottom of the OD [6]. In addition, due to the lack of a primary settling tank, the existence of combined sewage systems and the little attention paid to rainwater runoff in some developing countries, inorganic particle solids flow into the OD system by rainfall-induced erosion, aggravating inorganic solid deposition in sludge. Recent research has focused on the sludge deposition problem. Littleton [7], Deng [8,9], Zhang [10] and Qin [11] tried to improve OD flow patterns in curved and straight channels through the use of guide walls and submerged propellers, and by changing the working mode of the aeration plate. Li [12], Zhang [13], Xie [14], Fan [15] and Littleton [16] simulated the flow fields of different types of OD. However, few researchers have realized the influence of sludge deposition on nitrogen removal in ODs.

Although the deposition of inorganic particle solids in sludge has not aroused the attention of researchers elsewhere, it has received much attention in China. The "Major Science and Technology Program for Water Pollution Control and Treatment" of China has carried out preliminary studies on this problem [17–21]. Li found that the efficiency of pretreatment facilities has an important influence on sludge deposition in ODs [17]. Bai et al. developed a washing and separating device to separate sludge in municipal ditches and ODs [18,19]. Ji et al. developed a kind of hydrocyclone to remove grit from activated sludge and further developed a nitrogen and phosphorus removal activated-sludge system combined with bypass sludge reduction and a grit separation module [20,21]. However, due to the lack of basic data on the distribution and characteristics of deposited sludge, the application of the washing and separating device and the grit separation technology in wastewater treatment plant (WWTPs) is still limited.

In order to solve the above problems, we chose an emptied OD at a WWTP in Chongqing City, China, for a study of the characteristics and nature of deposited sludge at its bottom. Our aim was to elucidate the impact of sludge deposition on nitrogen removal and provide basic research data for the purpose of alleviating the sludge deposition problem.

2. Materials and methods

2.1. Description of the WWTP

The WWTP is located in Chongqing City, China. It consists of grit chambers and an activated sludge system consisting of an anaerobic tank and a modified Carrousel OD without a primary settling tank. This WWTP has been operated in stable conditions since 2002. It is shown in schematic in Fig. 1.

The treatment capacity of the Carrousel OD is 15,000 m^3 per day with an effective water depth of 3.7 m. The OD is further divided into anoxic and aerobic zones, with hydraulic retention times (HRT) of 3 h and 6 h, respectively. The solids retention time of the Carrousel OD is kept at 8d. The WWTP's most serious problem is the poor total nitrogen removal rate (40–50%).

As shown in Table 1, three surface aerators and four submerged propellers are used to push and mix wastewater. The main dimensions of the OD and the specific positions of the push flow equipment are shown in Fig. 2.

The average concentrations of chemical oxygen demand, suspended solids (SS), and inorganic suspended solids (ISS) of influent are 274 mg/l, 241 mg/l and 165.5 mg/l, respectively. The median particle size (D50) of influent is 113.26 um. The mixed liquor volatile suspended solids (MLVSS)/(mixed liquor suspended solids (MLSS) and the D50 of the mixed liquor in the Carrousel OD are 0.5 and 75.88 um, respectively.

2.2. Experimental methods

This study was carried out after the Carrousel OD was emptied.

(1) Sludge deposition height test: For areas with major sludge deposition, measurements were taken every 2 m or 1 m in the direction of flow, and every 1 m in the direction of OD width; for other areas, measurements were taken every 4–6 m in the direction of flow, and every 2 m in the direction of OD width.

(2) VSS/SS and D50 tests:

- Sampling section placement along the OD: Ten sampling sections were set up along the direction of flow. Sampling sections located in straight channels were arranged in the middle of the deposition area; considering the hydraulic flow pattern complexity of the large curvature bends, sampling sections were set in inlets, central areas, and outlets of the curve bends. Sampling sections were arranged near the inside wall along the bends with large curvature, where the sludge deposits tended to be deep.
- Vertical sampling point setting: When a section's sludge deposition height was more than 0.5 m,

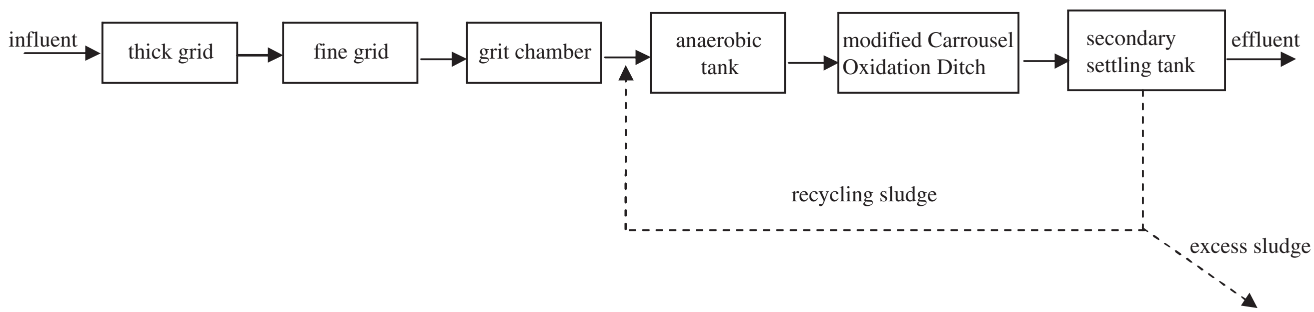

Fig. 1. Schematic of WWTP.

Table 1
Equipment installed in the Carrousel Oxidation Ditch

	Inverted umbrella surface aerators					Submerged propellers			
	Power/ kW	Aeration intensity/ $kgO_2 \cdot h^{-1}$)	No.	Type	Running direction	Power/ kW	Speed/ ($r \cdot min^{-1}$)	Number	Type
Constant speed	55	119	1# 3#	DS325Y	Counterclockwise	4	420	4	2500QJB-42-4
Variable speed	55	23–119	2#		Clockwise				

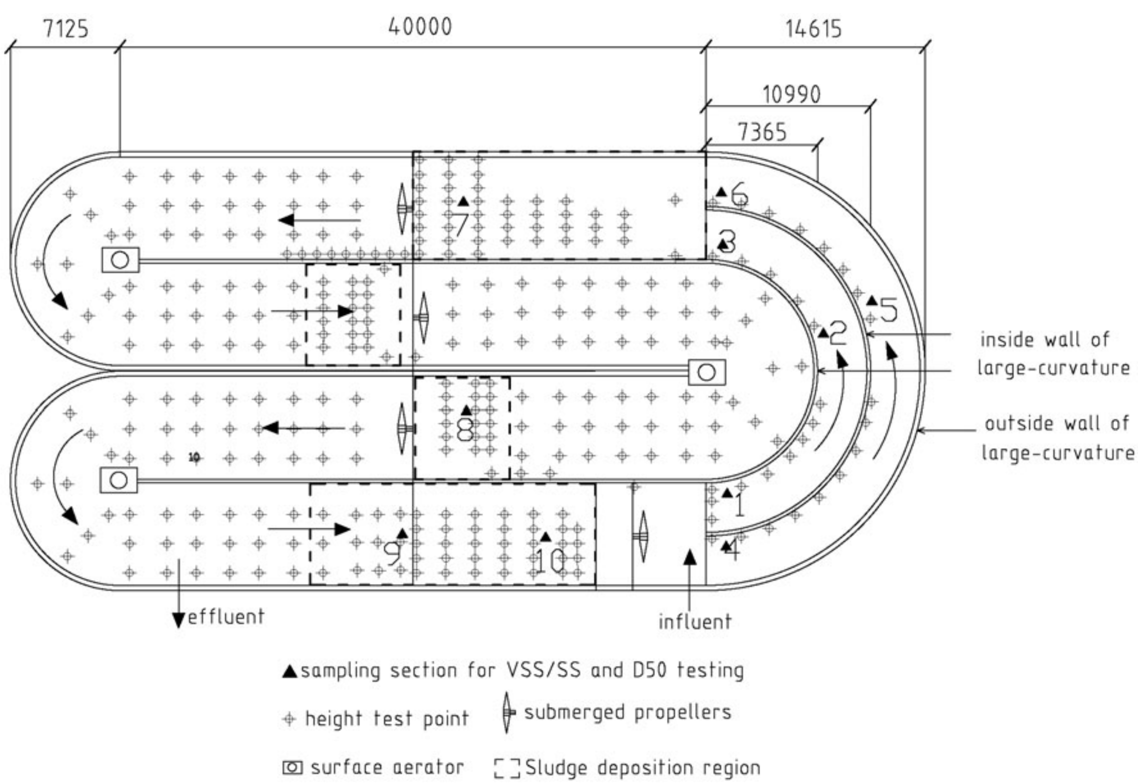

Fig. 2. Schematic diagram of sampling locations (unit: mm).

sections were divided into five layers; otherwise, sections were divided into three layers. The sampling point was in the middle of each layer.

Sampling sections and points are shown in Figs. 2 and 3.

2.3. Analytical methods

2.3.1. Sludge deposition height data processing

Surfer 10.0 software was used for data processing, performed with a linear Variogram Model (slope = 1.0, Aniso = 1.0) and the kriging-point meshing method.

2.3.2. Test indicators

The samples were placed in a crucible, and dried to constant weight at 105℃, to give SS. The samples were also tested for inorganic solids (ISS) by weighing after incineration at 600℃ for 2 h. The organic solids (VSS) were determined as the difference between SS and ISS.

The particle size was tested by using a laser particle sizer (BT-9300HT, Bettersize Instruments Ltd., China).

X-ray fluorescence spectra (XRF-1800, Shimadzu, Japan) were used to analyze the elemental composition of the deposits. The incinerated residue was dried, ground, and screened through a 200-mesh sieve for the XRF analysis.

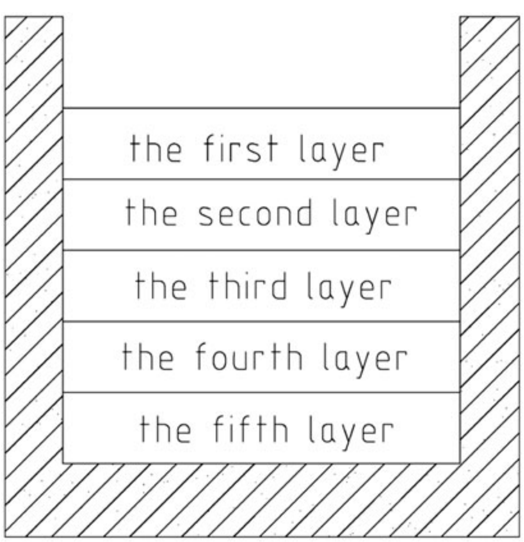

Fig. 3. Schematic diagram of vertical sampling locations.

3. Results

3.1. Sludge deposition height

The sludge deposition height distribution in the OD is shown in Fig. 4.

Sludge is deposited mainly at the back of submerged propellers and along the inside walls of the two large curvature bends. Due to the horizontal circulation and vertical flow, a complicated three-dimensional spiral flow is formed along the curve bends, making outside surface water flow to the bottom, and inside water flow to the outside surface from the bottom, causing the sediment to move from the concave wall toward the convex wall be deposited there [22]. Much sludge is deposited behind the submerged propellers due to the backwater formed there, where the bottom velocity less than 0.3 m/s [17].

The sludge deposition volume of each deposition region was calculated. The results are shown in Table 2.

It follows from the data in Table 2 that the total volume of deposited sludge accounts for about 19% of the effective volume of the OD. These deposits are located mainly in the anoxic zone, reducing the anoxic hydraulic retention time by 57%. The actual HRT in the anoxic zone is 1.29 and 1.71 h less than the original design value. The total nitrogen removal efficiency before and after removing deposited sludge is shown in Table 3. The total nitrogen removal rate was improved by 20% after removing deposited sludge. This brief HRT due to sludge deposition in the anoxic zone is insufficient for denitrification.

3.2. VSS/SS and particle size distribution

VSS/SS and particle size distributions in the 10 sampling sections along the OD and in the vertical sections are shown in Figs. 5–8.

The VSS/SS along the OD first decreased and then increased. The VSS/SS in the aerobic zone was higher than in the anoxic zone. Generally, the VSS/SS of deposited sludge was between 0.05 and 0.27, indicating that the main components of the deposited sludge are inorganic.

The D50 of the deposited sludge ranged from 67.14 to 251.87 μm. It first decreased and then increased along the OD, and it was higher in the aerobic zone than in the anoxic zone, like the VSS/SS. The size decreased gradually from the surface to the bottom. Microorganisms use the solid inorganic substances in wastewater as carriers, adhering to their surfaces and forming biofilms. Aerobic conditions are more conducive to the formation of

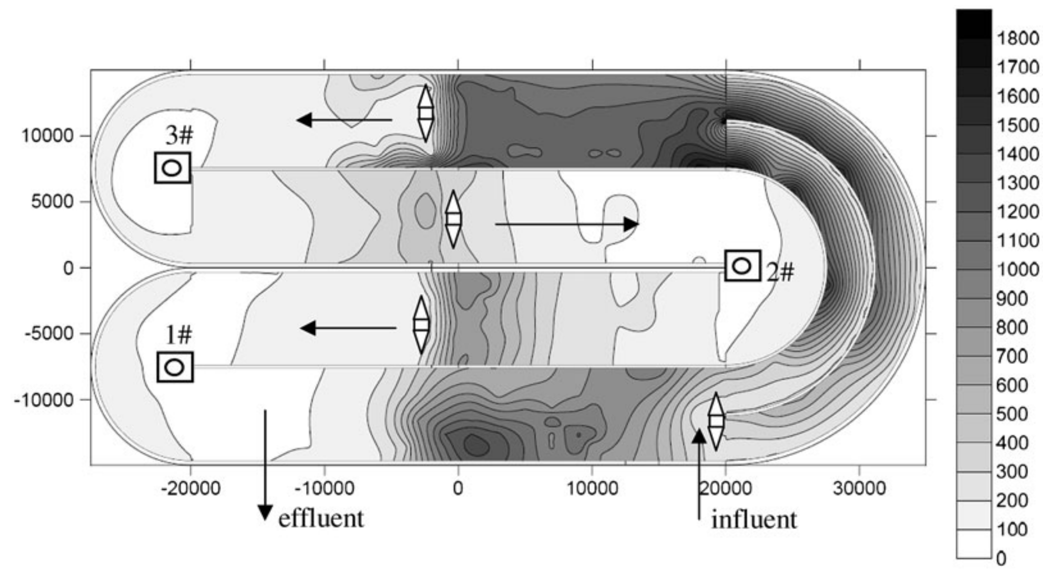

Fig. 4. Sludge deposition height distribution (unit: mm).

Table 2
Deposited sludge volumes

Sludge deposition region	Length (m)	Width (m)	Thickness (m)	Average thickness (m)	Volume (m^3)
The back-end of A submerged propeller	20	7.125	0.36–1.35	0.88 ± 0.25	125.40 ± 35.63
The back-end of B submerged propeller	20	7.125	0.91–1.41	1.2 ± 0.12	171.00 ± 17.1
The back-end of C submerged propeller	2	7	0.41–0.67	0.57 ± 0.09	7.98 ± 1.26
The back-end of D submerged propeller	3.6	7.125	0.25–0.89	0.64 ± 0.18	16.13 ± 4.54
Inside large curvature bend*		3.625	0.43–1.68	1.04 ± 0.45	217.29 ± 94.02
Outside large curvature bend*		3.625	0.42–1.55	1.06 ± 0.41	308.94 ± 119.49
Others			0.08–0.35	0.2 ± 0.12	214.26 ± 128.56
Sludge deposition total volume					1061.00 ± 400.60
Working volume of OD**					5,625

*Deposition area is calculated according to ring area, **Working volume = HRT × flux.

biofilms, so the VSS/SS and particle size in the aerobic zone were higher than in the anoxic zone.

Comparing Fig. 5 with Fig. 6, and Fig. 7 with Fig. 8, it is evident that VSS and D50 show the same trend, proceeding along the OD and in their vertical distributions. In accordance with Figs. 9 and 10, the VSS/SS and D50 of the deposited sludge are clearly correlated, with correlation coefficients of 0.86011 and 0.9512, respectively. These results show that inorganic substances from influent precipitate in the bottom of the OD together with sludge, through attachment, capture, entrapment, etc. This result is consistent with Wentzel's assumption regarding interaction between inorganic suspended solids and activated sludge [23].

3.3. Component analysis of deposited sludge

In order to analyze the components of the inorganic substances, the incinerated residues of second-layer samples from 9 sampling sections were submitted to XRF testing. The results are shown in Fig. 11.

Table 3
Total nitrogen removal efficiency before and after removing deposited sludge

	Monitoring time	Number of samples*	Concentration of influent total nitrogen (mg/l)	Concentration of effluent total nitrogen (mg/l)	Total nitrogen removal efficiency %
Before removing deposited sludge	From March 1st, 2012 to April 30th, 2012	61	40.77 ± 4.03	20.68 ± 2.38	49.26
After removing deposited sludge	From May 1st, 2012 to June 30st, 2012	61	40.94 ± 7.24	12.58 ± 2.55	69.28

*The data monitored by every day was provided by the WWTP.

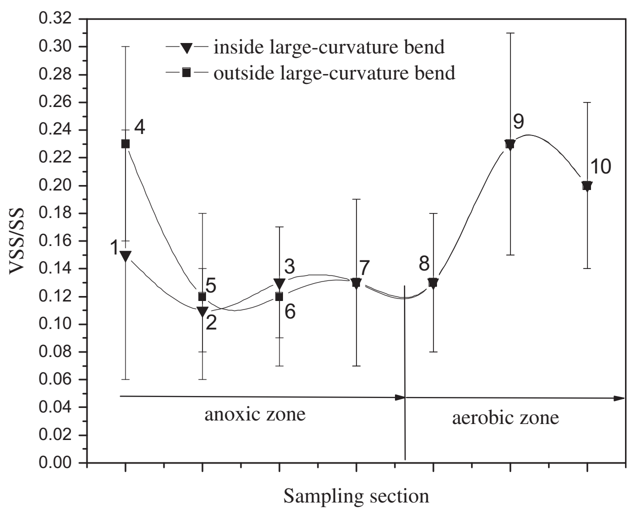

Fig. 5. VSS/SS distribution along the OD.

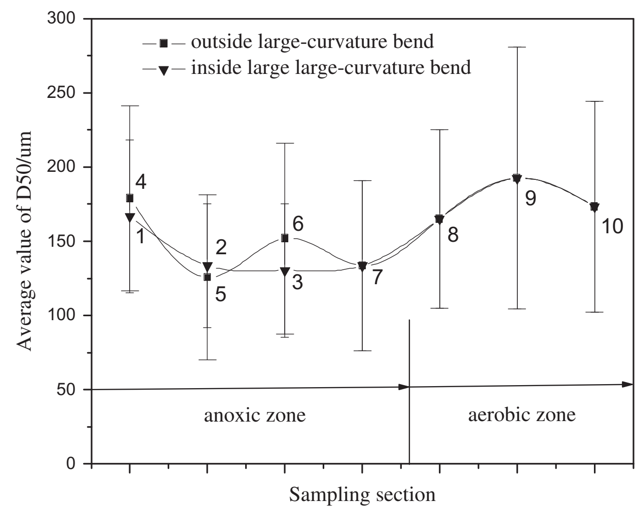

Fig. 6. D50 distribution along the OD.

The results in Fig. 11 show that the main inorganic components of incinerated residues were SiO_2, CaO, and Al_2O_3, with content ranging from 49 to 60%, 10 to 18%, and 9 to 10%, respectively. There were also small amounts of P_2O_5 and Fe_2O_3.

The influent ISS/SS of the WWTP was 0.69, higher than the traditional value of 0.2 [24]. Due to the combined sewage system of this WWTP, SiO_2 (as the main component of sand) is washed into sewage pipes by erosion due to rainfall, resulting in a large quantity of sand being deposited at the bottom of the OD. Additionally, the lack of a primary settling tank reduces the removal rate of sand, resulting in more sand deposition together with sludge.

4. Discussion

Although the flow pattern of the OD is designed specifically to accomplish nitrification and denitrification, there are reports of poor nitrogen removal by ODs. This is attributed to excess oxygen supply [2,3] and inappropriate sludge loading [4]. Although sludge deposition in ODs is well known, its influence on nitrogen removal has never before been recognized. The results in Table 2 demonstrate that the sludge deposition problem in the OD was very serious and that the sludge was mainly deposited in the anoxic zone. This reduced the hydraulic retention time and nitrogen removal rate by 57 and 20%, respectively. This implies that deposited sludge can reduce the denitrification time and weaken the efficiency of nitrogen removal. Our study should remind operators to pay more attention to the HRT of the anoxic zone, rather than only the influence of oxygen supply and sludge loading. Nitrogen removal efficiency is also improved by lengthening the HRT of the anoxic zone through removing deposited sludge.

The MLSS are made up of organic and inorganic solid materials. Most prior studies are concerned only with the organic component and ignore the inorganic

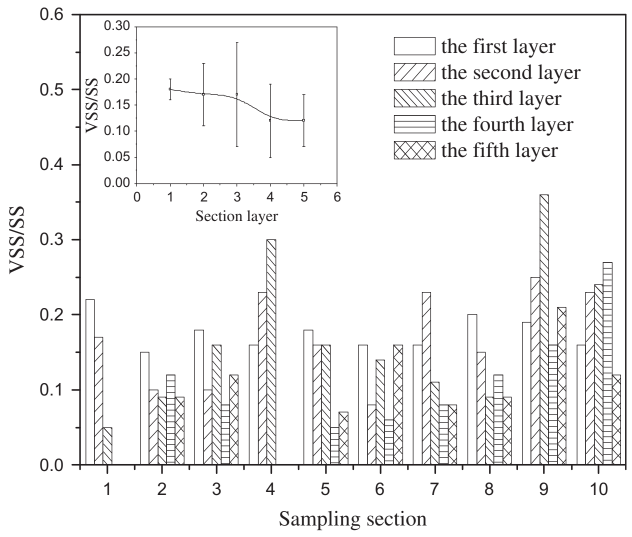

Fig. 7. Vertical distribution of VSS/SS.

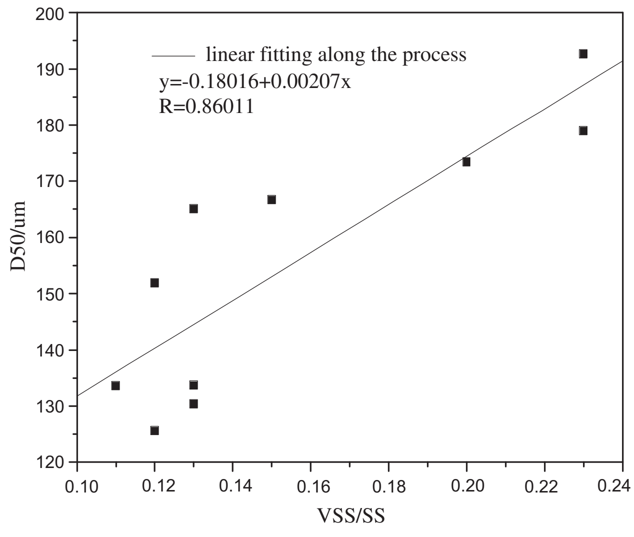

Fig. 9. Correlation between VSS and D50 along the OD.

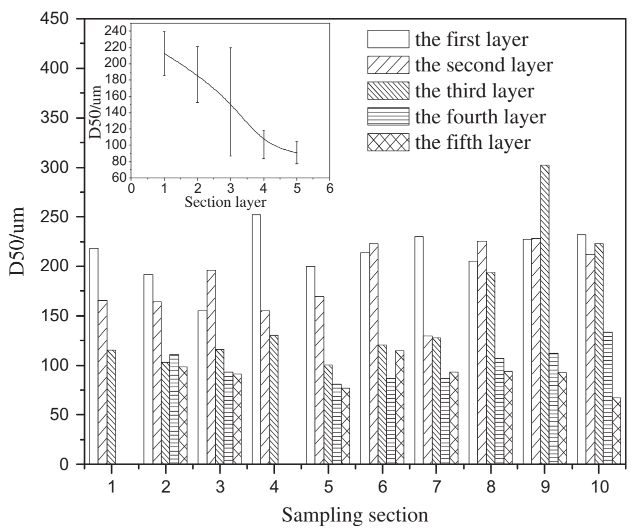

Fig. 8. Vertical distribution of D50.

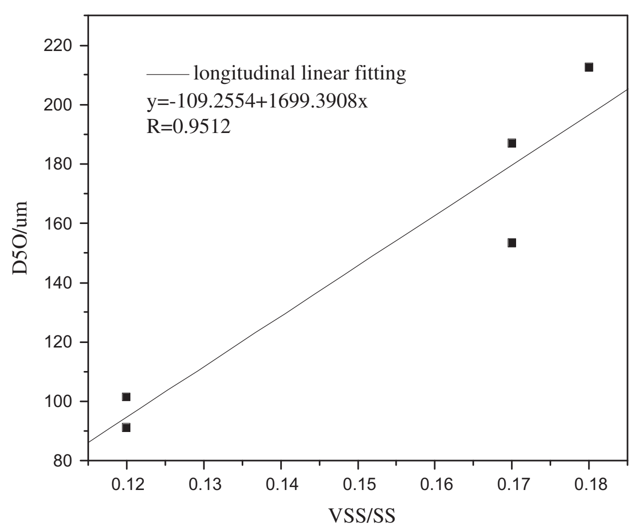

Fig. 10. Correlation between vertical VSS and D50.

component of the sludge. In order to derive a more accurate MLSS concentration, Wentzel et al. [23] measured the distribution of inorganic materials in the influent, bioreactor, and effluent. Due to the low concentration of influent inorganic solids, only a small fraction of the total inorganic solids (2.8–7.5%) was incorporated into the mixed liquor and had little impact on VSS/TSS (VSS/TSS = 0.75). Thus, Wentzel's study did not direct other researchers' attention to inorganic solids in sludge. The widespread use of combined drainage systems in many developing countries, the absence of primary settling tanks in WWTPs and lack of rainwater runoff control increase the inorganic solid concentration of influent and also aggravate its incorporation into sludge. According to Figs. 5, 7, and 11, the VSS/SS of deposited sludge was 0.05–0.27, and its main component was sand. These results suggest the seriousness of sludge deposition in developing countries' WWTPs, and the need for operators to pay attention to rainwater runoff and to control influent inorganic solids.

In our previous study, a hydrocyclone was developed to remove grit from activated sludge [20]. Feed solids diameter is one of the most important factors for a hydrocyclone [25,26], thus the D50 distribution of deposited sludge in the OD studied in this research is helpful for the design and operation of a hydrocyclone.

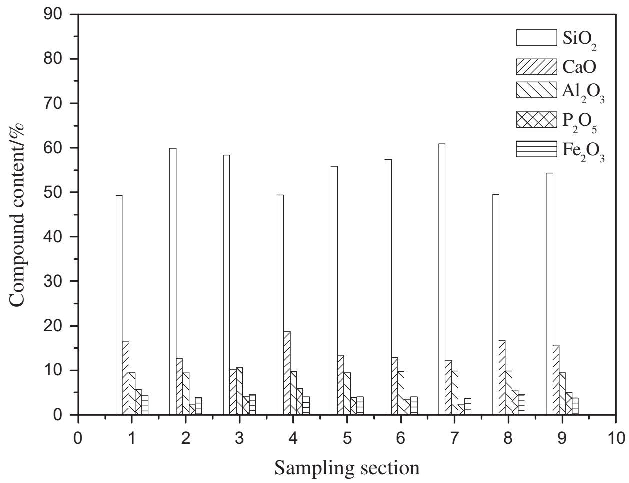

Fig. 11. Inorganic component characterization of deposited sludge.

5. Conclusion

(1) Sludge deposition in this WWTP was very serious. The sludge deposition height was 0.2–1.2 m, and the total volume of sludge deposition accounted for about 19% of the OD's effective volume. The deposited sludge was distributed mainly in the anoxic zone, at the backends of submerged propellers and along the inside walls of large-curvature bends, reducing the hydraulic retention time and nitrogen removal rate by 57 and 20%, respectively. Better nitrogen removal efficiency could be achieved by lengthening the HRT of the anoxic zone through removing deposited sludge from the OD.

(2) The VSS/SS of the deposited sludge was 0.05–0.27, and the main component was sand, due to erosion caused by rainfall and the absence of a primary settling tank. The D50 of the deposited sludge was 67.14–251.87 μm and is obviously correlated with VSS/SS. The sand precipitates together with sludge at the bottom of the OD through attachment, capture, and entrapment.

(3) The sludge deposition problem could be controlled very effectively by enhancing plug-flow and the aeration intensity. For the Carrousel OD, the best zones for clearing up or separating deposited sludge are the back-ends of submerged propellers and large curvature bends.

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References

[1] C.P. Grady, G.T. Daigger, H.C. Lim, Biological Wastewater Treatment, CRC Press, Marcel Dekker, New York, NY, 1999.
[2] B.A. Saida, H. Latifa, C. Hayet, S. Hedi, Aeration management in an oxidation ditch, Desalination 252 (2010) 172–178.
[3] X. Zhou, X.S. Guo, Y.P. Han, J.X. Liu, J.C. Ren, Y. Wang, Y.T. Guo, Enhancing nitrogen removal in an orbal oxidation ditch by optimization of oxygen supply: Practice in a full-scale municipal wastewater treatment plant, Bioprocess Biosyst. Eng. 35(2012) (2012) 1097–1105.
[4] Y.C. Liu, H.C. Shi, L. Xia, H.M. Shi, T.G. Shen, Z.Q. Wang, G. Wang, Y.Z. Wang, Study of operational conditions of simultaneous nitrification and denitrification in a Carrousel oxidation ditch for domestic wastewater treatment, Bioresour. Technol. 101 (2010) 901–906.
[5] I.D. Mantziaras, A. Stamou, A. Katsiri, Effect of operational cycle time length on nitrogen removal in an alternating oxidation ditch system, Bioprocess Biosyst. Eng. 34 (2011) 597–606.
[6] Water Environment Federation, Design of municipal wastewater treatment plants, Amer Society of Civil Engineers Press, Alexandria, 1992.
[7] H.X. Littleton, G.T. Daigger, Application of computational fluid dynamics to closed loop bioreactors Analysis o f macro-environment variations in simultaneous biological nutrient removal systems, Paper presented at the 74th Proceedings of Water Environment Federation Annual Conference & Exposition on Water Quality and Wastewater Treatment, Atlanta, GA, October 2001.
[8] H.Z. Yang, T. Wang, R.S. Deng, Research on flow characteristic of curve channel of integrated oxidation ditch, J. Chongqing Jianzhu Univ. 29 (2007) 106–109.
[9] R.S. Deng, L. Kuang, Y. Li, W.M. Li, T. Wang, Research and experiment on mix ed liquor of Orbal oxidation ditch, J. Chongqing Jianzhu Univ. 29 (2007) 86–89.
[10] D.J. Zhang, Y. Chen, D.Y. Xu, L.S. Guo, Z.S. Pang, Practically testing the distribution of flow rate and wastewater component in a full scale carrousel oxidation ditch, Chinese J. Environ. Eng. 3 (2009) 607–611.
[11] W.F. Qin, S.M. Li, Y.P. Li, L.M. Tan, Test and analysis on flow pattern of modified oxidation ditch, China Water Wastewater 24 (2008) 84–88.
[12] Z.L. Li, L.S. Guo, D.J. Zhang, D.Y. Xu, Simulation of liquid-gas flow in full-scale Caroussel oxidation ditch with surface aeration, J. Cent. South Univ. 19 (2012) 1615–1621.
[13] Z. Zhang, B.L. Li, X.Y. Xiang, C. Zhang, H. Chai, Variation of biological and hydrological parameters and nitrogen removal optimization of modified Carrousel oxidation ditch process, J. Cent. South Univ. 19 (2012) 842–849.
[14] W.M. Xie, R. Zhang, W.W. Li, B.J. Ni, F. Fang, G.P. Sheng, H.Q. Yu, J. Song, D.Z. Le, X.J. Bi, C.Q. Liu, M. Yang, Simulation and optimization of a full-scale Carrousel oxidation ditch plant for municipal wastewater treatment, Biochem. Eng. J. 56 (2011) 9–16.
[15] L. Fan, N. Xu, Z.Q. Wang, H.C. Shi, PDA experiments and CFD simulation of a lab- scale oxidation ditch with surface aerators, Chem. Eng. Res. Des. 88 (2010) 23–33.
[16] H.X. Littleton, G.T. Daigger, P.F. Strom, Application of computational fluid dynamics to closed loop bioreactors: I characterization and simulation of fluid- flow pattern and oxygen transfer, Water Environ. Res. 79 (2007) 600–612.
[17] B.L. Li, Z. Zhang, S.W. Liu, C.S. Lu, H. Chai, W.Z. Wang, X.G. Yuan, Sludge deposition analysis and flow pattern test on oxidation ditch integrated A/A/O Technique, J. Civil Arch. Environ. Eng. 33 (2011) 118–123.
[18] L. Bai, Y. Liang, J. Long, J. Shi, X. Yin, Z. Yu, C. Yue, S. Zhou, X. Zhu, Washing separation of municipal ditch mud comprises taking commercial municipal ditch mud in oxidation ditch through fixing grid into sludge slot, and dividing ditch sludge into heavy sand, light scum and sewage, CN102206026-A(China), (2011).

[19] L. Bai, Y. Liang, J. Long, J. Shi, X. Yin, Z. Yu, C. Yue, S. Zhou, X. Zhu, Commercial mud oxidation ditch washing separating device, has sludge tank, fender set on sludge receiving groove port connected to overflow port, fixed grill, stirring paddle set on front end of sludge tank, slag, and sand conveyor set, CN202046980-U(China), (2011).
[20] F.Y. Ji, X.B. Hu, S.A. Zong, X. Xu, P. Yan, X.L. He, L. Lu, X. Zhang, A grit separation module applied to remove grit of activated sludge in wastewater treatment plants, CN102302974A, (China), (2012).
[21] F.Y. Ji, Q. He, P. Yan, X. Xu, S.A. Zong, J.P. Fan, L. Lu, W.L. Shuai, A system for bypass sludge reduction, nitrogen and phosphorus removal and grit separation, CN102241462A (China), (2011).
[22] J.G. Yuan, C.J. Li, Solution of sludge deposit in modified carrousel oxidation Ditch, China Water Wastewater 25 (2009) 93–98.
[23] M.C. Wentzel, M.F. Ubisi, M.T. Lakay, G.A. Ekama, Incorporation of inorganic material in anoxic/aerobic activated sludge system mixed liquor, Water Res. 36 (2002) 5074–5082.
[24] Metcalf & Eddy, Wastewater Engineering: Treatment and reuse, 4th revised ed., McGraw Hill Higher Education Press, 2002.
[25] S.B. Kuang, K.W. Chu, A.B. Yu, A. Vince, Numerical study of liquid–gas–solid flow in classifying hydrocyclones: Effect of feed solids concentration, Miner. Eng. 31 (2012) 17–31.
[26] Q. Yang, W.J. Lv, L. Ma, H.L. Wang, CFD study on separation enhancement of mini-hydrocyclone by particulate arrangement, Sep. Purif. Technol. 102 (2013) 15–25.