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Removing Particulates from Centrate of Dredged Sediments at Suitanghe River, Shanghai

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ABSTRACT

The centrifugal dewatering of dredged slurry from a contaminated river would produce centrate that contained high levels of pollutants and particulates. The direct discharge of the centrate back to the river has predominant negative effects on the river water quality. In this study, particulates in the centrate were proposed to be removed by the use of a combined clarification + sand filtration + ultra filtration process. Jar tests revealed that dual conditioning by 100 mg/L polyaluminum chloride

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(PACl) followed by 30 mg/L polyacrylamide (PAM) obtained a more satisfactory effluent quality than single coagulant conditioning. Process parameters for clarification stage were then optimized using orthogonal tests at bench-scale tester. The helical-flow contact clarification could effectively remove particulate matters from the centrate with a hydraulic retention time (HRT) of 25 min. Since most pollutants were strongly associated with the particulates, the removal of suspended solids could effectively decontaminate the discharge as well. The effluent quality from sand filter could meet with the Class II criteria of Integrated Wastewater Discharge Standard in China (GB8978-1996, Integrated Wastewater Discharge Standard (in Chinese); National Environmental Protection Agency of China: Beijing, China, 1996), whereas that from ultrafilter met with the Water Quality Standard for Non-potable Use of China (CJ25.1–89, Water Quality for Non-protable Use (in Chinese); Construction Ministry of China: Beijing, China, 1989).

Key Words: Centrifugal dewatering; Dredged slurry; Centrate decontamination; Dual conditioning; Helical-flow contact clarification; Sand filtration–ultrafiltration.

INTRODUCTION

Shanghai is located at the estuary of the Yangtse River with a high river-net of approximately 3.41 km/km^2,[3] and nearly 7% of the total land areas are covered by water.[4] Rivers and the sediments in the six administrative districts of the urban areas of Shanghai are highly polluted owing to the direct discharge of municipal wastewater over the past centuries. The main pollutants include heavy metals, mostly Pb, Cd, Hg, Cu, and Zn, and organic matters. Investigations indicate that the heavy metals in the river sediments are enriched in the organic-rich, upper sediment layer and are mainly associated with the organic particulates.[5] Perin et al. reported similarly.[6]

Hydraulic suction could efficiently remove the heavily contaminated organic-rich sediment layer from the urban river.[7] The on-site centrifugal dewatering reduces the volume of the dredged sediment for further transportation and disposal.[7] The on-site centrifugal dewatering technique thickened the dredged slurry to a solid content higher than 70%, with 80–90% recovery of solids content.[8] However, the centrate from the centrifuge contained high concentrations of colloidal substances, thereby requiring further treatment for safe discharge. A pilot-scale, combined clarifier + sand

filter + ultrafilter process was used herein to separate the particulates in centrate using dual conditioners.

METHODS AND TESTS

Dredging Process

A pilot-scale hydraulic suction-centrifugal dewatering dredging plant was built at the Suitanghe River in the north of Yangpu District, Shanghai, as schematically illustrated in Fig. 1. The river is of 1.5 m bottom altitude (Wusong standard sea-level), 5.5 m bottom width, 1:1.75 side slope gradient, and 1.8 m average water depth. The net river discharge is regulated by the irregular semi-diurnal tide of Huangpu River. Municipal sewage contaminated the river water. The hydraulic process started to excavate the river sediment in 1998. The hydraulic suction of sediment was performed with a submerged centrifugal slurry pump, equipped with a high-pressure hydraulic gun to scour the sediments at a nominal capacity of 30 m^3/h. The pumped slurry was first passed through a vibrating screen (ϕ 8 mm) to a regulation tank and then was transported by a screw-metering pump to the centrifuge. The horizontal sedimentation centrifuge, with a drum diameter of 450 mm and a rotational speed of 3,000 rpm, provided an acceleration of 2,250 g and had a solid loading of 2.4 tons/h. The centrifuge dewatered the slurry and produced the sludge cakes and the centrate.

Part of the centrate (130–150 l/h) was introduced to the pilot plant shown in Fig. 2 (the enveloped region in Fig. 1). The pilot plant consisted of a helical-flow contact clarifier, followed by a sand filter and an ultrafilter. The centrate was first pumped into several storage tanks, and the solids content measured. A constant-flow-rate pump then sucked the centrate into the regulation tank and adjusted the solid content to 2%. The influent was then regulated at a solid content of 2.0 ± 0.1%. Helical-flow contact clarifier was the primary

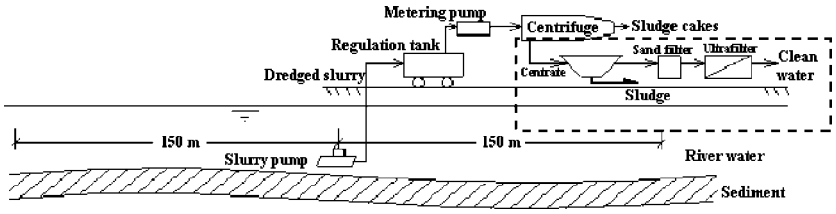

Figure 1. The schematic of the pilot-scale process. The enveloped area is the investigated process.

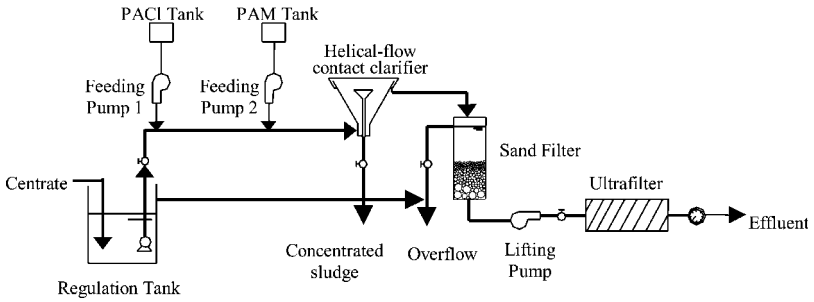

Figure 2. The flow diagram of the investigated process for solid–liquid separation for the centrate.

solid–liquid separator. The helical-flow contact clarifier had a cone with an angle of approximately 50° and a maximal radius of 0.27 m. The central hopper was 0.2 m in diameter, whose vertical position was adjustable. The hydraulic retention time was fixed at 25 min. The clarifier could not only accelerate the clarification of flocculated particulates at high hydraulic loading, but also effectively capture fine particles by the zone above the sludge hopper.[9] Orthogonal tests determined the major process parameters (discussed later).

The sand filter column had a diameter of 0.1 m and was filled with gravel (2–4 mm in diameter, and thickness of 50 mm), coarse sands (1.7–2.2 mm in diameter and thickness of 50 mm), and quartz sands (0.5 mm in diameter and thickness of 250 mm). The surface loading of the sand filter was 17.6 m^3/m^2-h.

The ultrafiltration (UF) membrane was a hollow fiber with a cutoff molecular weight of 100,000, made by the Eighth Plant of Ministry of Nuclear Industry, China. The operational transmembrane pressure ranged 28 to 37 kPag.

Centrate samples from different dredged locations were collected weekly, and the pH value ranged from 6.9 to 7.6. Table 1 lists the average sample compositions. The concentrations of pollutants considerably exceed

Table 1. The centrate quality.

	SS	COD	BOD	NH_4-N	TP
Total (mg/L)	36,400	10,600	604	70.5	65.1
Filterable (mg/L)	NA	298	72	31.2	0.62
NEPA Standard[a] (mg/L)	200	150	30	25	1.0

[a]Class II of Integrated Wastewater Discharge Standard, China.[1]

the current discharge standards of China (Class II of Integrated Wastewater Discharge Standard).[1] Comparing the pollutant concentrations in the influent centrate and its filtrate after filtering with a 0.45-μm membrane revealed that most pollutants were in a particulate form. Removal of solids from the water streams could not only reduce the suspended solids loading but also decontaminate the streams from most pollutants.

Jar Test

Jar tests determined the "optimal" conditioner dosage to the pilot-scale test. The following four coagulants were tested: (1) polyaluminum chloride (PACl) (30% available Al_2O_3 and 85% alkalization), (2) cationic polyacrylamide (PAM) (90% active composition and a molecular weight of 5 million), (3) aluminum sulfate (CP), and (4) polyiron sulfate (CP). All chemicals were purchased from Shanghai Chemical Reagent Co. Ltd. Jar tests were conducted in 1,000-ml measuring cylinders (420 mm in height and 70 mm in diameter) with a fixed amount of conditioner injected and reciprocating mixer mixed for 4 times in 10 s. In the case of dual conditioning, the second conditioner was added 20 min after the addition of the first conditioner. Sludge settling tests were then conducted in the cylinders by recording the supernatant–suspension interface height with settling time. The settling velocity was obtained by linearly regressing the height vs. time data. The final turbidity of supernatant was recorded after 90-min settling.

Other Tests

Weighing and drying at 105°C and 600°C, respectively, determined the total solids content (TS) and the volatile substance (VS) of samples. Suspended solids (SS) was the unfilterable part (through midvelocity quantitative filter paper) of the sample supernatant. Chemical oxygen demand (COD) was measured by dichromate method, and ammonia–nitrogen (NH_4-N) and total Kjeldahl nitrogen (TKN) by titrimetric method.[10] Total phosphorus (TP) was measured by ammonium molybdenum spectrophotometric method.[11] The inductively coupled plasma optical emission spectrometry (BARD, ICP2070) analyzed the heavy metal contents after acid-digestion,[12] despite mercury being measured by the cool-vapor atomic absorption method.[10]

RESULTS AND DISCUSSION

Pollutants in Streams

Table 2a lists the organic contents of the material streams. The loss rate denotes the fraction of pollutants transferred from the dredged slurry to the centrate during centrifugal dewatering. More than half of the pollutants in the influent slurry were transferred to the centrate rather than to the sludge cakes. Restated, the pollutants tended to enrich in the centrate, with the NH_4-N being the most enriched substance.

Table 2b lists the heavy metal contents in the material streams. The enrichment rate was defined as the ratio of heavy metal concentration in the centrate to that in the dredged slurry. This index correlates with the corresponding heavy metal levels in the in-situ sediments. The heavy metals seem to have a high affinity to the organic matters in the dredged slurry.

Jar Tests

Jar test was also conducted to examine the effects of adding the four aforementioned coagulants on the sludge characteristics, including the zone settling velocity (V), and the supernatant turbidity (T) after 60-min settling (100 mins for the aluminum sulfate test). Figure 3 depicts the measurement result, in which T_0 and V_0 are the reference values for the centrate before conditioning, that is, 342 NTU and 0.018 mm/s, respectively. The PACl, aluminum sulfate and polyiron chloride could considerably reduce the supernatant turbidity, but had only a little enhancement on the sludge settleability. On the turbidity removal, dosing PACl would lead to the lowest supernatant turbidity, while that of aluminum sulfate or of PAM did not effectively remove the turbidity.

Inorganic metal coagulants normally yield small and weak flocs, and are not appropriate conditioners in centrifugation dewatering since the high shear induced in the centrifuge would deteriorate the flocs and produce colloid particles.[13] The present PAM could not effectively remove the turbidity (74 NTU at minimum). But, the PAM had largely enhanced the sludge settleability. Hence, none of the four examined conditioners could simultaneously remove turbidity and enhance settling when used alone.

We look for a better performance by conditioning with dual conditioners. In this study, the combined dose of PACl (lowest turbidity achievable) and PAM (highest settling rate) was considered. Dual conditioning tests were carried out to determine the optimal parameters of coagulation including

Table 2a. The organic matter and nutrient contents of the material streams.

Material streams	COD (mg/l)		NH_4-N (mg/l)		TKN (mg/l)		TP (mg/l)	
	Total	Filterable	Total	Filterable	Total	Filterable	Total	Filterable
Dredged slurry	18,300	218	88.5	29.8	448	36.9	112	0.48
Centrate	10,600	298	70.5	31.2	334	37.6	65.1	0.62
In-situ sediments[a]	181,000	NA	NA	NA	4,100	NA	1,230	NA
Loss rate[b]	0.51	NA	0.70	NA	0.66	NA	0.51	NA

[a] in mg/kg.
[b] The ratio of the relevant contaminant amount of the centrate to that of the dredged slurry. The weight ratio of the two material streams was 0.885:1.

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Table 2b. Average heavy metal concentrations in investigated material streams.

	Heavy metals (mg/kg)						
Material streams	Zn	Cu	Pb	Cr	Cd	Hg	As
Dredged slurry	2440	129	62.5	336	1.61	0.10	1.49
Sludge cake	27.5	128	27.6	298	1.46	0.04	1.25
Centrate	9780	160	186	811	4.63	0.15	2.20
In-situ sediments	2360	151	66.0	311	1.59	ND[a]	1.49
River water	79.2	23.8	19.9	68.8	0.15	0.15	9.07
Enrichment rate[b]	4.00	1.24	2.97	2.41	2.88	NA	1.48

[a] ND: not detectable.
[b] The ratio of the heavy metal concentration of the centrate to that of the dredged slurry.

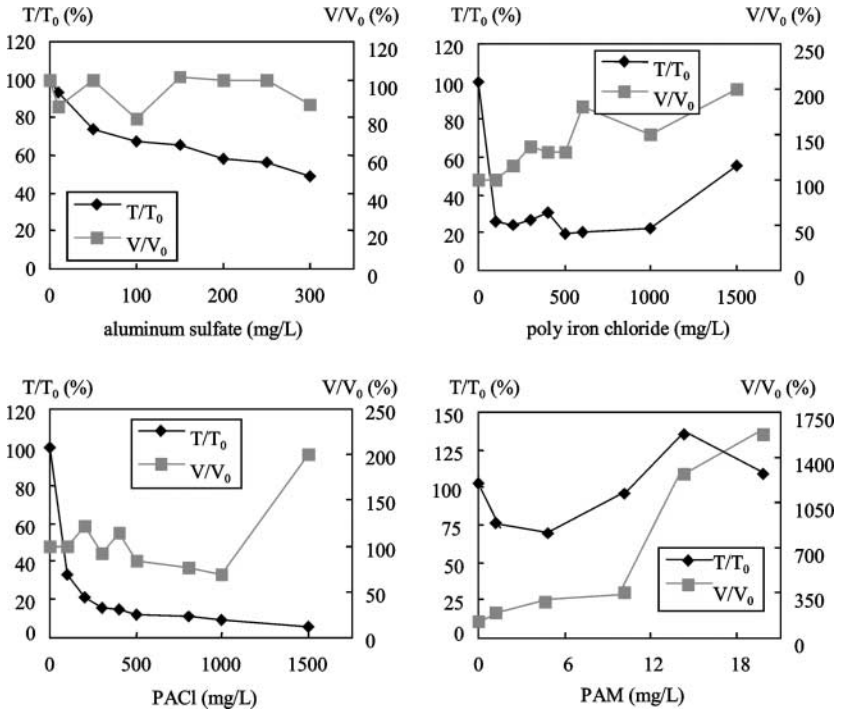

Figure 3. Effects of different coagulants on centrate clarification ($T_0 = 342$ NTU and $V_0 = 0.018$ mm/s).

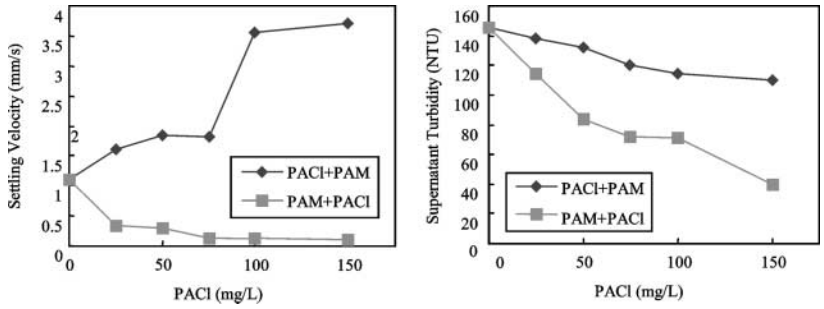

Figure 4. Performance of dual conditioning tests with PACl + PAM and PAM + PACl (pH 7.4. PAM = 30 mg/L).

the sequence of conditioner addition (Fig. 4) and dosages under different initial solid concentrations (Fig. 5). In Fig. 4, with a centrate solid content of 2.3%, the PACl + PAM process produced a much higher settling velocity than the PAM + PACl process. In fact, although the latter could lead to a lower turbidity at the same PACl dose, it deteriorated the sludge settleability. The dual conditioning with PACl + PAM was thus adopted in the subsequent pilot-scale tests.

To obtain a sufficiently high settling velocity, say 1 mm/s, the PAM dosage should be adjusted along with the centrate solid content. Figure 5

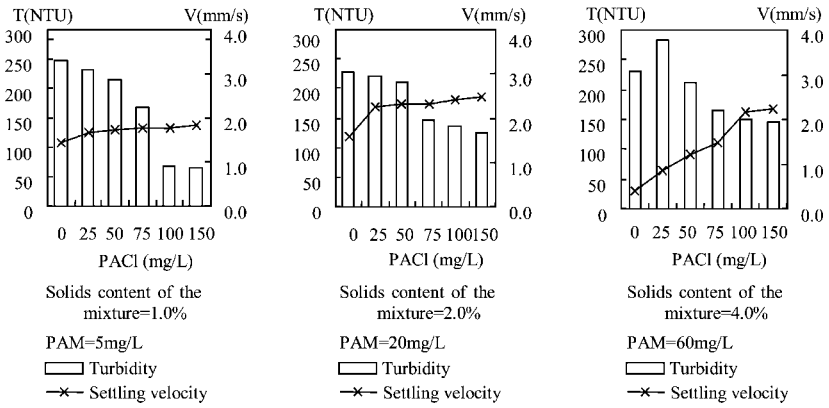

Figure 5. The performance of dual conditioning tests with PACl + PAM and PAM + PACl at various solids contents in centrate (pH 7.4).

Table 3. The configurations of the bench-scale and pilot-scale helical contact clarifier.[a]

Parameter	Unit	Pilot-scale device	Bench-scale model	Scale-up ratio
Loading	m/hr	2.4 m/hr	2.4 m/hr	1
Influent rate	m/s	2–12 m/s	2–12 m/s	1
Tank radius	m	3.26	0.27	12
Treating amount	m^3/hr	20	0.138	144
Hopper radius	m	2.4	0.2	12
Hopper height	m	1.2	0.1	12

[a] The influent compositions were identical for both bench-scale and pilot-scale tests.

suggests that dosing 100 mg/L of PACl could reduce the supernatant turbidity to less than 150 NTU, regardless of the centrate solid content.

Process Parameters of Clarifier

The solid–liquid separation efficiency of the helical-flow contact clarifier was the most influential factor that determined the overall performance of the investigated process. We adopted the orthogonal tests to determine the "optimal" operational parameters by a bench-scale clarifier, including the nozzle velocity (A), conditioner dosage (B, PACl or PAM), coagulation time (C), and the hopper height (D).[14] Table 3 lists the sizes of the bench-scale and the pilot-scale clarifiers. Three levels of factors, denoted herein as level I, II, and III, were adopted in the following orthogonal test. The system response included the COD (O) and turbidity of clarified water (T). The solid content of the discharged sludge was also measured. Tables 4a and 4b list the responses of the orthogonal test using PACl and PAM as the conditioner, respectively. The solids content of discharged sludge from the clarifier (S) was considered in Table 4b.

The significance of the investigated process parameters could be realized using the standard deviation (S.D.) of the response when this particular parameter was fixed. Figures 6a and 6b present the standard deviations using the parameter levels listed in Tables 4a and 4b, respectively. When using PACl as the conditioner, the significance of process parameters for COD removal follows the sequence: B (PACl dose) $>$ C (coagulation time) $>$ A (nozzle velocity) or D (hopper height). A sufficiently low COD of the effluent is obtainable with a high level of PACl dose (higher than 100 mg/L) and a coagulation time of 10 s. On the other hand, the impact of process parameters on the turbidity removal is A $>$ B $>$ D $>$ C. A low turbidity is obtainable

Table 4a. The orthogonal tests using PACl as coagulant.

	Factor				Response	
No.	Nozzle velocity (A) (m/s)	PACl dose (B) (mg/L)	Coagulation time (C) (s)	Hopper height (D) (mm)	Turbidity (NTU)	COD (mg/L)
1	5.2	50	0	350	135	109
2	5.2	100	5	300	75	105
3	5.2	200	10	250	74	80.6
4	2.9	50	5	250	92	109
5	2.9	100	10	350	80	96.9
6	2.9	200	0	300	46	90.8
7	1.9	50	5	300	27	107
8	1.9	100	0	250	23	91.2
9	1.9	200	10	350	15	72.0
$\sum(T)\|_{(I)}$	284	244	204	230		
$\sum(T)\|_{(II)}$	218	178	194	148		
$\sum(T)\|_{(III)}$	65	135	169	189		
S.D. of $\sum(T)$	91.7	44.8	14.7	33.5		
$\sum(O)\|_{(I)}$	294	325	291	278		
$\sum(O)\|_{(II)}$	297	293	321	302		
$\sum(O)\|_{(III)}$	270	243	250	281		
S.D. of $\sum(O)$	12.1	33.7	29.1	10.7		

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Table 4b. The orthogonal tests using PAM as coagulant.

	Factor				Response		
No.	Nozzle velocity (A) (m/s)	PAM dose (B) (mg/L)	Coagulation time (C) (s)	Hopper height (D) (mm)	Turbidity (NTU)	COD (mg/L)	Solid content of discharged sludge (kg/m^3)
1	5.2	30	0	250	134	765	39
2	2.9	50	0	300	124	835	45
3	1.9	70	0	350	96	812	55
4	5.2	70	5	300	225	772	42
5	2.9	30	5	350	480	805	51
6	1.9	50	5	250	570	856	93
7	5.2	50	10	350	108	864	48
8	2.9	70	10	250	174	807	60
9	1.9	30	10	300	350	767	50
$\sum(T)\|_{(I)}$	467	964	878	354			
$\sum(T)\|_{(II)}$	778	802	699	1280			
$\sum(T)\|_{(III)}$	1020	495	684	632			
S.D. of $\sum(T)$	226.3	194.5	88.1	388			
$\sum(O)\|_{(I)}$	2400	2336	2410	2430			
$\sum(O)\|_{(II)}$	2450	2560	2430	2370			
$\sum(O)\|_{(III)}$	2440	2390	2437	2480			
S.D. of $\sum(O)$	21.6	95.4	11.4	45			
$\sum(S)\|_{(I)}$	129	140	139	192			
$\sum(S)\|_{(II)}$	156	186	186	137			
$\sum(S)\|_{(III)}$	198	157	158	154			
S.D. of $\sum(S)$	28.4	19	19.3	23			

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Table 4c. The "optimal" parameters for helical-flow contact clarification identified by the orthogonal test.

Factor	Nozzle velocity (m/s)	Dosage (mg/L) PACl	Dosage (mg/L) PAM	Coagulation time (s)	Height of central sludge hopper (mm)
"Optimal" value	5.2	100[a]	30[a]	10	300

[a] Adjusting according to the initial solid content of influent.

with low nozzle velocity and high PACl dose. A high nozzle velocity vigorously agitated the slurry and disrupted the aggregates, thereby deteriorating the settleability and increasing the clarified water turbidity. A 10-s coagulation is sufficient to remove COD from the clarified water. No clear correlation existed between the turbidity and COD of clarified water.

When using PAM as the conditioner, on the other hand, Fig. 6b reveals that the significance of the parameters on COD removal follows: B (PAM dose) > D (hopper height) > A (nozzle velocity) or C (coagulation time). A low COD was obtainable using 30 ppm PAM, with negligible effects of either the nozzle velocity or the coagulation time. The impact of parameters on turbidity removal follows: D > A > B > C. A low turbidity is obtainable with hopper height of 350 mm, a high nozzle velocity, and high PAM dose. The significance of process parameters under investigation resembles each other to the solids contents of discharged sludge.

According to the results of orthogonal tests on bench-scale clarifier and the economic concern, the "optimal" parameters were chosen and listed in Table 4c. These parameters were adopted in the subsequent pilot-scale tests.

Pilot-Scale Test

With the operational parameters determined the clarifier, the pilot-scale test was conducted and samples collected. Dual conditioners were employed for centrate conditioning. The clarified water from the helical-flow contact clarifier was fed into the sand filter. Table 5 lists the effluent quality from the sand bed. The clarified water flow rate would decline to only 25% of its initial flow rate (80 L/hr) after 330-min operation, at the time the COD of the effluent had yet to markedly increase. A vast amount of black aggregates were noted to accumulate on the filter surface. We set in a 10-min backwash at a flowrate of

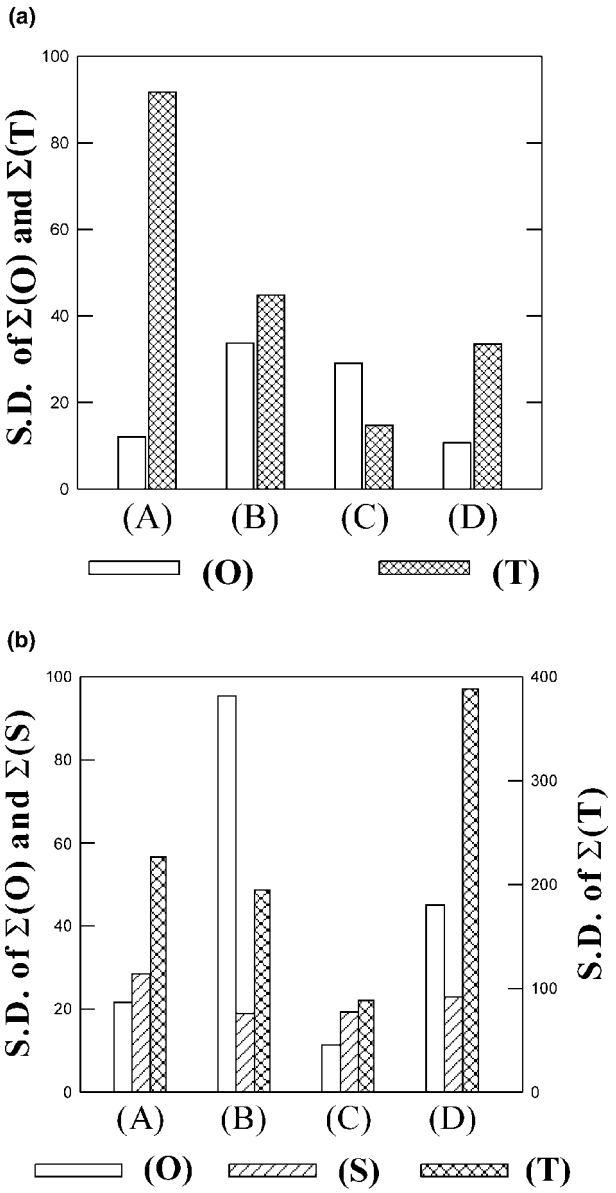

Figure 6. (a) The standard deviation when using PACl as coagulant (parameters listed in Table 4a). (b) The standard deviation when using PAM as coagulant (parameters listed in Table 4b).

Table 5. The flow rate and quality of effluent during the operation cycle of sand filter.

Time (min)	COD (mg/L)	NH_4-N (mg/L)	TKN (mg/L)	Turbidity (NTU)	TP (mg/L)	Flow rate of clean water (L/hr)
0	145	14.9	21.0	22	2.22	80
30	170	16.0	23.5	18	2.56	75
90	113	14.6	25.2	12	2.03	70
150	137	17.1	30.8	22	2.19	62
210	145	29.9	30.9	11	2.12	60
300	148	36.8	41.4	18	2.01	40
330	156	38.5	41.9	13	1.98	20
After backwash	143	16.9	27.9	24	2.06	80

200 L/h after a cycle of 6-hr sand filtration to remove the accumulated aggregates. The filtrate from the sand filter had been pumped through the ultrafilter at a constant rate of 133 L/h. Table 6 lists the effluent quality from the ultrafilter and the noted transmembrane pressure. The influent quality fluctuated with time but it did not affect the effluent quality. The pressure increased from 28 kPag to 37 kPag after 2-h operation and was kept unchanged afterward. No serious membrane polarization was observed during the operation. The TP in the effluent considerably decreased, which might be attributable to filtering/adsorption action by the dynamic cake formed on the membrane surface.

Table 6. The effluent qualities and the operational pressure of ultrafilter.

Time (min)	COD (mg/L)	NH_4-N (mg/L)	TKN (mg/L)	Turbidity (NTU)	TP (mg/L)	Transmembrane pressure (kPa)
0	58.5	10.5	13.4	0.4	1.47	28
30	56.5	10.9	13.2	0.7	1.45	32
60	48.4	15.0	17.8	0.7	0.69	35
120	24.2	27.4	30.2	0.9	0.21	37
180	44.4	36.9	34.1	0.7	0.17	37
240	32.3	13.9	18.0	0.4	0.15	37
300	34.3	10.8	14.6	0.4	0.13	37
360	39.1	11.0	15.6	0.7	0.13	37

Table 7a. The performance of the pilot-scale process for treating the centrate.

	Influent centrate	Supernatant from contact clarifier		Effluent from sand filter		Effluent from ultrafilter		Standard	
	ave	ave	max	ave	max	ave	max	—[a]	—[b]
COD (mg/L)	9900	662	860	136	156	35.2	48.4	50	150
NH_4-N (mg/L)	76.0	28.2	31.8	18.0	29.9	11.9	19.2	10–20	25
TKN (mg/L)	318	32.8	43.4	26.3	30.9	16.1	24.9	NA	NA
Turbidity (NTU)	NA	77.0	110	18.7	23.0	0.50	0.90	30	NA
TP (mg/L)	67	2.01	2.54	1.9	2.30	0.133	0.686	NA	1.0
SS (mg/L)	35600	60.0	92.0	10.0	14.0	0	0	5–10	200

[a] Water Quality Standard for Non-potable Use, China.[2]
[b] Class II of Integrated Wastewater Discharge Standard, China.[1]

Table 7b. Heavy metal concentrations of the effluent from sand filter (mg/l).

Parameters	Zn	As	Cu	Pb	Cd	Cr	Hg
Value	0.208	0.080	0.050	0.050	0.003	0.005	0.0014

Table 7 lists the effluent qualities from various units. The system operated continuously and smoothly for years, with sand filter backwashing at a 6-hr interval. The effluent from the sand filter met with the river discharge standards of China,[1] and could be directly discharged back to the dredged river with no restriction. Meanwhile, the effluent from the ultrafilter could meet with the Chinese quality standard for nonpotable use, like green area irrigation (Water Quality Standard for Non-potable Use).[2] The solids content of the concentrated sludge collected at the helical-flow contact clarifier could reach up to 6.6% and could be easily dewatered by mechanical means. The proposed combined process is hence feasible to effectively remove the pollutants from the centrate, mostly in particulate form, of the dredged slurry at Suitanghe River, Shanghai.

CONCLUSIONS

The centrate of hydraulically dredged slurry from a contaminated river contains particulate pollutants and heavy metals. Efficient solid–liquid separation of centrate is required before its appropriate discharge. A combined process consisting of a helical-flow contact clarifier was proposed to separate the particulates from the centrate. The jar tests showed that dual conditioning by PACl and PAM could provide satisfactory turbidity removal and settleability improvement, which was used in subsequent tests. Helical-flow contact clarifier could run with high volumetric loading, with its operational parameters determined by orthogonal tests (HRT of 25 min, feeding PAM 30 mg/L, 10 s as PACl fed at 100 mg/L). After helical-flow contact clarification and sand filtration processes, the effluent quality can be discharged to rivers.[1] The effluent from an ultrafiltration process can meet the water quality standard[2] for nonpotable reuse.

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