Optimization of Chemical Enhanced Primary Treatment Process

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1 Introduction

As the first phase of Shanghai BLG Sewer Treatment Plant, a Chemically Enhanced Preliminary Treatment (CEPT) process was selected to suit effluent discharge via a long estuary outfall in deep water. CEPT relies on adding coagulants in the treatment process for the effective removal of phosphorus, one of the key nutrients in the formation of "red tides". The study has found that phosphorus removal efficiency and chemical dosage are highly dependent on the efficiency of suspended solids removal in the treatment system.

In the base design of CEPT process for the BLG plant, the typical coagulant dosage is determined as 80 mg/L, which needs total 96,000 kg per day in order to achieve expected solids, COD and Phosphorus removal [Plant design capacity = 1,200,000 (m3/day)]. Because of the large design capacity and significant amount of coagulant dosage in the daily operations at the BLG plant, it is important to reveal the mechanism of Phosphorus and COD removal in the CEPT process in order to significantly reduce coagulant usage.

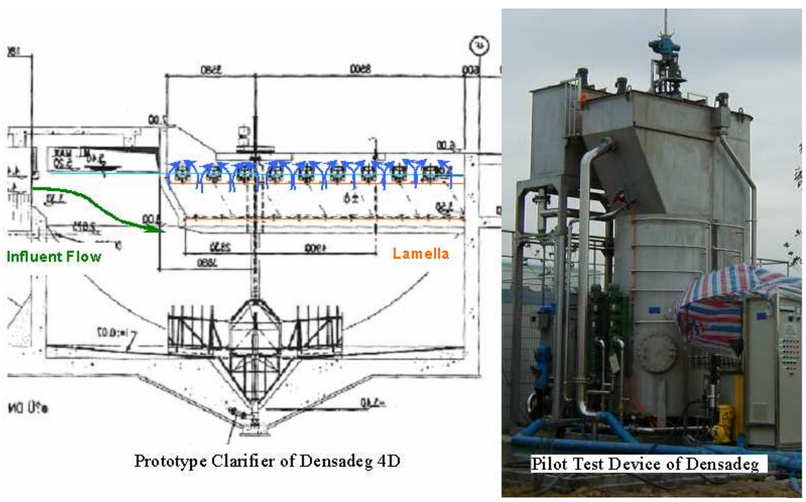

Figure 1 Clarifier prototype and its pilot testing unit

The major process optimization in this study includes following two aspects as:

1. A clear correlation between Phosphorus removal and process operation parameters, based on data of the pilot tests collected by Shanghai Municipal Engineering Design Institute (SMEDI, Jan. 2001), provides the optimized operational strategies for the selected CEPT process.

2. An optimized clarifier hydraulic structure, based on CFD model simulations, illustrates significantly enhanced effluent quality and capacity.

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2 Correlation between Phosphorus removal and operation parameters

Figure 1 shows the pilot-testing unit used for Shanghai BLG Sewer Treatment Plant. The SMEDI (2001) systematically collected the operational data in the pilot tests of the CEPT treatment process.

Table 1 presents the collected operational data in the pilot tests. The four major process influent parameters measured in the pilot tests versus system operation time are Surface Overflow Rate (SOR), influent Suspended Solids concentration, influent Phosphorus and influent COD. The three major system effluent parameters collected during testing period are SS, Phosphorus and COD. In addition to two different coagulants used in the tests, three different polymers, i.e. 8173, 9901 and AS32 were tested. The further information for BOD, Nitrogen removal and sludge draw-off concentration were occasionally collected in the tests.

In the first part of study, one of the major objectives is to explore a reliable correlation between the efficiency of Phosphorus (as well as COD) removal and the process operation parameters, based on the pilot testing data provided by SMEDI (Jan. 2001) and Shanghai Urban Construction Engineering Design Institute (SUCEDI, Nov. 2001).

2.1 Correlations of Single Variable versus Effluent P

Figure 2 presents the pilot test data for system Effluent Phosphorus versus Effluent SS concentration. The test results indicate somewhat correlation between effluent P and effluent SS concentration. It can be observed that as the effluent SS concentration of process increases, the effluent P concentration has the similar increasing trend. However, the wide spread of data points means that more parameters rather than only an effluent SS concentration could affect the system effluent P.

Using the same set of data, Figures 3 presents the system effluent SS concentration with respect to Coagulant Dosage (mg/L). Two sets of the pilot test data are corresponding to Ferric Chloride and Alum Sulfate. The coagulant dosage is in the range of 35 to 80 mg/L in the pilot tests. There is no strong correlation was found between coagulant dosage and clarifier effluent SS concentration in this dosage range. Obviously, the clarifier effluent SS concentration is affected by more parameters, such as clarifier operation conditions, clarifier hydraulic efficiency and solids settling property, etc. In the tested range of coagulant dosage (35~80 mg/L), coagulant dosage may have some impact on solids settling property. However, the direct impact of coagulant dosage on clarifier effluent SS concentration cannot be observed in the tested dosage range. The pilot data shows that Ferric Chloride could have slightly better performance than that of Alum Sulfate in terms of solids removal.

Using the same set of data, Figure 4 presents the correlation between effluent Phosphorus and coagulant dosage. The certain correlation between effluent P and coagulant dosage can be observed. The pilot results indicate that as coagulate dosage increase the effluent

Phosphorus reduces. The fairly wide data spread indicates the effluent Phosphorus must be affected by some other parameters too, however.

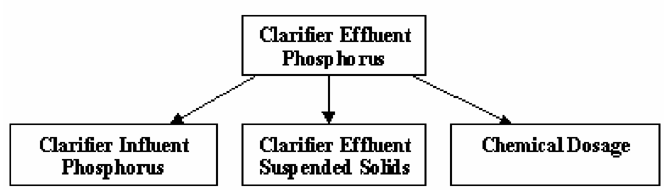
2.2 Correlations of Two Variables versus Effluent P

It could be accepted that the effluent phosphorus may be related to both coagulant dosage and process influent phosphorus (amount of Phosphorus entering into system). For the same set of data Figure 5 presents the correlation between the Phosphorus removal [(P-Po)/P] and dosage, where P and Po present the influent and effluent Phosphorus concentrations, respectively. It can be concluded that the higher dosage gives higher Phosphorus removal percentage. Nevertheless, the very large variation spread of the data in Figure 5 means that more effect factors should be simultaneously included in the analysis of Phosphorus removal for a CEPT process.

2.3 Correlations of Three Variables versus Effluent P

As shown in chart below, this study assumes that the final effluent Phosphorus of system could be directly affected by following three major variables as Coagulant dosage; Clarifier effluent SS concentration; and Clarifier influent Phosphorus concentration. It implies that the clarifier flow condition, hydraulic efficiency, influent MLSS and solids settling property, etc. could impact the clarifier effluent SS thus, indirectly impact the process effluent P. To reduce the amount of variables, two dimensionless variables are assumed as the Phosphorus removal and the relative coagulant dosage. The relative coagulant dosage is defined as Dosage/Effluent SS, based on the concept that the higher dosage normally gives lower effluent phosphorus and higher effluent SS always generates the reverse impact on effluent Phosphorus.

If there is a relationship among the four variables and a certain variable change could be found in the four-dimensional system it should make the same set of data (presented in previous Figures 2 to 5) convergence to a line (or a curve).



In this study a composite variable (Dosage/Removal Ratio) has been found due to the insistent effort together with a little bit fortunateness, which makes all of test data (collected by SMEDI in 2001) convergence to an almost perfect line for the Phosphorus removal as shown in Figures 6.

3 Coagulant Selections

Figure 6 shows the convergent linear relationship between a relative coagulant dosage and the Dosage/Removal Ratio, which is given as [Relative Dosage – P removal] divided by P removal. The pilot test data clearly indicates that both Ferric Chloride and Alum Sulfate have almost identical tangential rate and intercept distance in Figure 6.

According to the field data analysis, it can be concluded that both coagulants used in the pilot tests have very similar performance in terms of Phosphorus removal efficiency. It also found that iron salt gives somewhat better performance for suspended solids removal. To obtain a higher Phosphorus removal efficiency it is more important to properly choose a coagulant dosage rather than to select which coagulant between the Iron salt and Alum Sulfate.

4 Phosphorus Removal Model in a CEPT Process

As shown in Figures 6 and 7, a linear equation between Relative Dosage and Dosage/Removal Ratio has been obtained by using a simple linear regression, which is:

$$[\text{Dosage}/SSC - (P-P_o)/P]/[(P-P_o)/P] = 1.0992\ (\text{Dosage}/SSC) - 0.5855$$

Where Dosage = Coagulant dosage for either Ferric chloride or Alum sulfate
P = System influent Phosphorus
Po = Clarifier effluent Phosphorus
SSC = Clarifier effluent SS concentration

The dimension of the model (formula) developed above is balanced. Therefore, there are no unit specifications for any variables in the model as long as the same unit is used.

As shown in Figure 7, the final model for Phosphorus removal can be written as:

$$(P-P_o)/P = \text{Dosage} /(0.4145 * SSC + 1.0992\ \text{Dosage})$$

The data based on the average value of another independent test (SUCEDI and TJ University 2001) is also included the Figure 7. The comparison shows a very good agreement between the model values, base on the data collected by SMEDI (2001) and the data tested by SUCEDI/TJ Univ. (2001).

5 Applications of P removal Model

The model has revealed a meaningful principle for Phosphorus removal in a CEPT process, i.e. the Phosphorus removal is largely dependent on the solids removal. For example, if a clarifier effluent SS could be controlled around 15 mg/L, the dosage would be only 35 mg/L for a given Phosphorus removal of 80%. However, if the effluent SS went up to 60 mg/L the dosage requirement would be higher than 120 mg/L to obtain the same Phosphorus removal.

On other hand, if an economic dosage of 35 mg/L is given, a clarifier operation with effluent SS concentration of 15 mg/L will have the phosphorus removal of 80%. However, for the same dosage, the phosphorus removal percentage in an operation with effluent SS of 55 mg/L will dramatically reduce to about 56%.

The Phosphorus removal model here combined with a CFD based process/clarifier model could be a very powerful tool to optimize a CEPT design/operation on following aspects as:

1. Reveal the mechanism of Phosphorus removal previously unclear,
2. Determine optimized operational strategies, which can used to achieve a best cost-effective Phosphorus removal;
3. Provide a clarifier design with a higher hydraulic efficiency, which can provide better solids removal thus, significantly minimize the demanding of coagulant dosage

For example: the computer modeling results (see Figure 8) illustrate that if the clarifier effluent SS concentration could be controlled in a low level (10~20 mg/L) due to the clarifier design optimization, the coagulant dosage variations have very limited impact on Phosphorus removal percentage. In this case, the economical coagulant dosage (40 mg/L) should be used to significantly save usage of coagulant. The design optimization also reduces the burden of sludge disposal and relieve the impact of sludge disposal on environmental while maintaining enough Phosphorus removal efficiency. Using the principle the existing design dosage could be reduced more than 50% in the plant operation (approximately 50,000 kg/per day).

On another hand, if the clarifier effluent SS went up to a high level (50~60 mg/L) due to some uncertainties, the increase of coagulant dosage (up to 100 mg/L) could be an effective way temporally applied to maintain the Phosphorus removal around 75%.

6 Enhance Performance and Capacity of Prototype Process/Clarifier

6.1 Why a CFD based Process/clarifier Model

An optimized design for a pilot test unit (in terms of hydraulic efficiency in settling compartment) may not guaranty the highest hydraulic efficiency in their prototype. It would have risks for a designer to directly adopt the flow limit obtained from a pilot test unit. As shown in Figure 1 there are significant differences between the pilot unit and its prototype in terms of clarifier configuration, size, water depth, influent and effluent structure, etc. According to the scale model principle the depth of a settling tank for a pilot unit must be close to the depth of its prototype since the solids settling velocity of MLSS cannot be changed between the model and its prototype.

Therefore, any significant water depth differences between model and prototype may produce intolerable error in the application of results. Normally, the model deformation in horizontal plan is selected (see Figure 1).

For a given SOR to obtain desired hydraulic regime and higher capacity in a prototype is always more difficulty than that in a pilot unit due primarily to a much higher overall flow through the prototype and a stronger turbulence level in a larger and deeper prototype.

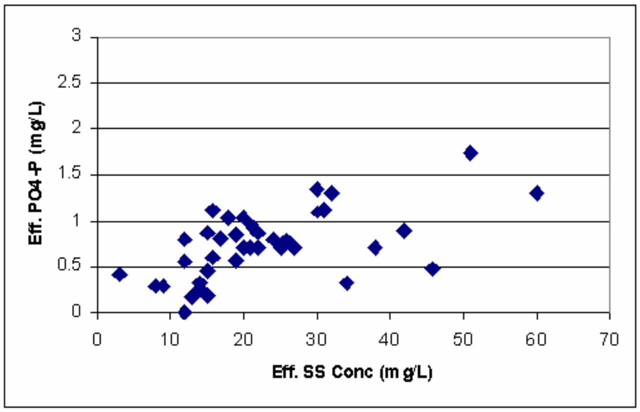


Figure 2 Correlation between effluent P and effluent SS concentration

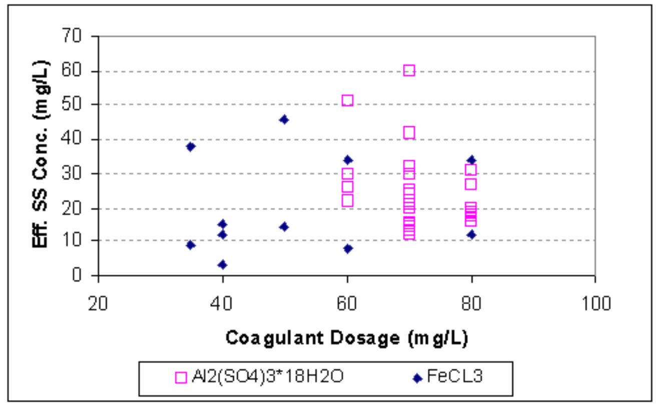


Figure 3 Correlation between effluent SS and Coagulant dosage

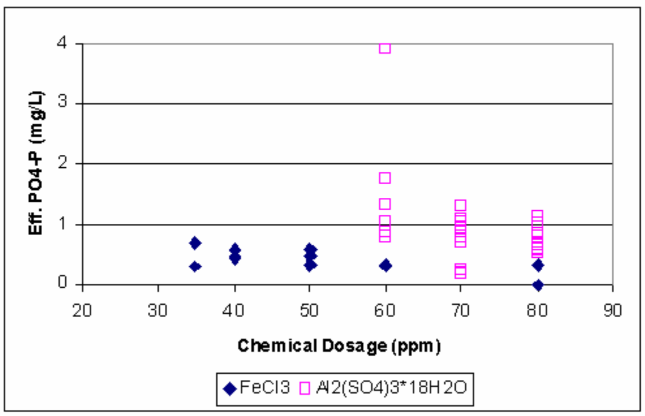


Figure 4 Correlation between effluent P and flocculation chemical dosage

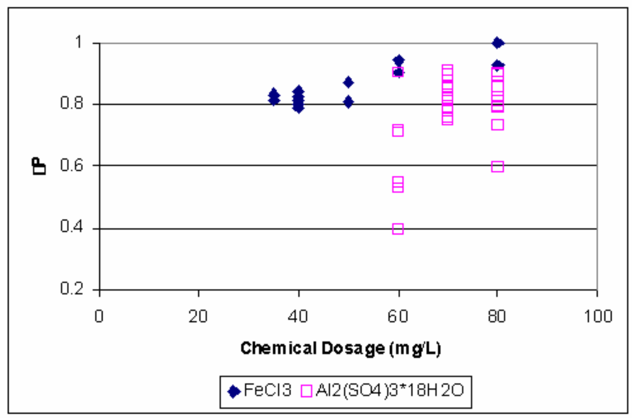


Figure 5 Correlation between P removal and chemical dosage

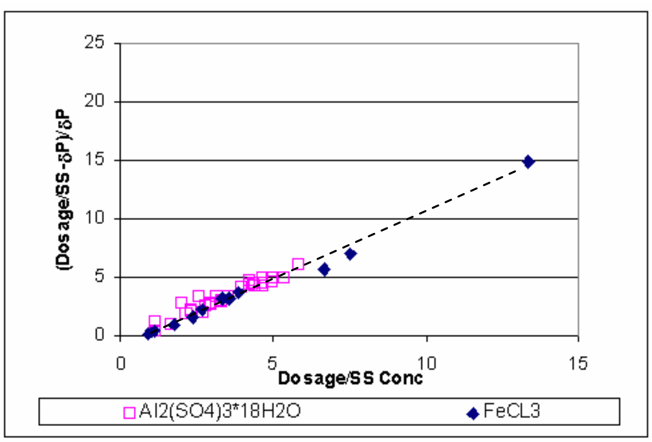


Figure 6 Correlative relationships between relative dosage and dosage/P removal ratio revealed in this study based on pilot testing data of SMEDI (Jan. 2001)

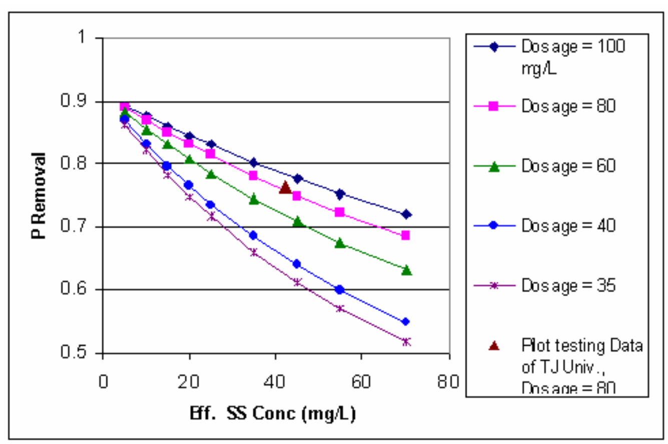


Figure 7 Impact of Clarifier Effluent SS and Flocculation Chemical Dosage on Phosphorus Removal Efficiency
[(P – Po)/P = Dosage /(0.4145*SS + 1.0992 *Dosage)]

6.2 Glass Box Modeling Technology

The unsteady three-dimensional process/clarifier model developed by Dr. Zhou and Dr. McCorquodale (1992) is based on the CFD theory. This unique model is a powerful tool to evaluate any clarifier designs and modifications by simulating tank internal hydraulics behavior and sludge blanket movement. The clarifier model proposed here has been applied to many projects for more than 10 years.

The topic of clarifier modeling is not new; the first model was developed and published over 60 years ago. However, many of the models developed have been crude approximations of clarifier behavior, relying on over-simplifications or ‘correction factors’ and based mainly in solids flux equations. In recent years, some CFD modelers often tried to obtain the clarifier modeling technology by simply adopting a commercial available CFD package. The strong numerical instability due to the density variations in their clarifier model makes the simulation convergence almost impossible and forces them to falsely disconnect the density impact with flow simulations.

This fully Mass Conservative Process/Clarifier Model is unique in that it successfully combines Computational Fluid Dynamics with solids flux theory to provide a full and accurate picture of the hydraulic and solids regimes (under strong density impact) within the clarifier while maintaining full mass conservation during the entire simulation period.

6.3 Design Optimization

The original prototype at BLG WWTP has front feed weir and is equipped with lamellar (see Figure 1 too). The average water depth is 7.7 m. Although the pilot test device provided fairly good performance in the tests, the significant enhancement of clarification in its prototype system was obtained due to the design optimization. The optimized influent baffle provides better influent mixing and isolation between the clarifier influent and effluent than that in the original prototype design thus, gives significantly enhanced clarification. The optimized baffle is able to sufficiently utilize the deep-water depth of 7.7 meters in

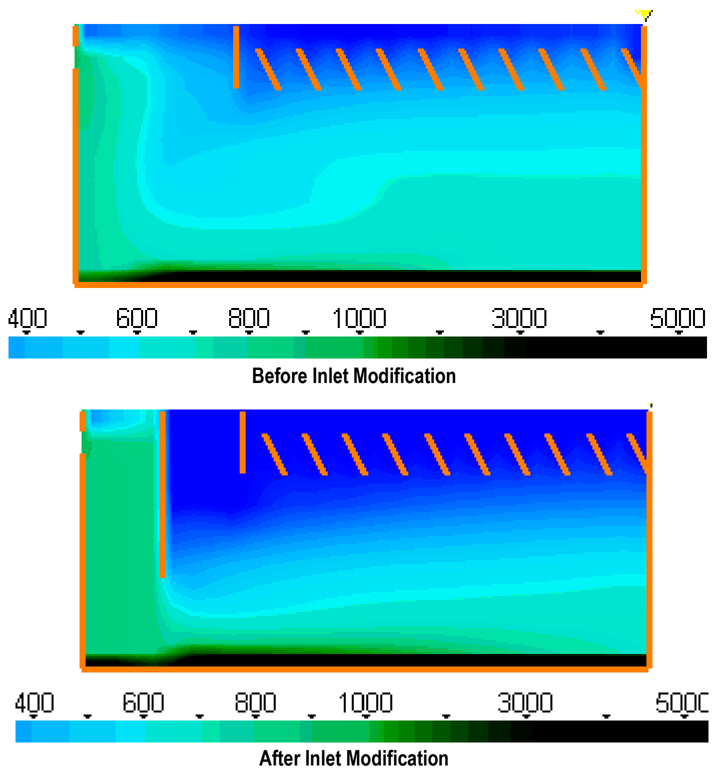


Figure 8 Comparison of solids field in Base Design with that of optimized design, MLSS = 1000 mg/L and SOR = 10.0 m3/m2/h

the existing design to create better separation between the tank influent and effluent along the vertical direction.

Figure 8 presents the comparison of solids fields, which were simulated by a CFD based "Glass Box" process/clarifier model (Zhou and McCorquodle 1992), between two prototype clarifiers before and after design optimization.

In the contrast with the isolation provided by the extended influent baffle, the strong turbulence diffusion has been predicted in the original prototype due to the poor separation between the influent and effluent. The results have been clearly shown in the Figure 8. In the original prototype design, the distance (separation) between the clarifier influent and the effluent in the horizontal direction is very limited due to the compact size of tank (17 meters). Therefore, the separation between the influent and the effluent in the vertical direction becomes more critical in this case to guaranty enough clarification and a better hydraulic efficiency before the effluent entering into Lamella.

6.4 CEPT Capacity

As shown in Figure 9, in the operations with influent MLSS of 1000 mg/L, the clarifier capacity approximately increases from 6.7 to 9.3 m3/m2/h for a recommended SS discharge standard of 15 mg/L due to application of the optimized influent baffle. The modification gives about 39% increase of clarifier capacity. For the effluent SS standard of 30 mg/L used in the base design, the application of the modification is able to increase the clarifier capacity from 8.0 to 10.0 m3/m2/h, which provides about 25% increase of clarifier capacity.

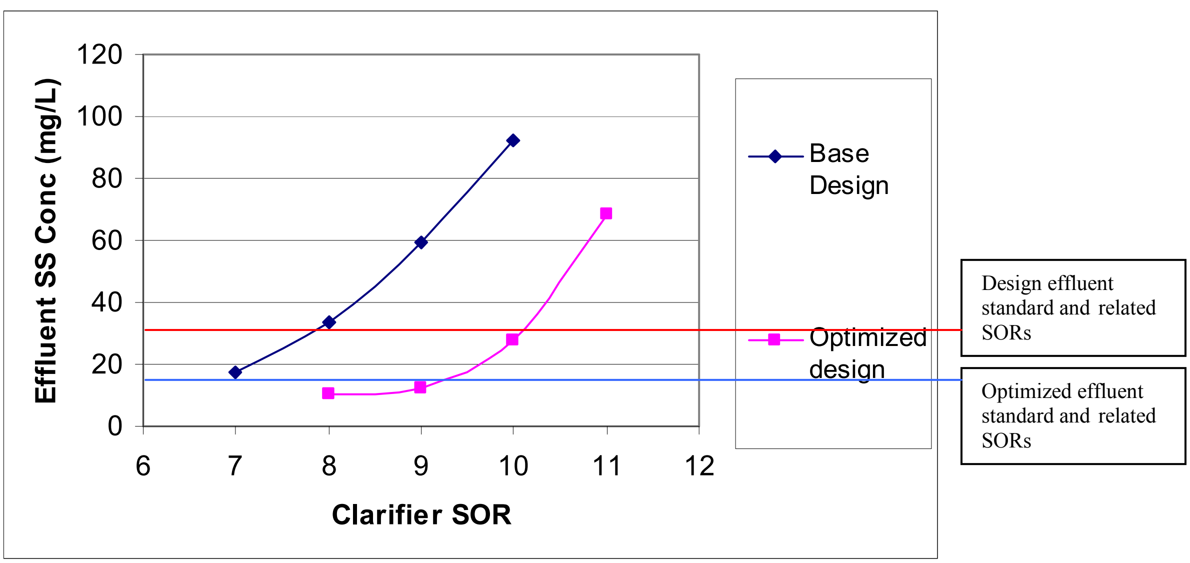


Figure 9 Clarifier flow capacity in base design and optimized alternative
(MLSS = 1000 mg/L and Co = 10 mg/L)

6.5 Operational Cost

Using the clarifier modeling results presented in Figure 9 together with the Phosphorus removal model, the coagulant dosage is less than 40 mg/L in the optimized clarifier under the operation condition with a MLSS of 1000 mg/L and a typical SOR of 9.5 (m3/m2/h). It would be more than 200 mg/L in the clarifier with base design (given Phosphorus removal of 80%).

6.6 Optimized Design Protocols

The operation of BLG WWTP would need about 100 Ton chemicals everyday for the design dosage of 80 mg/L. According to the results of the Phosphorus removal model, for a given Phosphorus removal percentage, the lower solids effluent concentration in the CEPT could substantially reduce the coagulant dosage demanding in a routine operation.

As shown in Figure 9, for the SOR of 10.2 m3/m2/h and MLSS of 1000 mg/L in the optimized clarifier the effluent SS concentration is approximately 30 mg/L, which satisfies the SS Discharge Standard. However, if this SOR value were selected as the clarifier design SOR, the coagulant dosage would be 80 mg/L for the given Phosphorus removal of 80%. The alternative gives lower construction cost due to the smaller tankage but needs a much higher operational cost. To reduce the operational cost, the design SOR may select 9.5 m3/m2/h in order to control the effluent SS below than15 mg/L. In this case, the coagulant dosage needs only 35 mg/L. The cost for coagulant and sludge disposal could be dramatically reduced.

To reduce the chemical dosage to a level of 35~40 mg/L without decreasing the Phosphorus removal percentage, the process SS effluent standard of 15 mg/L should be recommended to replace the conventional standard of 30 mg/L by very limited increasing clarifier footage.

7 Conclusions

The clarifier model has been used in this study to simulate the details of flow and solids fields in a CEPT process. Using the CFD modeling results together with the P removal model presented in this study, the following conclusions can be obtained as:

1. The distance (separation) between the clarifier influent and the effluent in the horizontal direction is very limited due to the limitation of the existing tank length of 17 meters. Therefore, the separation between the influent and the effluent in the vertical direction becomes more critical. The optimized influent baffle provides better influent mixing and isolation than the base design thus; gives significantly enhanced clarification. The modification sufficiently utilizes the deep-water depth of 7.7 meters.

2. To reduce the dosage from 80 to 40 mg/L without decreasing the Phosphorus removal percentage, the system effluent standard of 15 mg/L is recommended to replace the conventional standard of 30 mg/L by lowering clarifier design SOR.

3. In the CEPT process using the optimized design protocols and the existing clarifier design, the coagulant dosage in daily operation could be reduced to 50% of the design value. However, the maximum clarifier SOR is only 6.7 m3/m2/h thus, the alternative needs a bigger tankage.

4. For the CEPT process with both of optimized clarifier design and design protocols, the coagulant dosage in daily operation reduces to more than 50%. The design SOR of optimized clarifier achieves 9.5 (m3/m2/h) while keeping the effluent SS concentration below than 15 mg/L. The optimized design needs a total tankage 19% smaller than that required in the existing design with a poor SS discharge standard of 30 mg/L.

8 References

Zhou, Siping and McCorquodale, J.A., "Modelling of Rectangular Settling Tanks", Vol. 118, No. 10, October 1992, Journal of Hydraulic Engineering, ASCE, pp 1391-1405.

Zhou, Siping, McCorquodale, J.A. and Vitasovic, Z.," Influences of Density on Circular Clarifier with Baffles", Vol. 118, No. 6, Nov./Dec. 1992, Journal of Environmental Engineering, ASCE, pp 829-847.

Table 1 Possible impact factors on Phosphorous and COD removal in the enhanced primary treatment process (SMEDI, 2001)

Date	Sampling time (hour)	SOR (m3/ m2/h)	Return Flow (%)	FeCL3 (mg/L)	Al2(SO4) 3*18H2O (mg/L)	8173 (mg/L)	9901 (mg/L)	AS32 (mg/L)	Inf. COD (mg/L)	Eff. COD (mg/L)	Removal %	Inf. SS (mg/L)	Eff. SS (mg/L)	Removal %	Inf. PO4-P (mg/L)	Eff. PO4-P (mg/L)	Removal %
Operation Conditions of tested pilot unit									Performance								
Jan. 7	4	12.5	0	80		0.33			246	68.8	72.0	154	12	92.2	2.55	0	100.0
	6	12.5	0	80		0.33			390	80.9	79.3	183	34	81.4	4.6	0.32	93.0
Jan. 8	2.5	13	0	60			0.5		198	77	61.1	78	34	56.4	3.41	0.33	90.3
	4.5	13	0	60			0.5		471	71	84.9	270	8	97.0	5.45	0.3	94.5
Jan. 9	3	12.5	0	40			0.5		255	115	54.9	117	3	97.4	2.73	0.43	84.2
	4	12.5	0	40			0.5		221	125	43.4	45	15	66.7	2.59	0.46	82.2
	5	12.5	0	40			0.5								2.59	0.48	81.5
Jan. 10	3	12.5	0	40			0.5		259	108	58.3	99	12	87.9	2.77	0.55	80.1
	4	12.5	0	40			0.5		259	117	54.8				2.77	0.58	79.1
Jan. 11	3.5	12.5	0	50			0.5		245.9	80.9	67.1	164	14	91.5	2.59	0.33	87.3
	5.5	12.5	0	50			0.5		295.2	87.35	70.4	143	46	67.8	2.52	0.48	81.0
	6	12.5	0	50			0.5								3.07	0.58	81.1
Jan. 12	4	12.5	0		60		0.5		637.5	94.2	85.2	263	22	91.6	9.33	0.87	90.7
	6	12.5	0		60		0.5		234.3	105.9	54.8	113	26	77.0	2.74	0.79	71.2
Jan. 13	2.5	12.5	0		60		0.5								3.67	1.05	71.4
	4.5	12.5	0		60		0.5		442.3	263.5	40.4				6.44	3.89	39.6
	5.5	12.5	0		60		0.5		210	101.3	51.8	81	30	63.0	2.81	1.33	52.7
	Mixing		0		60		0.5		273.9	154.1	43.7	110	51	53.6	3.85	1.74	54.8
Jan. 14	4	12.5	0		80		1		698.9	167.5	76.0	168	18	89.3	7.1	1.02	85.6
	5	12.5	0		80		1		301.6	130.1	56.9				3.1	0.65	79.0
	6	12.5	0		80		1		203	89.9	55.7	95	19	80.0	3.19	0.85	73.4
	6.5	7.5			80		1										
	Mixing		0		80		1		371.1	155.8	58.0	155	17	89.0	4.21	0.81	80.8
Jan. 16	4	7.5	0		80		0.5		185.7	90.1	51.5	77	31	59.7	2.77	1.12	59.6
	5	7.5	0		80		0.5		494	90.9	81.6	238	16	93.3	5.86	0.6	89.8

Jan. 17	3	15	0		80		1.5		191	107	44.0	103	19	81.6	2.8	0.57	79.6
	6	15	0		80		1.5		485	114	76.5				5.6	0.53	90.5
	Sampling time (hour)	SOR (m3/ m2/h)	Return Flow (%)	FeCL3 (mg/L)	Al2(SO4)3 *18H2O (mg/L)	8173 (mg/L)	9901 (mg/L)	AS32 (mg/L)	Inf. COD (mg/L)	Eff. COD (mg/L)	Removal %	Inf. SS (mg/L)	Eff. SS (mg/L)	Removal %	Inf. PO4-P (mg/L)	Eff. PO4-P (mg/L)	Removal %
Operation Conditions of tested pilot unit									Performance								
Jan. 18	3	17.5	0		80		1.5		253	136	46.2	96	27	71.9	4	0.7	82.5
	6	17.5	0		80		1.5		201	90.5	55.0	81	20	75.3	3.4	0.7	79.4
Jan. 20	2	17.5	3		70			1	220	105	52.3	112	25	77.7	3.7	0.7	81.1
	4	17.5	3		70			1	301	105	65.1	187	21	88.8	4	0.7	82.5
	6	17.5	3		70			1	620	175	71.8	340	32	90.6	6	1.3	78.3
Jan. 21	2	17.5	3		70			0.8	336	116	65.5	166	30	81.9	4.5	1.1	75.6
	3.5	17.5	3		70			0.8	281	105	62.6	135	24	82.2	3.7	0.8	78.4
	5	17.5	3		70			0.8	223	99	55.6	110	22	80.0	2.8	0.7	75.0
Jan. 22	2	17.5	3		70			0.6	270	100	63.0	138	21	84.8	6.5	0.96	85.2
	4	17.5	3		70			0.6	370	95	74.3	307	15	95.1	6.3	0.87	86.2
	6	17.5	3		70			0.6	315	97	69.2	222	21	90.5	5	0.7	86.0
Jan. 23	2	17.5	3		70			0.4	210	90	57.1	118	20	83.1	5.6	1.04	81.4
	4	17.5	3		70			0.4	188	70	62.8	98	12	87.8	4.7	0.8	83.0
	6	17.5	3		70			0.4	220	86	60.9	125	16	87.2	5.8	1.11	80.9
Jan. 24	2	17.5	3		70			0.2	210	105	50.0	108	60	44.4	7.2	1.3	81.9
	4	17.5	3		70			0.2	425	90	78.8	190	42	77.9	6.3	0.9	85.7
Jan. 25	2	12.5	4		70			0.3	156	36	76.9	132	13	90.2	2	0.18	91.0
	4	12.5	4		70			0.3	115	42	63.5	120	14	88.3	1.8	0.26	85.6
	6	12.5	4		70			0.3	105	38	63.8	100	15	85.0	1.9	0.2	89.5
Jan. 29	2	12.5	4	35				0.3	184	96	47.8	62	9	85.5	1.8	0.3	83.3
	5	12.5	4	35				0.2	592	124	79.1	230	38	83.5	3.8	0.7	81.6
Ave.		14.0		50.0	71.5				303.7	104.4	62.4	145.8	23.1	81.2	4.1	0.8	80.6