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NH_3-N Degradation Dynamics and Calculating Model of Filtration Bed Height in Constructed Soil Rapid Infiltration

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Abstract: The research on Constructed Soil Rapid Infiltration (CSRI) system is in its infancy at home and abroad. There are several details about the mechanism and application of CSRI system needed to be further studied. A major limitation in the current research is the absence of degradation dynamics of pollutants, and the height of filtration bed in CSRI system currently determined by empirical judgment lacks accuracy and logicality. To solve these two problems, the soil column of CSRI system was utilized to treat domestic wastewater, meanwhile, the NH_3-N degradation dynamics were studied according to the Monod equation, the research of Mann A T and the NH_3-N degradation law. Then the mathematical model of filtration bed height was built based on NH_3-N degradation dynamics equation in the soil column. It has been proven that within a limited range this model can calculate the appropriate height of filtration bed accurately in order to optimize technological parameters of hydraulic load and the concentration of influent NH_3-N, improving the effluent quality of CSRI system.

Keywords: degradation dynamics; Monod equation; domestic wastewater; filtration bed height; NH_3-N; constructed soil rapid infiltration

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1 Introduction

Traditional sewage land treating systems suffer from several ubiquitous shortcomings and disadvantages, such as lower hydraulic load rates, lower wastewater treating capabilities per unit area, and being easy to plug (Li and Jiang, 1995; He *et al.*, 2003; Tuncsiper *et al.*, 2009). To overcome the hurdles mentioned above, the constructed soil rapid infiltration (CSRI) system sewage treating was developed based on the summarization of all kinds of land treating systems (Liu, 2006). During the development process, the rapid infiltration land treating system and constructed wetland system were used mainly for reference. By learning from their advantages and offsetting their weaknesses, the CSRI system, a new wastewater treatment technique with special characteristics was designed systematically. However, the research on CSRI system is in its infancy and many of its aspects need to be further studied.

CSRI system accomplishes the purification of wastewater via absorbing, entrapping and decomposing the pollutant in water by the permeating medium or via the microorganism growing on the medium (Sun *et al.*, 2003; Guo *et al.*, 2006). Owing to the unique structure and influent mode of CSRI system, the microorganisms are distributed widely on the surface of the permeating medium. With the variation of influent period, the surface of permeating medium is in the aerobic and anaerobic conditions alternately, and the treatment efficiency is further improved. The whole treatment process with no chemical, mechanical aeration and high energy-consuming equipment in use makes the cost of investment and operation in treatment facilities greatly reduced (Zhang, 2007). The results of previous re-

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searches have shown that this technology has obvious effects on treating urban domestic sewage and polluted surface water, with removal rates up to 85%–90% for COD_{cr}, over 90% for NH_3-N, and over 95% for SS and LAS (Kang *et al*., 2009). Besides, this technology has other characteristics including high hydraulic loading (generally more than 1 m/d), relatively small occupied area compared with traditional land treatment technology, simple technical process, low investment and low operation cost. Therefore, CSRI system with obvious advantages has important application value in wastewater treatment in medium and small cities (Wang *et al.*, 1993; Wang *et al.*, 2010).

Domestic and foreign specialists have done a lot of researches and applications on CSRI system, and obtained some valuable information and results. Through pilot experiments and practical projects, some specialists analyzed the running impacts of the existing CSRI system, and found that the CSRI system built in the southern and eastern parts of China ran normally and stably with high outlet water quality and high capability of buffering the shock load (Liu, 2006; Yao, 2006; Wang *et al*., 2008). Outlet quality indexes, such as COD_{cr}, BOD, SS and NH_3-N could reach Standard A of 'Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant' (GB18918-2002), and retain in long-term running. However, TN and TP could not meet the standards. Ma *et al*. (2008) evaluated the removal efficiencies towards different pollutants in CSRI system, and indicated that removal efficiencies towards turbidity, COD, SS and NH_3-N were excellent while that towards TN and TP was limited. Liu (2008) researched the operation methods of CSRI system in details and found that the removal efficiency towards organics was improved apparently by shortening the influent period, increasing the frequency of influent and drying switch, and enhancing the aeration efficiency of CSRI system. In order to find the reasonable hydraulic loading cycle (HLC) for CSRI system, He *et al*. (2002) investigated the differences between CSRI systems and rapid infiltration (RI) systems, analyzing each aspect affected by HLC adjustment in CSRI system. Then a new method of HLC design was put forward: The flooding period should be small enough to avoid NH_3-N breakthrough while the drying period must be long enough to guarantee the nitrification of most NH_3-N. In order to calculate the optimal filter height, Xu *et al*. (2011) established a mathematical model on the basis of the material balance equation and the organics degradation rule, and found that there was some deviation between the calculated value and the actual value. In order to improve the removal rate of TN and TP, scholars have done a great many researches. Chen (2008) and Zhao (2010) found that COD_{cr}, NH_3-N and TN in effluent could achieve the requirements of Standard A of 'Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant' (GB18918-2002) through growing plants on the surface of CSRI pool and adding sustained release carbon sources into CSRI system. Kang (2006) found that the removal rate of TP could be up to 98.7% when sponge iron was added into the filter materials of CSRI system.

The results mentioned above showed that many scholars have paid attention to the selection of filtrating material, the operation mode, the contamination removal efficiency, *etc*. However, systematic knowledge about the pollutant degradation characteristics in CSRI is still very superficial. Additionally, the filtration bed height of CSRI system is determined mostly by empirical judgment based on some specific treatment goals and requirements, which is inaccurate, unscientific and not rigorous (He *et al.*, 2001; Ye *et al.*, 2008).

With this in mind, our study focused on applying the simulation soil column of CSRI system in treating domestic wastewater and investigating the NH_3-N degradation dynamics characteristics based on Monod equation, the rules of NH_3-N removal in different influent concentration and hydraulic loads. Then mathematical model was built to calculate the appropriate height of CSRI filter layer, which could optimize the CSRI treatment process and provide valuable references for factual design and operation in engineering.

2 Materials and Methods

2.1 Experimental installation

A soil column of CSRI system was built for simulating the practical project. The main body of the soil column reactor contained a PVC pipe with an internal diameter of 21 cm and a height of 210 cm. The filter material included 90% natural sand, 5% marble sand and 5% zeolite sand, and the height of filtration bed was 150 cm. Sampling ports were installed every other 25 cm from top down, and the flow direction was vertically down (Fig. 1).

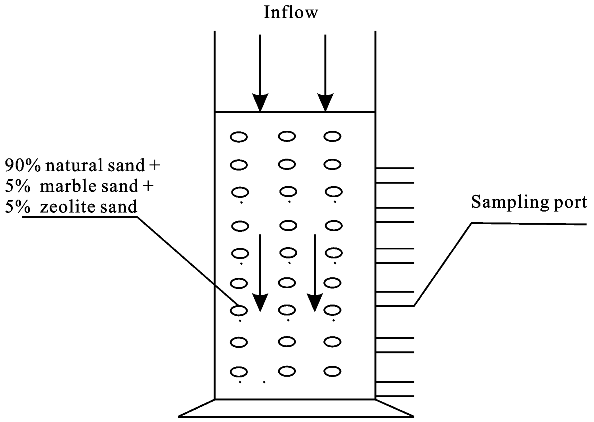

Fig. 1 Experimental installation

2.2 Experimental method

Water tested was the residential quarter wastewater. The concentration of NH_3-N in the undiluted raw water was about 50 mg/L, and the water samples containing NH_3-N with various concentrations were obtained by diluting the raw water. CSRI system started with raw water running for a period, and then showed stable removals of NH_3-N, which meant that it went into regular period. Then the tests were conducted in conditions with different concentrations of influent NH_3-N (tests 1–5) and different hydraulic loads (tests 6–10). In order to observe the degradation rules of NH_3-N when the height of filter layer changes, the residual concentrations of NH_3-N in water samples from sampling ports were detected according to *Methods of Water and Wastewater Monitoring and Analysis* (edition 4) (State Environmental Protection Administration, 2002), and the specific experimental conditions were as follows:

(1) In tests 1–5, the residual concentrations of NH_3-N in different water samples from sampling ports were detected when the concentrations of influent NH_3-N were 41.20 mg/L, 36.24 mg/L, 27.64 mg/L, 18.59 mg/L and 9.50 mg/L, respectively, under different heights of filter layer and invariable hydraulic load (the hydraulic load in these tests was 1 $m^3/(m^2\cdot d)$ or 1 m/d).

(2) In tests 6–10, the residual concentrations of NH_3-N in different water samples from sampling ports were detected when hydraulic load was 2.5 m/d, 2.0 m/d, 1.5 m/d, 1.0 m/d and 0.5 m/d, respectively, under different heights of filter layers and invariable concentrations of influent NH_3-N (the concentration of influent NH_3-N in these tests was 36.24 mg/L).

2.3 Derivation of mathematical models

2.3.1 Derivation of NH_3-N degradation dynamics model

In CSRI system, NH_3-N is removed and degraded by microorganisms ultimately. Therefore, in our study, NH_3-N degradation dynamics model in CSRI system was built based on Monod equation and NH_3-N degradation rules in order to provide the fundamental basis for actual engineering design and operation.

The Monod equation explains the quantitative relationship between growth characteristics of microorganisms and the substrate concentration (Dette *et al.*, 2005; Strigul *et al.*, 2009). Its fundamental equation is as follows (Monod, 1949):

$$\frac{\mathrm{d}s}{\mathrm{d}t} = v_{\max}\frac{xs}{K_s + s} \tag{1}$$

where t is reaction time (1/d); s is substrate concentration (mg/L); x is biomass concentration (mg/L); $v_{\max}$ is maximal specific degradation rate (1/d); K_s is saturation constant (mg/L) (Stanescu and Chen-Charpentier, 2009). When $s \gg K_s$, the kinetics is first-order and as $s \ll K_s$, the kinetics becomes zeroth-order (Monod, 1949).

Monod equation indicates that under low substrate concentrations, the relationship between degradation velocity of substrate and its concentration can be described as a first order relation where the limitative factor of substrate degradation is its concentration. Under these conditions, microorganisms are at the declining multiplication period because of the low substrate concentration. When substrate concentration is high, microorganisms are in the logarithmic growth phase, and substrate is degraded at maximum velocity that is described as zero-order reaction relation; in this situation, there is no relation between substrate concentration and substrate biodegradation rate (Monod, 1949; Sun *et al.*, 2010).

Additionally, the CSRI system is a plug-flow reactor and Mann thought that when it was in a stable state the degradation kinetics of substrate by biofilm conformed to first order reaction of Monod equation (Mann and Stephenson, 1997), thus:

$$\frac{\mathrm{d}s}{\mathrm{d}t} = -K_1 s \tag{2}$$

where biomass is unchangeable when the system stays steady, and K_1 is velocity constant (1/d). This integrates to

$$\ln\frac{s_e}{s_0} = -K_1 t \qquad \text{or} \qquad \frac{s_e}{s_0} = \exp(-K_1 t) \tag{3}$$

where s_0 is influent substrate concentration (mg/L) and s_e is effluent substrate concentration (mg/L).

According to Equation (3), the following equation can be obtained:

$$t = -\frac{1}{K_1}\ln\frac{s_\mathrm{e}}{s_0} \tag{4}$$

where t is relevant to volume load of filter, thus:

$$t = \frac{k}{u} \tag{5}$$

where k is biomass constant (mg/m^3) which is related to volume load and hydraulic feature; u is volume load (mg/(m^3·d)) and can be expressed as:

$$u = \frac{Qs_0}{HA} = \frac{qs_0}{H} \tag{6}$$

where H is the depth from sample ports to filter bed surface (m); A is cross-sectional area (m^2); Q is flow rate (m^3/d).

The following equation is obtained by substituting Equation (3) with Equation (4) and Equation (6):

$$\ln\frac{s_\mathrm{e}}{s_0} = \frac{-K_1k}{u} = -\frac{K_1kA}{Qs_0}H = -\frac{K_1k}{hs_0}H \tag{7}$$

where h is hydraulic load (m/d).

When define

$$\frac{K_1k}{hs_0} = m \tag{8}$$

Equation (7) can be expressed as:

$$\ln\frac{s_\mathrm{e}}{s_0} = -mH \tag{9}$$

where m is the coefficient reflecting the degradation efficiency of pollutant in CSRI system.

2.3.2 Derivation of filter layer height calculation model

With the features (including the surface area, shape, piling pattern and porosity of filter material, the properties of biomembrane, *etc.*) in CSRI system invariable, the values of K_1 and k in Equation (8) are fixed, and the value of m in Equation (9) turns out to be determined by s_0 and h. The effects on the removal efficiency of NH_3-N come from the concentration of influent NH_3-N and hydraulic load in CSRI system should be taken into account and the Equation (8) is revised to:

$$m = \frac{K_1k}{{s_0}^a h^b} \tag{10}$$

where a is a coefficient related to the concentration of influent NH_3-N and b is a coefficient related to the hydraulic load, which are important parameters that reflect the stability of CSRI system (Gao and Gu, 2000), and the variation range of the removal rate of NH_3-N can be affected by a when the s_0 changes within a certain range. Similarly, it can be affected by b when h changes within a certain range.

The fixed value of K_1k can be described as:

$$n = K_1k \tag{11}$$

Then Equation (8) is reduced to:

$$m = \frac{n}{{s_0}^a h^b} \tag{12}$$

where n is a coefficient related to hydraulic load and quality of influent NH_3-N.

The following equations are obtained from equations (9) and (10):

$$\frac{s_\mathrm{e}}{s_0} = \exp\left(-\frac{n}{{s_0}^a h^b}H\right) \tag{13}$$

$$H = \frac{{s_0}^a h^b \ln(s_\mathrm{e}/s_0)}{-n} \tag{14}$$

3 Results

3.1 NH_3-N removal rules in CSRI system

In the initial stage of system operation, the removal of contamination by CSRI filter is mainly due to adsorption and retention, and 15 days later, the concentrations of effluent NH_3-N are stable, which is indicative of successful membrane hanging, and then the removal of NH_3-N owes to microbial degradation. Towards the whole CSRI system, retention and adsorption act as a cushion, and the removal of NH_3-N mainly depends on the degradation by microorganisms (Mu *et al.*, 2003).

As shown in Table 1, when the hydraulic load is 1 m/d, and the concentrations of influent NH_3-N vary from 9.50 mg/L to 41.20 mg/L, the removal rates of NH_3-N by different depths of filter layers in the CSRI system are disparate, which decrease exponentially along the depth of filter layer. The degradation of NH_3-N mainly occurs in the upper filter layer: the removal rate of NH_3-N comes up to about 50% and 70% of the total removal rate in 0–50 cm section and 0–75 cm section of CSRI system, respectively. In the upper filter layer, the microorganisms multiply fast because of the large quantity of nutrient density in wastewater and the relatively high removal rate of NH_3-N. Then the removal rate of NH_3-N descends gradually along with the increasing height of the filter layer because of the lower concentration of remaining NH_3-N and the slower propagating rate of microorganisms in the bottom filter section. A similar trend of variation in self-purification of polluted rivers has been found. In CSRI system, the total removal rate of NH_3-N increases with the increase of the concentration of inflow NH_3-N. For example, the total removal rate of NH_3-N is 67.58% under inflow NH_3-N with the concentration of 9.5 mg/L with corresponding effluent concentration of 3.08 mg/L, while the total removal rate of NH_3-N reaches 83.86% under inflow NH_3-N with concentration increasing to 41.2 mg/L with corresponding effluent concentration of 6.65 mg/L. The effluent concentration of NH_3-N is relatively stable, which can be accorded with the first class of Standard A in 'Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant' (GB18918-2002). Overall, the CSRI system shows high and stable removal efficiency of NH_3-N in the concentration range and a strong anti-shock capability under a high load.

Learned from Table 2, with the invariable concentration of inflow NH_3-N, the increasing of hydraulic load results in curtate times of sewage retention in filter layer and biochemical reaction among microorganism, then it leads to the decrease of water quality. The total removal rate of NH_3-N in CSRI system comes up to 91.97% when the hydraulic load is 0.5 m/d and the concentration of influent NH_3-N is 36.24 mg/L, however, the removal rate of NH_3-N drops to 64.40% when the hydraulic load increases to 2.5 m/d and the concentration of effluent NH_3-N is 12.90 mg/L.

3.2 Solution of model parameter (*m*)

The parameter m in Equation (9) reflects the removal efficiency of NH_3-N in CSRI system. Under the invariable features (including the surface area, shape, piling pattern and porosity of filter material, the properties of biomembrane, *etc*.) in CSRI system, the value of m is determined by the hydraulic load and the concentration of influent NH_3-N.

According to the analyses above, the relationship between the ratios of s_e (the concentrations of effluent NH_3-N from sampling ports) and s_0 (the concentrations of influent NH_3-N) and H (the depth of sampling ports) can be expressed as an equation of the exponential form. Under a series of changing s_0 or h (hydraulic load), with s_e/s_0 as ordinate and H as abscissas, the software Origin,

Table 1 Residual concentrations of NH_3-N in water samples at different heights of filter layer with hydraulic load of 1 m/d

Test ordinal	NH_3-N concentration (mg/L)						
	0 cm1)	25 cm	50 cm	75 cm	100 cm	125 cm	150 cm
1	41.20	30.57	22.42	16.20	12.60	9.30	6.65
2	36.24	27.90	20.88	14.94	11.68	8.71	6.43
3	27.64	21.65	16.98	12.99	9.39	7.47	5.62
4	18.59	14.56	11.59	8.83	6.77	5.68	4.86
5	9.50	7.12	6.15	5.64	4.10	3.35	3.08

Note: 1) The residual concentrations of NH_3-N at 0 cm were the same as the concentrations of influent NH_3-N

Table 2 Residual concentrations of NH_3-N in water samples at different heights of filter layer

Test ordinal	Hydraulic load (m/d)	NH_3-N concentration (mg/L)						
		0 cm1)	25 cm	50 cm	75 cm	100 cm	125 cm	150 cm
6	2.5	36.24	33.2	27.94	22.83	19.65	16.92	12.90
7	2.0	36.24	31.8	25.76	20.87	17.15	13.79	9.50
8	1.5	36.24	29.11	23.30	18.45	15.45	10.00	8.00
9	1.0	36.24	27.90	20.88	14.94	11.68	8.71	6.43
10	0.5	36.24	23.80	15.53	9.50	6.90	5.01	2.91

Note: 1) The residual concentrations of NH_3-N at 0 cm were the same as the concentrations of influent NH_3-N, which were invariable a data analysis and science drawing software, was applied to fit the values of s_e/s_0 and H in the form $s_e/s_0 = \exp(-mH)$ to work out the value of m.

Data of tests 1–5 in Table 1 and tests 6–10 in Table 2 were fitted as shown in Fig. 2 and Fig. 3, and the value of m solved and relevant parameters were listed in Table 3.

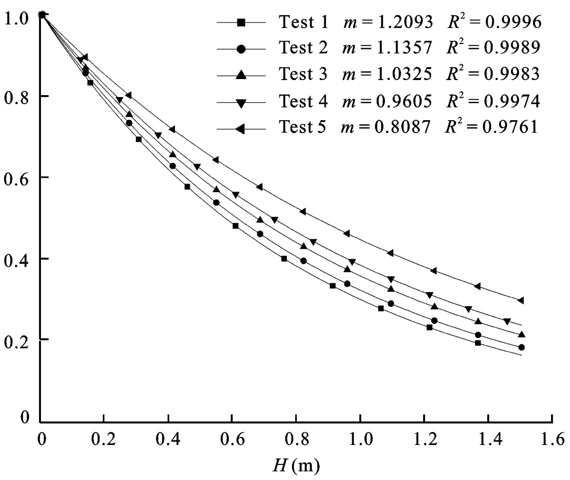

Fig. 2 Fitting curve between H and s_e/s_0 of tests 1–5

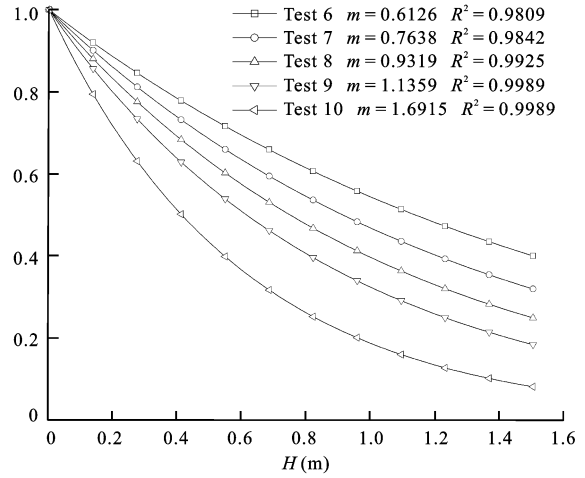

Fig. 3 Fitting curve between s_e/s_0 and H of tests 6–10

All values of R^2 of fitting curves are greater than 0.97 in tests 1–10 shown in Table 3, which is indicative of the feasibility of using Equation (9) to express the degradation dynamics of NH_3-N. In tests 1–5, the correlation equation $m = 0.0977s_0 + 0.7364$ ($R^2 = 0.9815$) was obtained via fitting s_0 and m according to linear function, while $m = -0.6571\ln h + 1.6562$ ($R^2 = 0.9915$) was obtained via fitting h and m according to logarithmic function in tests 6–10. The value of m reflects the removal efficiency of NH_3-N in CSRI system. With the invariable hydraulic load, the removal rate of NH_3-N and the value of m increases simultaneously with the concentration of influent NH_3-N increasing, on the other hand, with the invariable concentration of influent NH_3-N, the removal rate of NH_3-N and the value of m decrease simultaneously with the hydraulic load increasing.

3.3 Calculation model of filter layer height

Usually, in CSRI system, the pollution removal rate increases with the height of the filter layer. However, the increasing of the height of the filter layer will result in more cost in investment. Therefore, designing an appropriate and economic height of filter layer is the most central for setting up a CSRI system. The height of filter layer is designed generally according to experience, which is short of accuracy and logicality. Hu *et al.* (2010) found that NH^+_4-N, compared with organics, was much easier penetrating through the filter layer. Therefore, the Equation (14) was built on basis of NH_3-N degradation dynamics equation to calculate the appropriate height of the CRIS filter layer in this research.

The values of model parameters n, a and b can be obtained from the test data (Fig. 1 and Fig. 2):

(1) Calibration of n and a

According to $m = ns_0^{-a}h^{-b}$, when h is 1 m/d, $m = ns_0^{-a}1^{-b} = ns_0^{-a}$, with the values of s_0 as abscissa and m as ordinate, the software Origin is used to fit the relation

Table 3 Relevant parameters of fitting curve between H and s_e/s_0 of tests 1–10

Test ordinal	Influent NH_3-N concentration (mg/L)	NH_3-N removal rate (%)	m	R^2	Test ordinal	hydraulic load (m/d)	NH_3-N removal rate (%)	m	R^2
1	41.20	83.86	1.2093	0.9996	6	2.5	64.40	0.6126	0.9809
2	36.24	82.26	1.1359	0.9989	7	2.0	73.79	0.7638	0.9842
3	27.64	79.67	1.0325	0.9983	8	1.5	77.92	0.9313	0.9925
4	18.59	73.86	0.9605	0.9974	9	1.0	82.26	1.1357	0.9989
5	9.50	67.58	0.8087	0.9761	10	0.5	91.97	1.6915	0.9989

curve between s_0 and m (tests 1–5 in Table 3) in the forms of $m = ns_0^{-a}$ to work out the values of n and a (the fitting curve is shown in Fig. 4).

Then we get the values from Fig. 4: n = 0.4373, a = –0.2678 and R^2 = 0.9754.

(2) Calibration of b

When s_0 is 36.24 mg/L, $ns_0^{-a} = 0.4373 \times 36.24^{0.2678} = 1.1436$, $m = 1.1436h^{-b}$ is obtained, with the values of m as ordinate and h as abscissa, the software Origin is applied to fitting the relation curve between m and h (tests 6–10 in Table 3) in the form of m / 1.1436 = h^{-b} to work out the value of b (the fitting curve is shown in Fig. 5). Learning from Fig. 5, b = 0.5826 and R^2 = 0.9934, which means that the results of data fitted are creditable. Under this experimental condition, the calculating model of the height of the filtration bed is obtained by substituting the values of n, a and b into Equation (14):

$$H = \frac{s_0^{\,a}h^b\ln(s_e/s_0)}{-n} = \frac{h^{0.5826}\ln(s_e/s_0)}{-0.4373s_0^{0.2678}} \qquad (15)$$

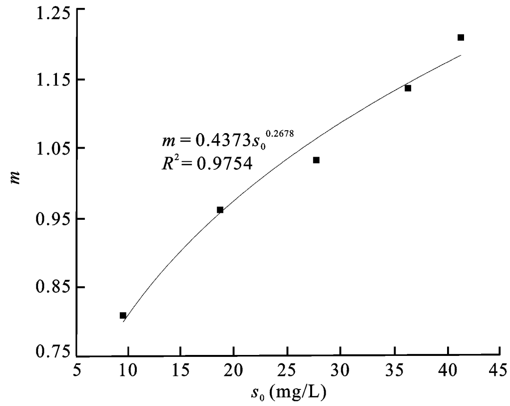

Fig. 4 Fitting curve between s_0 and m

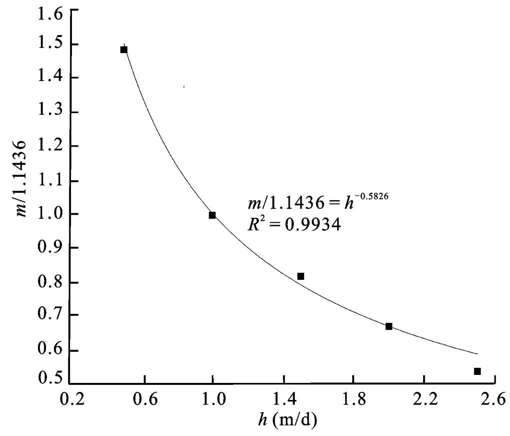

Fig. 5 Fitted curve between h and m/1.1436

3.4 Verification of calculation model of filter layer height

When the simulation soil column of CSRI system worked under five different concentrations of influent NH_3-N and hydraulic load (including test 11: s_0 = 80.21 mg/L, h = 3 m/d; test 12: s_0 = 39.25 mg/L, h = 2 m/d; test 13: s_0 = 30.51 mg/L, h = 1 m/d; test 14: s_0 = 21.48 mg/L, h = 0.5 m/d; test 15: s_0 = 12.51 mg/L, h = 0.75 m/d), the residual concentrations of effluent NH_3-N from certain height of the simulation soil column were detected. Then results were substituted into Equation (15) to calculate the corresponding height of the filtration bed. The actual values of H were compared with the corresponding calculated values (Fig. 6).

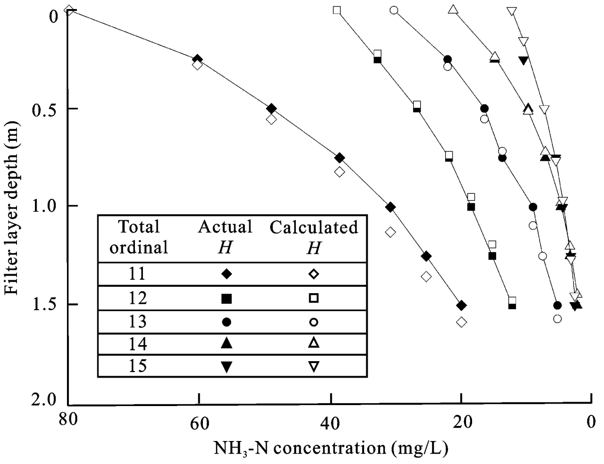

Fig. 6 Comparison between actual values and calculated values of filter layer height

As indicated in Fig. 6, H calculated by Equation (15) under the condition that tests 11–15 are in accordance with the corresponding actual H, which means that the economical and appropriate height of filter layer can be worked out by Equation (15) accurately according to the hydraulic load, the concentrations of influent NH_3-N and the effluent quality in CSRI system. The parameters of Equation (15) are calibrated under the influent NH_3-N with concentrations of 9.50–41.20 mg/L and the hydraulic load of 0.5–2.5 mg/d. Although the concentration of influent NH_3-N and hydraulic load in test 11 exceed the calibrated range of model, the deviation between calculated values of height and the corresponding actual values is small, which shows that the CSRI system has a strong anti-shock capability under the high load of NH_3-N.

4 Conclusions

NH_3-N degradation dynamics in CSRI system was investigated systematically and the model used for acquiring economical and appropriate height of filter layer was built successfully. In general, we summarize the conclusions of this study as follows:

(1) Within certain concentration range of NH_3-N, the degradation of NH_3-N occurs mainly in the upper filter layer and the total removal rate of NH_3-N is proportional to the concentration of inflow NH_3-N. It descends gradually along with the increasing height of the filter layer, which is shown in an exponential form relationship. The increaseof the hydraulic load can result in the increase of the outlet water amount and the decrease of water quality under invariable concentration of inflow NH_3-N. The CSRI system shows high and stable removals ability of NH_3-N and a strong anti-shock capability under high load of NH_3-N.

(2) Based on the removal rules of NH_3-N and Monod equation, herein we come up with the NH_3-N degradation dynamics equation: $s_e/s_0 = \exp(-mH)$. Meanwhile, through calibrating parameter m using the experimental data, we obtained different equations which decide the value of m. The value of m is proportional to the concentration of influent NH_3-N, which can be expressed as $m = 0.0977s_0 + 0.7364$ (in tests 1–5); the removal rate of NH_3-N and the value of m both decrease with the increase of the hydraulic load which can be expressed as $m = -0.6571\ln h + 1.6562$ (in tests 6–10).

(3) The model of the filter layer height in CSRI system was built based on the NH_3-N degradation dynamics. The experiment results show that the economical and appropriate height of the filter layer can be calculated accurately by the model according to the hydraulic load, the concentrations of influent NH_3-N and the effluent quality in CSRI system.

(4) The model of the filter layer height is representative and can serve for the actual project because it was proposed through actual test. However, because some hypotheses were taken into account during the calculation process, there will be some deviations between the actual results and the calculational results. Therefore, when the external conditions change in actual project, the parameters of the model must be revised based on the actual characteristics of the filter layer and the reactor.

(5) The model is only on the basis of degradation rules of NH_3-N. In order to set up and improve the database of CSRI system, the degradation rules of organic pollutant, TP and so on will be used to build the mathematical model for calculating the appropriate filter layer height in CSRI system in further research.

References

Chen Junmin, 2008. *A Study on the Mechanism of Constructed Rapid Infiltration System and the Application for Rural Domestic Sewage Treatment*. Chengdu: Southwest Jiaotong University. (in Chinese)

Dette H, Melas V B, Pepelyshev A *et al.*, 2005. Robust and efficient design of experiments for the Monod Model. *Journal of Theoretical Biology*, 234(4): 537–550. doi: 10.1016/j.jtbi.2004.12.011

Gao Tingyao, Gu Guowei, 2000. *Water Pollution Control Engineering*. Beijing: The Higher Education Press. (in Chinese)

Guo Jingsong, Wang Chunyan, Fang Fang *et al.*, 2006. Applicability study of CRI treating sewage in the Three-Gorges reservoir region. *Environmental Science*, 27(11): 2327–2332. (in Chinese)

He Jiangtao, Zhong Zuoshen, Tang Minggao, 2001. New method of solving contradiction of rapid infiltration system land use. *Geosciences*, 15(3): 339–345. (in Chinese)

He Jiangtao, Duan Guangjie, Zhang Jinbing *et al.*, 2002. Discussion on hydraulic loading and effluent effect in wastewater infiltration land treating systems. *Earth Science-Journal of China University of Geosciences*, 27(2): 203–208. (in Chinese)

He Jiangtao, Ma Zhenmin, Zhang Jinbing *et al.*, 2003. Discussion on the problem of clogging in wastewater infiltration land treating systems. *China Environmental Science*, 23(1): 85–89. (in Chinese)

Hu Baowei, Cheng Wen, Han Zhen *et al.*, 2010. Experimental study on degradation law of organic matter and ammonia nitrogen in biological aerated filter. *Journal of Hydraulic Engineering*, 41(3): 374–378. (in Chinese)

Kang Aibin, 2006. *A Study of Removal Phosphorus and Severa Stages Treatment Process on CRI*. Beijing: China University of Geosciences. (in Chinese)

Kang Aibin, Zhu Ming, Chen Honghan *et al.*, 2009. Treatment of simulated livestock wastewater by constructed rapid infiltration system. *China Water & Wastewater*, 25(19): 65–67. (in Chinese)

Li Xianfa, Jiang Chuncai, 1995. Constructed wetland systems for water pollution control in North China. *Water Science and Technology*, 32(3): 349–356.

Liu Jiabao, 2006. *Study on Contaminant Removal Mechanism and Efficiency of Constructed Rapid Infiltration System*. Beijing: China University of Geosciences. (in Chinese)

Mann A T, Stephenson T, 1997. Modeling biological aerated filters for wastewater treatment. *Water Research*, 31(10): 2443–

2448.

Ma Limin, Liu Cong, Cui Chengying *et al.*, 2008. Optimizing operational parameter of constructed rapid infiltration system in urban wastewater treatment. *Technology of Water Treatment*, 34(6): 41–57. (in Chinese)

Monod J, 1949. The growth of bacterial cultures. *Annual Review of Microbiology*, 3: 371–394. doi: 10.1146/annurev.mi.03.100149.002103

Mu Xinmin, Huang Peihong, Zhang Jinbing, 2003. An on-site experimental study on the treatment of Maozhou river water by constructed rapid infiltration system in Shenzhen. *Journal of Basic Science and Engineering*, 11(4): 370–377. (in Chinese)

Stanescu D, Chen-Charpentier B M, 2009. Random coefficient differential equation models for bacterial growth. *Mathematical and Computer Modelling*, 50(5–6): 885–895. doi: 10.1016/j.mcm.2009.05.017

State Environmental Protection Administration, 2002. *Methods of Water and Wastewater Monitoring and Analysis* (edition 4). Beijing: China Environmental Science Press. (in Chinese)

Strigul N, Dette H, Melas V B, 2009. A practical guide for optimal designs of experiments in the Monod Model. *Environmental Modeling & Software*, 24(9): 1019–1026. doi: 10.1016/j.envsoft.2009.02.006

Sun Jing, Guo Wei, Li Xiaoning *et al.*, 2003. Optimization of nitrogen and phosphorus removal from municipal sewage by rapid infiltration land treatment system. *Urban Environment & Urban Ecology*, 16(6): 32–33. (in Chinese)

Sun Kaibiao, Tian Yuan, Chen Lansun *et al.*, 2010. Nonlinear modelling of a synchronized chemostat with impulsive state feedback control. *Mathematical and Computer Modelling*, 52(1–2): 227–240. doi: 10.1016/j.mcm.2010.02.012

Tuncsiper B, Ayaz, S C, Gunes K, 2009. A serial-operated constructed wetland system to control water pollution. *Fresenius Environmental Bulletin*, 18(9): 1648–1653.

Wang Dongbo, Zhang Ziyun, Li Xiaoming *et al.*, 2010. A full-scale treatment of freeway toll-gate domestic sewage using ecology filter integrated constructed rapid infiltration. *Ecological Engineering*, 36(6): 827–831. doi: 10.1016/j.ecoleng.2010.03.005

Wang Ming, Wu Yongfeng, Zhong Zuoshen, 1993. *Wastewater Rapid Infiltration Land Treatment*. Beijing: Geological Publishing House. (in Chinese)

Wang Chunyan, Guo Jinsong, Wang Fei *et al.*, 2008. Influence study of constructed rapid infiltration system constructed by purple soil on sewage nitrogen removal performance. *Journal of Chongqing University*, 31(6): 688–693. (in Chinese)

Xu Wenlai, Zhang Jianqiang, Liu Yun, 2011. Organic matter degradation kinetics and filter layer height calculation model in constructed rapid infiltration system. *Fresenius Environmental Bulletin*, 20(4): 37–45.

Yao Ruoxu, 2006. *Construction of the Constructed Rapid Infiltration and Its Application Study in Three-Gorges Reservoir Region*. Chongqing: Chongqing University. (in Chinese)

Ye Jianfeng, Xu Zuxin, Li Huaizheng, 2008. Dynamic rule of organic matter removal in vertical-flow constructed wetland. *Environmental Science*, 29(8): 2166–2171. (in Chinese)

Zhang Quan, 2007. *Lab-scale Study on Two Stages Constructed Rapid Infiltration System Applied in Livestock Husbandry Wastewater*. Beijing: China University of Geosciences. (in Chinese)

Zhao Fuxiang, 2010. *Study on the Technology of High Concentration Domestic Sewage Treatment by Ecology Constructed Rapid Infiltration System* (*ECRI*). Beijing: China University of Geosciences. (in Chinese)

Zheng Yi, 2008. *Studies on Constructed Rapid Infiltration System at Various Oxygen Supply Conditions*. Changsha: Hunan Normal University. (in Chinese)