Refitted inclined plate for improving suspended solids removal in standard storm-water sumps

Yiping Zhang, Anchao Chen, Ping Zhang, Yongchao Zhou and Tuqiao Zhang

ABSTRACT

Suspended solids (SS) in the storm-water makes up a significant source of total suspended solids in wet weather flow. With appropriate modification and maintenance, the standard sumps in the drainage system can remove SS from storm-water runoff as a best management practice device. To increase the removal efficiency, especially in the condition of high flow rate, inclined plates, based on the shallow pool sedimentation theory, have been designed and refitted to the sump. Its performance under the different surface load and flow rate were evaluated through scale models. The results show that the preliminary design, Model A, had limited removal efficiency, and even played a negative role sometimes due to the concentrated flow in the axis. The optimizations through installing a non-uniform porous baffle (Model B) and adopting inverted V-shaped plates (Model C) were improved, and results show that removal efficiency rate can be increased by around 15–20%, even at high flow rates. Moreover, too many plates cannot improve the removal rate further, because they make the cross-section decline and lead to higher velocity between plates.

Key words | inclined plate sedimentation, refitted sump, storm-water management, suspended solids removal

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INTRODUCTION

Storm-water runoff on receiving waters is recognized as an important problem in urban water environments. After rainfall, the inputs may contribute to a variety of receiving water pollutants such as nutrients, suspended solids (SS), pathogens, metals and synthetic organics (Chebbo & Gromaire 2004; Rossi *et al.* 2006; Pongmala *et al.* 2015). Meanwhile, the SS in storm-water was confirmed to be a good carrier for many pollutants, such as nutrients, toxic metals, metalloids and synthetic organics, and more than 80% of these compounds are linked to SS (Chebbo & Bachoc 1992; Zhou *et al.* 2017). Moreover, the SS themselves will cause many problems, increasing the turbidity of the receiving water, resulting in decreased activity and growth of the photosynthetic organisms, after settling in water. They will pose a long-term threat because of their oxygen demand and gradual accumulation of toxic pollutants (Aryal *et al.* 2010). Thus, the SS are considered as an important index for evaluating pollution, and the removal of SS from storm-water runoff has great significance to the urban water environment.

In the last decades, a variety of storm-water best management practices such as infiltration basins, detention ponds, bioretention, constructed wetlands and underground devices have become popular in many countries (Boogaard *et al.* 2017; Macnamara & Derry 2017; Smolek *et al.* 2017). Among them, underground devices including hydrodynamic separators, underground settling devices and filters are attractive for removing SS from storm-water runoff in dense urban areas because they have a small footprint (Wilson *et al.* 2009). Many studies have been carried out to understand how well these devices remove particulates from storm-water (Carlson *et al.* 2006; Howard *et al.* 2011; Lucas & Babatunde 2017). Saddoris *et al.* (2010) noted that the removal capability of these devices largely depends on the designer's special designs and the later maintenance program.

Recently, it has been recognized that standard sumps, which have already been commonly installed in storm-water collection systems, can remove the SS in storm-water. Faram & Harwood (2003) indicated that a standard sump

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has a slightly better ability for removing SS than catch basins, so a simple retrofit to increase SS retention during large storms would be useful. Howard *et al.* (2012) designed a porous baffle, named the SAFL baffle, which was tested as a retrofit to the sump. Two structures proposed by Ma & Zhu (2015) were found to be effective in SS removal. However, these retrofits had limited removal efficiency under high flow or had high water head loss, which will increase urban flood risk during rainstorms. Moreover, it is important to consider the cost of maintenance and sustainability during the design of the devices (Marques & Berg 2011; Marques *et al.* 2015).

The objective of this study is to explore the new designs to modify standard sumps. A preliminary design was tested and then two improved designs were considered, which can improve the SS removal efficiency under the high flow rate, and also the water head loss was evaluated. The structure designs are based on the shallow pool theory which was proposed by Hazen and widely used in sedimentation tank design for removing SS.

METHODS

Experiment setup and materials

A model was set up based on the Froude number similarity criteria, as the flow in our study typically has large Reynolds number and the effect of viscosity is negligible. For a prototype of a 1.2 m square sump with a depth of 1.2 m, the model was constructed of methyl methacrylate at the scale of $L_r =$ 2.67 (where L_r is the model scale), and the discharge ratio $Q_r = L_r^{2.5} = 11.61$. Thus, the model consisted of a square sump of 450 mm in length and a total height of 900 mm, with 150 mm in diameter for the inlet and outlet pipes as shown in Figure 1, respectively. The effluent water from the model would be treated through a filter and discharged to a water tank and then recycled by an electric pump. The flow rate was controlled by a valve and measured by a magnetic flow meter.

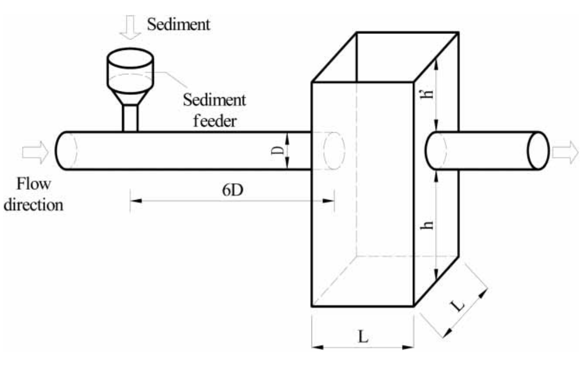

Figure 1 | Sketch of the standard sump model setup; $L = 450$ mm, $h = 450$ mm, $h' = 300$ mm, $D = 150$ mm.

Model sand was used to simulate the SS in the experiments, with true density of 1.42 g/cm^3. Its size distribution was analyzed by a Malvern-MS2000 as shown in Figure 2, and the particle size of the model sand is mainly distributed in 150–325 μm, and the median particle diameter is 240 μm. In each test, a total of 2,000 g model sand was fed from a sand feeder located at 0.9 m upstream of the inlet pipe from the sump and its mass flow rate was controlled at a pre-determined rate by adjusting the feeder bottom opening size. The model sand was suspended and well mixed before it entered the sump. Meanwhile, the water surface elevation of the inlet and outlet was measured with a laser range finder in order to calculate energy loss. At the end of each test, the model sand captured in the sump was dried and weighed; a mass balance approach (Wilson *et al.* 2009) was used in the experiment to assess the SS removal efficiency, which is given by Equation (1):

$$\eta = \frac{m}{M} \times 100\% \qquad (1)$$

where η = removal efficiency (%), m = the mass of model sand captured in the sump (kg); M = total mass of model sand (kg).

Model designs

Increasing the flow time in standard sumps and reducing the flow velocity (Ma & Zhu 2015) and the required settling

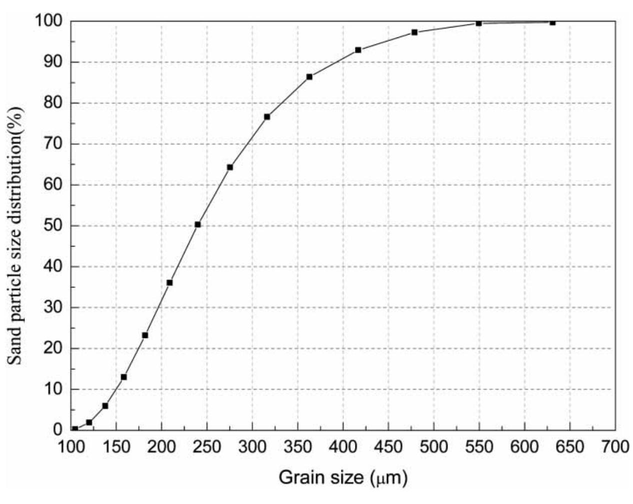

Figure 2 | The particle size distribution of the model sand.

height of particles can improve the removal efficiency of SS. Based on shallow pool sedimentation theory (Hansen & Culp 1967), a preliminary design named Model A was studied at first. The side flow lamella was adopted in Model A, as shown in Figure 3(a), due to its low water head loss. The plate was 30 cm × 26 cm with the thickness of 3 mm and the horizontal angle of 60°. Model A with different number of inclined plates represents different

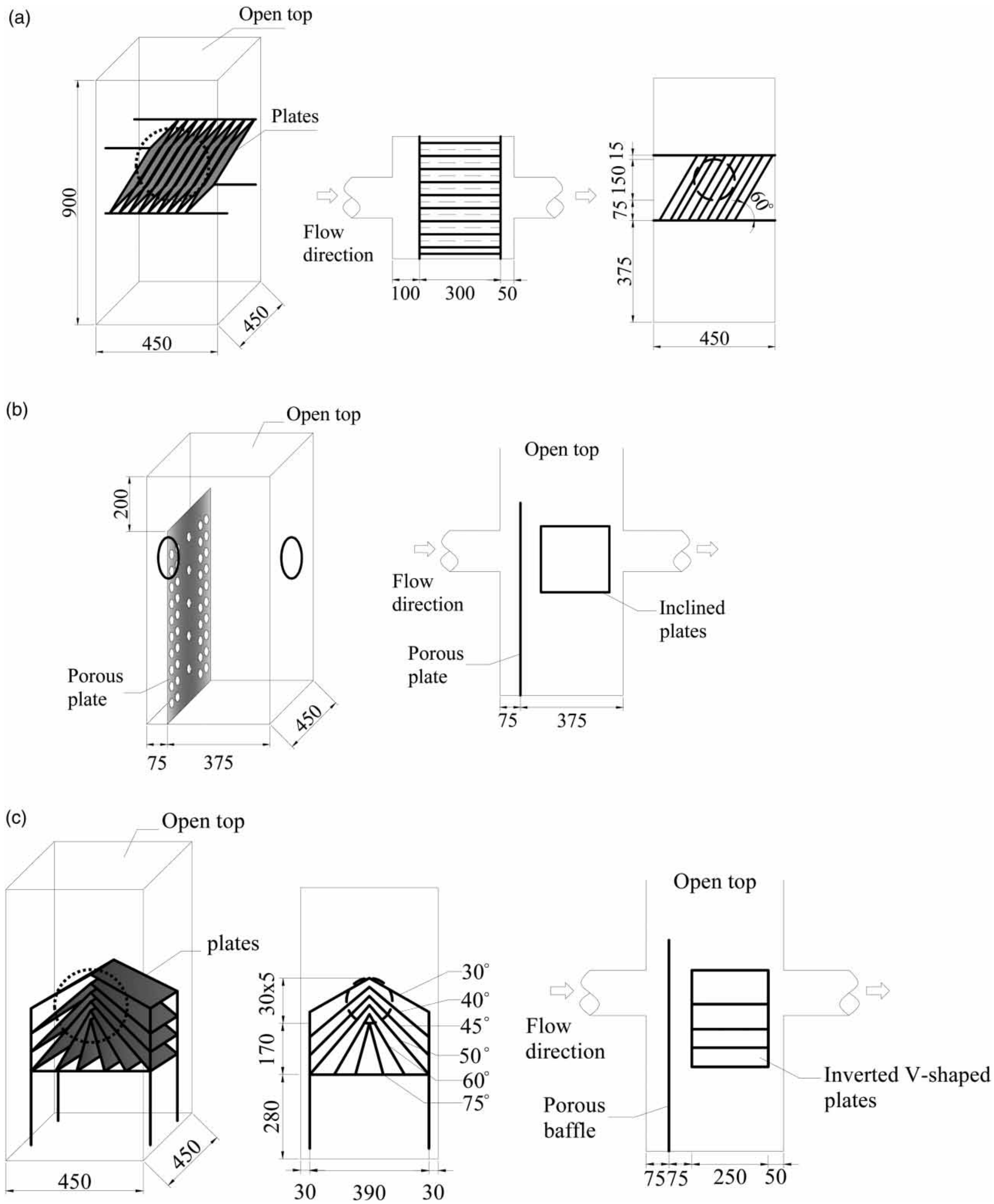

Figure 3 | The design of the Model A (a): general plan (left), plan view (middle), across section view (right); and improved equipment designs of Model B (b) and Model C (c). All dimensions are in millimetres.

surface loads (q (m^3/m^2.h)) and it can be calculated by the Equations (2) and (3):

$$q = \frac{Q}{A + nA_0} \tag{2}$$

$$A_o = A_1 \cos\theta \tag{3}$$

where A (m^2) is bottom area of the original sump, Q (m^3/h) is flow rate, A_1 (m^2) is inclined plate area, θ and n are the horizontal angle and number of the plates.

Based on the experiment and observation of the preliminary design, two improved equipment models, Model B and Model C, were proposed, as shown in Figure 3(b) and 3(c). The non-uniform porous baffle was 450 mm × 700 mm, with the porosity of 15%, vertically placed 75 mm away from the inlet side, leaving 20 mm under the open top of the sump. It was designed to avoid 'short circuit' flow, and helped flow to distribute uniformly in the sump. The inverted V-shaped plate was to increase the utilization of the plate area. All structures mentioned above were tested under the flow rate of 5.0, 6.0, 7.0, 8.0 and 9.0 L/s respectively, Meanwhile, the water surface elevation of the inlet and outlet was also measured.

RESULTS AND DISCUSSION

Preliminary design

Figure 4 gives the results of SS removal efficiency for the Model A (A-1, A-2, A-3, A-4 represents the model with different number of the inclined plates) and the original sump. Under the flow rate of 5.0–9.0 L/s, the removal efficiency of the original sump was 52.7%, 39.0%, 31.1%, 22.8% and 17.9% respectively. At low flow rates (5.0–6.0 L/s), Model A can increase SS removal rate by around 5–10%, but at high flow rates (more than 7.0 L/s), the plates had limited removal efficiency. They even played a negative role sometimes. This is mainly because the refitted inclined plates make the flow much more concentrated along the axis compared with the original model, and the diffusion of both sides was not obvious especially in the high flow rate condition as shown in the Figure 5. Therefore, in the case of low flow rate, the refitted inclined plates can improve the removal efficiency of SS. However, the plates will make the 'short circuit' flow more serious and it does not work in the condition of high flow rate. So significant removal of SS was difficult. On the other hand, the cross-section space cannot be efficiently utilized in the arrangement of inclined plates in the sump. It is also the reason why Model A cannot improve its surface load further, so SS removal rate also cannot be increased.

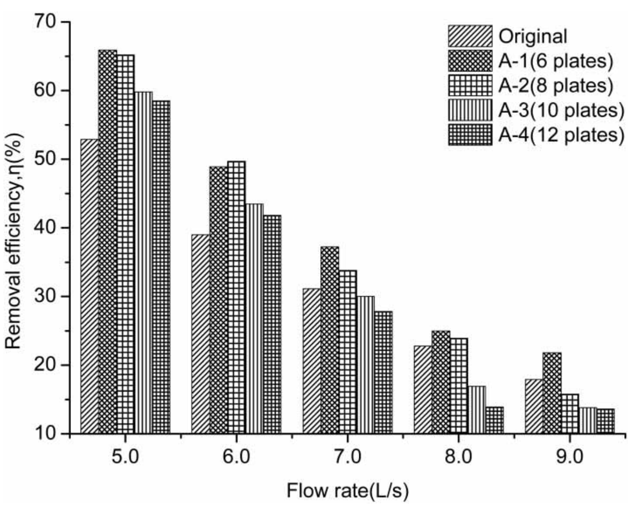

Figure 4 | The SS removal efficiencies for structure A with a different number of inclined plates and the original sump.

Based on the above analysis, a non-uniform porous baffle was designed, to install in the sump, which can distribute the flow uniformly in the whole cross-section of sump as shown in Figure 3(b) (Model B). In addition, an inverted V-shaped inclined plate was presented to improve the space utilization rate of the sump to improve it surface load further as shown in Figure 3(c) (Model C).

Improved design

The SS removal efficiency of the improved Model B (B-1, B-2, B-3, B-4 represent the model with different number of the inclined plates) and Model C is shown in Figure 6. Under different flow rates, the improved Model B-3 and Model C performed better than Model A-3 and the original structure, although those models have same plate area (surface load). In contrast to the original sump, Model B-3 and Model C can increase removal efficiency rate by around 15–20%, even at high flow rates. The results indicate that all inclined plates have played a role in SS removal after installation of the non-uniform porous baffle.

The improved removal efficiency can be defined as Equation (4):

$$\eta_{\text{improved}} = \eta_{B(C)} - \eta_{\text{original}} \tag{4}$$

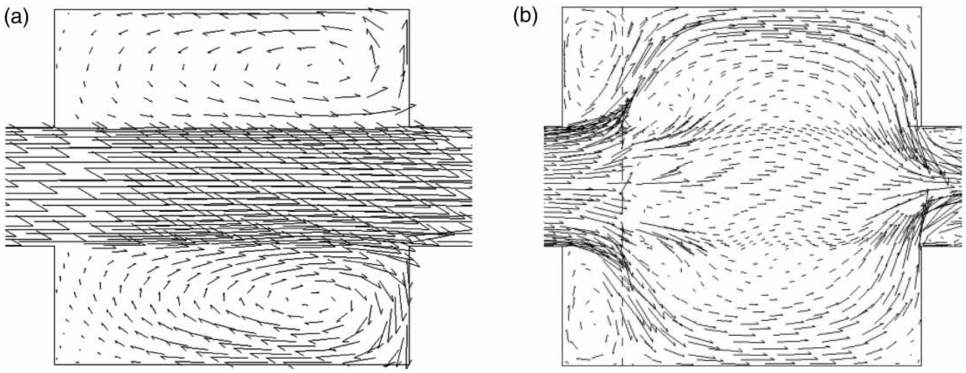

Figure 5 | Flow patterns in the standard sump model (a) without porous plate and (b) with porous plate for the flow rate of 7.0 L/s.

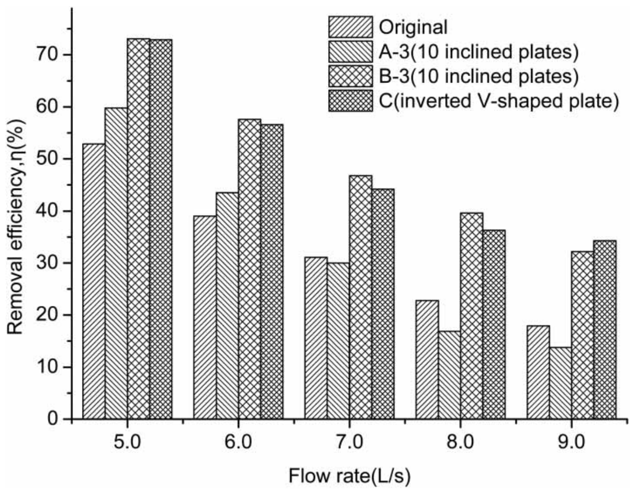

Figure 6 | The SS removal efficiencies for the original sump, preliminary design Model A-3, Model B-3 and Model C.

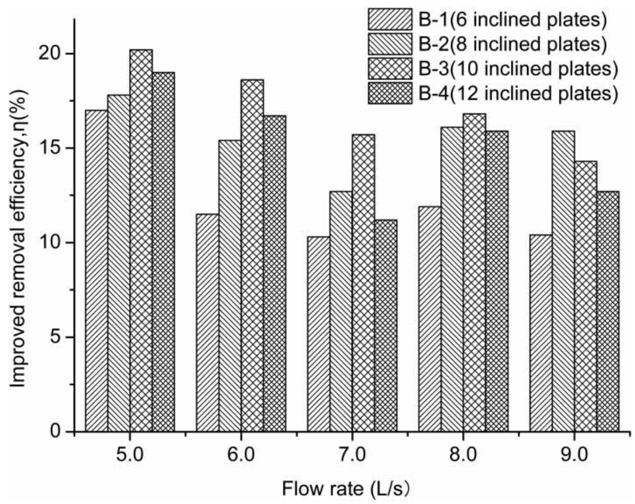

Figure 7 | The SS removal efficiencies for the improved Model B with different number of the inclined plates (surface load).

where η_{improved} is the improved removal efficiency (%), $\eta_{B(C)}$ is the removal efficiency of Model B or Model C (%), η_{original} is the removal efficiency of original sump (%).

Figure 7 illustrates the degree of the improved removal efficiency by the Model B with different number of inclined plates (surface load). It can be found that the η_{improved} increases with the surface load under the condition of flow rate less than 8 L/s, while it declines slightly with the surface load when flow rate reaches 9 L/s. It might because the effective cross-section area decreased with the increase of inclined plates, which makes the velocity between two plates increase, and η_{improved} falls to 1–4% instead. It implies that too many inclined plates will cause the drop of removal rate.

The relationship of removal efficiency and surface load

According to the shallow pool sedimentation theory, the removal efficiency of SS in the ideal sedimentation tank is only related to the surface load. In the present experiment, the surface load q can be calculated by Equations (2) and (3). Table 1 shows the surface load q of Model B (with different number of plates), Model C and the original sump at different flow rates. The reduction rate of surface load, γ (%), can be calculated as Equation (5):

$$\gamma = \frac{q_{\text{original}} - q}{q_{\text{original}}} \quad (5)$$

where q_{original} is the surface load of original sump ($m^3/m^2{\cdot}h$).

The relationship between the reduction rate of the surface load and the improved removal efficiency is plotted in Figure 8. As shown in Figure 8, the flow rate has a great influence on the removal of SS since the flow pattern in the standard sump was different from laminar flow. Under the flow rate of 5.0–8.0 L/s (corresponding to the prototype flow rate 58.1–92.9 L/s), the surface load reduction rate of

Table 1 | The surface load of original sump and the improved Model B and Model C

Flow rate (L/s)	Original Surface load q	B-1 Surface load q	B-2 Surface load q	B-3 Surface load q	B-4 Surface load q	C Surface load q
5.0	0.0247	0.0113	0.0096	0.0083	0.0073	0.0074
6.0	0.0296	0.0073	0.0115	0.0100	0.0088	0.0089
7.0	0.0346	0.0158	0.0134	0.0116	0.0103	0.0104
8.0	0.0395	0.0181	0.0153	0.0133	0.0117	0.0119
9.0	0.0444	0.0203	0.0172	0.0149	0.0132	0.0134

Note: The unit for surface load *q* is $m^3/m^2{\cdot}h$.

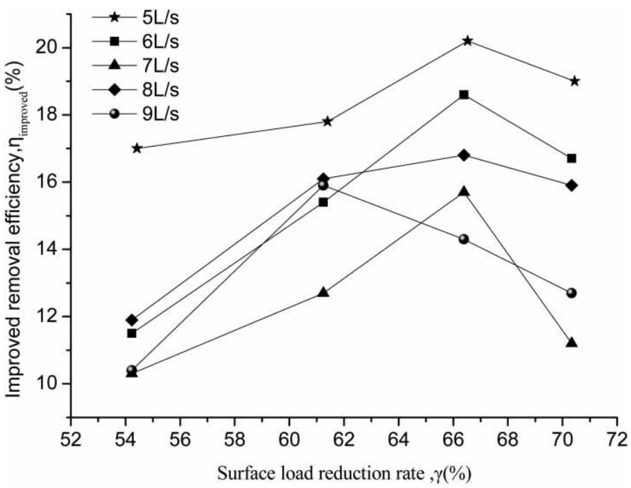

Figure 8 | The relationship between the reduction rate of the surface load and the improved SS removal efficiency.

66% can achieve a better removal efficiency. But at the flow rate of 9 L/s (corresponding to the prototype flow rate 104.5 L/s), the ideal surface load reduction rate is about 61%; this result is consistent with the deduction that the excessive plates will cause a negative impact as discussed previously.

Water head loss

It is necessary to assess the safe performance through observing the increase of water head loss after installation of inclined plates. The sump may overflow and make the urban flood risk be high if the head loss is too large. The water head loss of Model B (with different number of plates), Model C and the original sump at different flow rates is shown in Table 2. The results show that the water head loss caused by the refitted structure is almost negligible: the maximum increase in water head loss was determined to be 0.8 cm at the flow rate of 9.0 L/s.

Table 2 | The water head loss for the improved and the original sump

Flow rate (L/s)	Original Head loss (cm)	B-1 Head loss (cm)	B-2 Head loss (cm)	B-3 Head loss (cm)	B-4 Head loss (cm)	D Head loss (cm)
5.0	0.9	1.2	1.2	1.3	1.2	1.0
6.0	0.9	1.2	1.2	1.3	1.5	1.0
7.0	0.9	1.4	1.4	1.5	1.5	1.0
8.0	1.0	1.5	1.6	1.5	1.8	1.1
9.0	1.1	1.8	1.8	1.8	1.9	1.3

CONCLUSIONS

In this study, a model test is proposed to modify the structure design of standard sumps for improving SS removal efficiency. According to the shallow pool sedimentation theory, a preliminary design, Model A, was tested firstly. Base on the results of the Model A, two improved designs, Model B and Model C, were assessed. Comparing the results of Model B with different surface loads, Model B-3, whose surface load reduction rate is about 66%, has the best performance at different flow rates. Both Model C and Model B-3, which have similar surface load, can improve the removal efficiency by around 15–20%. Even at high flow of 9.0 L/s (corresponding to the prototype flow rate 104.5 L/s), Model B-3 and C can improve the removal efficiency by 14.3% and 16.3% respectively. Meanwhile, the water head loss which was induced by the refitted structure was almost negligible. As for practical application, we propose to set a certain slope for the bottom of the sump; sediment will slide into one end of the sump under the action of gravity and then the sediment can be cleared by suction method. However, the modified sumps need to be examined by the practical application and evaluated in further research.

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