Field performance of self-siphon sediment cleansing set for sediment removal in deep CSO chamber

Yongchao Zhou, Yiping Zhang and Ping Tang

ABSTRACT

This paper presents a study of the self-siphon sediment cleansing set (SSCS), a system designed to remove sediment from the deep combined sewer overflow (CSO) chamber during dry-weather periods. In order to get a better understanding of the sediment removal effectiveness and operational conditions of the SSCS system, we carried out a full-scale field study and comparison analysis on the sediment depth changes in the deep CSO chambers under the conditions with and without the SSCS. The field investigation results demonstrated that the SSCS drains the dry-weather flow that accumulated for 50–57 min from the sewer channel to the intercepting system in about 10 min. It is estimated that the bed shear stress in the CSO chamber and sewer channel is improved almost 25 times on average. The SSCS acts to remove the near bed solids with high pollution load efficiently. Moreover, it cleans up not only the new sediment layer but also part of the previously accumulated sediment.

Key words | CSO chamber, field performance, self-siphon sediment cleaning set, sewer sediment

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INTRODUCTION

The sediment deposits in a sewer system have been recognized as one of the main causes of both hydraulic and environmental problems (Butler *et al.* 2003; Passerat *et al.* 2011). Traditionally, sewer pipe maintenance consists of regularly extracting sediment with power rodding, balling, jetting and pigging from the sewer system. These conventional cleaning-up processes usually take a lot of human and material resources. In the last few decades, the flushing technique has been proposed and adopted by many authors for preventive treatment and cleaning of the sewer system, due to the advantages of possible automation and application on large sewers with respect to other traditional cleaning methods (Ashley *et al.* 2004). Many published studies (Bertrand-Krajewski 2003; Pisano *et al.* 2003; Bertrand-Krajewski *et al.* 2004) have focused on the use of flushing devices. Some flushing devices, such as Tipping Flushers®, HYDROSELF® and Hydrass®, have been developed in Switzerland, Germany and France, and widely used in Europe for cleaning accumulated sludge in combined sewer overflow (CSO) and stormwater storage–sedimentation tanks (Fan *et al.* 2003). Moreover, Campisano *et al.* (2007) investigated the scouring performance of flushing waves produced by hydraulic flushing gates, and obtained indications for the design and positioning of flushing devices in sewer channels. On the other hand, the new non-deposition design criteria for sewers have also been presented by Vongvisessomjai *et al.* (2010).

CSO chambers in the intercepting sewer system are important hydraulic control structures. The sediment scour process in the stormwater structures differs from the unidirectional scour and sediment transport process that occurs in pipes and flumes (Avila *et al.* 2011). Therefore, the sediment in the CSO chamber can't be easily cleaned by means of conventional and flush technologies, especially for deep CSO chambers in Liuzhou, China.

The deep CSO chambers in Liuzhou are quite special. They consist of an overflow chamber, an intercepting chamber and a discharge chamber as shown in Figure 1. The intercepting wastewater flows up to the intercepting chamber through the branch intercepting sewer. Then, the intercepting sewer collects the wastewater from each CSO chamber along the river and conveys it to the treatment plant. Usually when the stormwater runoff exceeds the intercepting capacity, the excess flows over the weir to the discharge chamber and discharges through the combined

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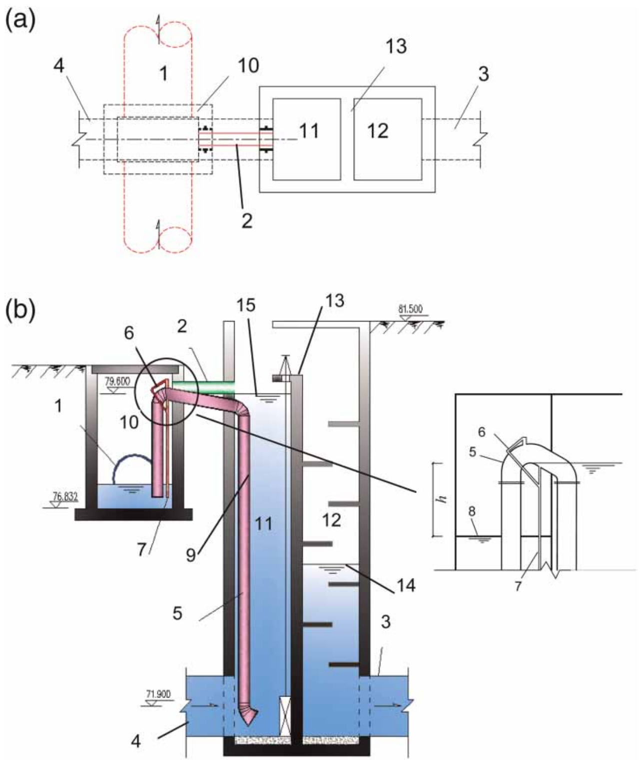

Figure 1 | The plan and profile of the deep CSO chamber in the intercepting sewer system in Liuzhou. (a) Plan view and (b) cross-sectional view with installation of SSCS. 1, Main intercepting sewer; 2, the branch intercepting sewer; 3, the combined sewer outlet; 4, combined sewer channel; 5, self-siphon pipe; 6, air evacuation pipe of self-siphon set; 7, auxiliary siphon pipe; 8, siphon head; 9, siphon-breaking hole; 10, intercepting chamber; 11, overflow chamber; 12, discharge chamber; 13, weir; 14, water level of receiving water; 15, intercepting water level.

sewer outlets into the receiving waters. Dry-weather flow velocities are typically inadequate to maintain settleable solids in suspension, and a substantial amount of solids tend to accumulate in the overflow chamber. After several years of operation, it was found that the problem of sediment deposition in CSO chambers is very serious. Consequently, it leads to the chambers suffering from both hydraulic and environmental problems.

To overcome the problem mentioned above, we designed a self-siphon sediment cleansing set (SSCS) to suck the sediment from the overflow chamber bottom to the intercepting chamber. Then, the sediment and associated pollutants can be entrained and transported to the treatment plant by high-velocity flow in the main intercepting sewer during dry weather instead of flushed to the receiving water during wet weather (Figure 1(b)). However, the performance of the SSCS in terms of sediment removal efficiency has not been studied in the full-scale system. A field study and comparison analysis of sediment depth change in the deep CSO chambers under the conditions with and without the SSCS were carried out during the 2010 and 2011 field seasons to get a better understanding of the sediment removal effectiveness. The study was conducted periodically throughout the wet-weather and dry-weather periods.

MATERIALS AND METHODS

Design of the SSCS

As shown in Figure 1(b), the water level in the overflow chamber and self-siphon pipe rises slowly with the inflow of dry-weather flow. Just before it reaches the top of the self-siphon pipe turn, water enters the auxiliary siphon pipe, whereby the drop of water can evacuate the air from the self-siphon pipe via the air evacuation pipe. The resulting suction pulls water rapidly over so that a large volume of water flows down the pipe, starting the siphon action. When the water level in the overflow chamber decreases to a siphon-breaking hole level, the siphon process will be broken. Accordingly, the SSCS acts to convert small, continuous flows into large, intermittent dosing flows requiring no power. It has been installed in the chamber since the reconstruction process in November 2010.

Measurement

A comparison analysis between the B2–2 CSO chamber without the SSCS and the B2–3 CSO chamber with installation of the SSCS was conducted in this study. The sediment profiles in the CSO chambers were measured with Pipe Profiling Sonar (1512USB, Marine Electronics Ltd.).

As shown in Figure 2, Survey 1 and Survey 4 were implemented on 25 June 2010 and 10 June 2011. Just before these two dates, several heavy rain events and consequent CSOs occurred. Survey 2 and Survey 3 were carried out on 13 November 2010 and 12 April 2011. There were no rain events that led to the overflow for more than two months before these two surveys.

CSO chamber conditions

The sizes (length × width × height) of the B2–2 and B2–3 chambers are 3.00 × 2.00 × 10.35 m and 3.00 × 2.00 × 10.54 m, respectively. The water depths in their overflow chambers are 8.85 and 9.04 m. However, the dry-weather

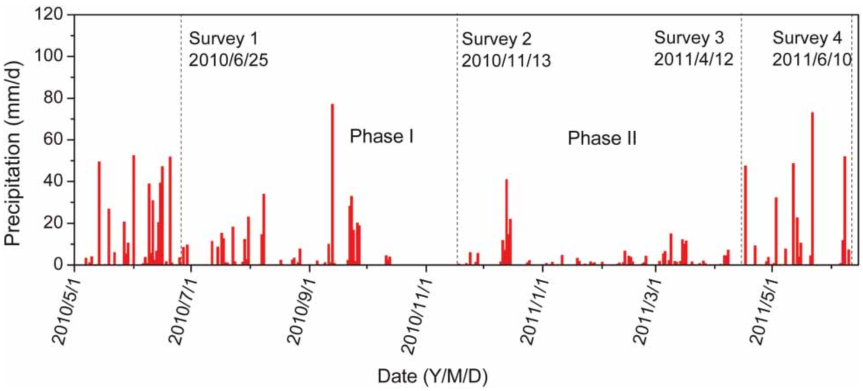

Figure 2 | The distribution of rainfall events and the time of sediment surveys in Liuzhou.

flowrate in B2–3 is 46.8 L/s, greater than that in B2–2 (19.1 L/s) due to the difference in their surfaces.

RESULTS

The operating status of the SSCS

After Survey 2, the B2–3 CSO chamber was equipped with the SSCS. Its operating status was monitored periodically. The operating status of the SSCS for 12 h on 12 March 2011 is shown in Table 1.

As shown in Table 1, 10 siphons were produced by the SSCS over nearly 12 h. Its cycle time was 65 min on average. The time of the siphon process was 10 min stably while the water level rose again in 50–57 min according to the dry-weather flowrate.

The results of sediment profiles

Figures 3 and 4 show the sediment profiles in four surveys of the axis of the B2–2 and B2–3 CSO chambers, respectively.

As shown in Figure 3, without the SSCS system, a thick deposit of sediment covered the bottom of the chamber. More than one-half of the cross-section of the inlet sewer pipe was blocked by sediment. During the dry weather, the thickness of the sediment layer increased significantly as shown in Figures 3(b) and (c). Meanwhile, the high-concentration suspended solids (SS) was detected by the

Table 1 | The operating states of the SSCS

Cycle	Time (hh:mm)	Operating status	Water level (m)	Cycle	Time (hh:mm)	Operating status	Water level (m)
I	8:02–8:13	Siphon beginning	8.52	VI	14:24–14:34	Siphon beginning	8.64
	8:13	Siphon broken	7.16		14:34	Siphon broken	7.28
	8:13–9:53	Water level rising	7.16		14:34–15:27	Water level rising	7.28
II	9:53–10:14	Siphon beginning	8.65	VII	15:27–15:38	Siphon beginning	8.62
	10:14	Siphon broken	6.82		15:38	Siphon broken	7.31
	10:14–11:05	Water level rising	6.82		15:38–16:33	Water level rising	7.31
III	11:05–11:16	Siphon beginning	8.62	VIII	16:33–16:43	Siphon beginning	8.61
	11:16	Siphon broken	6.91		16:43	Siphon broken	7.29
	11:16–12:12	Water level rising	6.91		16:43–17:40	Water level rising	7.29
IV	12:12–12:22	Siphon beginning	8.64	IX	17:40–17:50	Siphon beginning	8.64
	12:22	Siphon broken	6.98		17:50	Siphon broken	7.3
	12:22–13:18	Water level rising	6.98		17:50–18:43	Water level rising	7.3
V	13:18–13:28	Siphon beginning	8.64	X	18:43–18:52	Siphon beginning	8.66
	13:28	Siphon broken	7.18		18:52	Siphon broken	7.35
	13:28–14:24	Water level rising	7.18		18:52–19:46	Water level rising	7.35

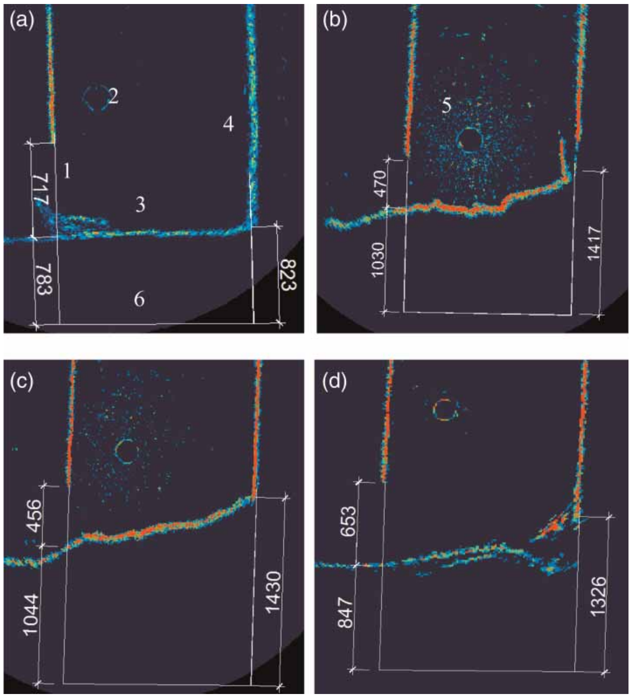

Figure 3 | The sediment deposition in the B2–2 chambers in June 2010 (a), November 2010 (b), April 2011 (c) and June 2011 (d). 1, Remaining cross-sectional area of combined channel; 2, sonar scanning probe; 3, sediment surface; 4, wall of chamber; 5, suspended solid; 6, bottom of overflow chamber.

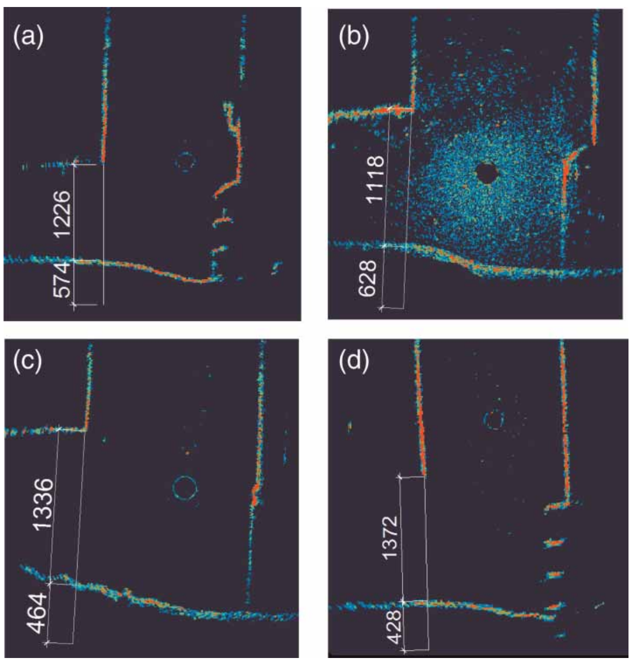

Figure 4 | The sediment deposition in the B2–3 chambers in June 2010 (a), November 2010 (b), April 2011 (c) and June 2011 (d).

sonar probe on the surface of the sediment layer. A thick sediment layer was also built up on the bottom of the B2–3 chamber as shown in Figure 4. It can be seen from Figure 4(b) that the sediment layer was thickened and a high-concentration SS was detected to suspend on the bottom of the chamber in November, 2010. After installation of the SSCS, the high-concentration SS was removed thoroughly as shown in Figure 4(c).

The profiles of SS concentration

The profiles of SS concentration in the B2–2 and B2–3 deep CSO chambers were monitored using a multi-depth water sampler in the third field survey, and the results are shown in Figure 5. From Figure 5(a), it was observed that the SS concentrations in the B2–2 chamber increased significantly at the bottom, which reached about 0.6 g/L at a layer 0.5 m from the bottom. In contrast, the SS concentrations in the B2–3 chamber were reduced to a range of 0.09–0.13 g/L in the whole vertical cross-section, as shown in Figure 5(b) after installation of the SSCS.

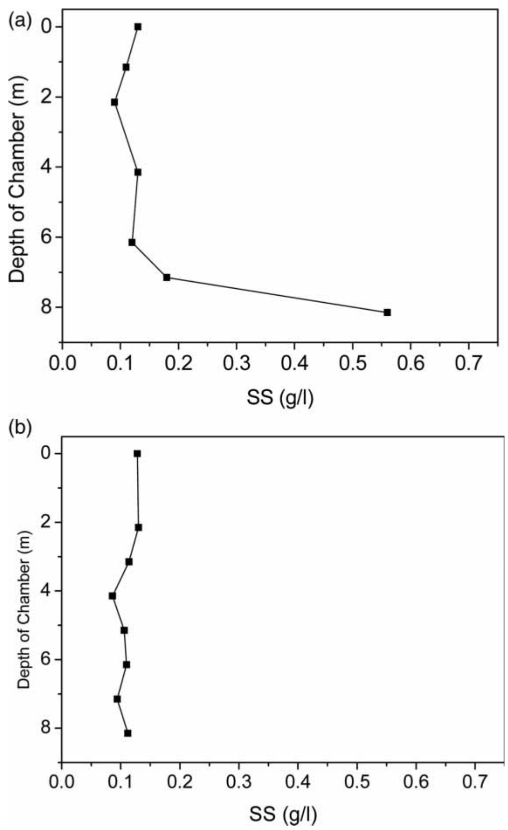

Figure 5 | SS concentration profiles of B2–2 (a) and B2–3 (b) CSO chambers in the third field survey.

The results of sediment layer thickness

The variation of sediment layer thickness on the bottom of the B2–2 and B2–3 chambers and blockage percentage of its sewer channel over a year are shown in Figure 6.

As shown in Figure 6(a), the sediment layer thickness in the B2–2 chamber was increased greatly during nearly two months of dry weather between Survey 1 and Survey 2 (from September to November 2010, as shown in Figure 2), and reached its highest level in April 2011. When heavy rain events occurred in the next wet-weather period, the sediment erosion appeared again. The sediment thickness reduced significantly to the level of June 2010.

On the other hand, the thickness of the sediment layer in the B2–3 chamber was increased during the dry-weather period of October and November 2010, as shown in Figure 6(b). After installation of the SSCS after Survey 2, the thickness of the sediment layer dropped instead of increasing, and the decrease reached about 200 mm. The sediment thickness in April 2011 was almost similar to that in the next wet-weather period, June 2011.

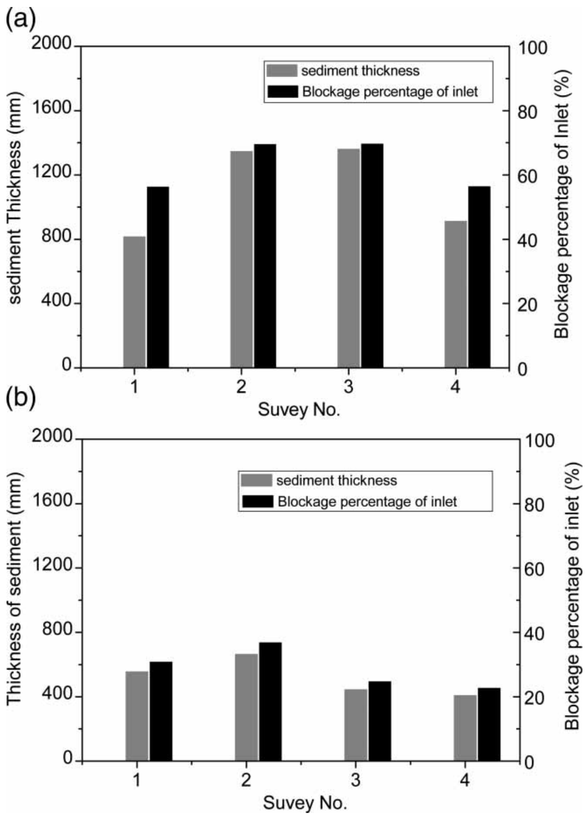

Figure 6 | The thickness and blockage percentage variation of sediment on the bottom of the B2–2 (a) and B2–3 (b) chambers.

DISCUSSION

As shown in Table 1, the SSCS acts to produce a periodic siphon, which drains the dry-weather flow that accumulated for 50–57 min from the sewer channel to the intercepting system in 10 min. It effectively converts small, continuous flows into large, intermittent dosing flows, and the average velocity in the chamber and its sewer channel increases almost five times. The uniform steady flow bed shear stress is related to the freestream fluid velocity through a friction coefficient via the quadratic relation:

$$\tau_0 = C_f \frac{1}{2} \rho U^2 \quad (1)$$

where C_f is a friction coefficient, U is the freestream fluid velocity (m/s) and ρ is the fluid density (kg/m^3). According to Equation (1), the bed shear stress can be increased up to almost 25 times on average. It is helpful for sediment erosion. Moreover, the instantaneous flowrate can increase by about eight times, especially in the early stage of the siphon by estimating from the Bernoulli equation. The constant siphons produced by the SSCS also prevent the sediment deposition from consolidation on the bottom.

It was observed that the deep overflow chambers were prone to forming a high-concentration SS layer on the surface of the sediment during the dry weather from Figures 3 and 5(a). Those solids had a high volatile solids content of 56% with a real density of 0.8 g/cm^3. They were highly polluting contents and are known as near bed solids (Arthur & Ashley 1998), potentially causing environment impacts if washed out into watercourses. So, it is necessary to detect the layer continuously to investigate its formation and disappearance further. From the results of Survey 4, it can be inferred that the accumulated sediment in the year was scoured and re-suspended again in the next wet-weather period and discharged with CSO into the receiving water, becoming the main pollution source for the receiving water.

From Figure 4, it is observed that the SS layer with high-content pollution also appeared in the B2–3 chamber in the second survey. However, it can be seen from Figures 4(c) and 5(b) that the layer was sucked up effectively by the SSCS and transported to the intercepting system if the SSCS was installed. Therefore, we conclude that the SSCS acts to remove the near bed solids effectively.

With installation of the SSCS after the second survey, the variations in sediment layer thickness and blockage percentage of the sewer channel in the bottom of the B2–3 chamber were quite different from those in the B2–2 chamber, as shown in Figure 6. It can be inferred that the SSCS can clean not only the new sediment layer but also part of the previously accumulated sediment, as shown in Figure 6(b). The sediment entrained by stormwater runoff and discharged with CSO was decreased insignificantly in the wet-weather period in 2011. However, the siphon-lift capacity of the SSCS was related to the parameters of the siphon head and cross-sectional area. The quantitative relation of siphon-lift capacity and the parameters should be investigated further in order to design the parameters of the SSCS.

CONCLUSION

The SSCS for the sediment removal in deep CSO chambers is presented in this paper. Through an operating status investigation, sediment survey and the SS profile detection, the performance of the SSCS in sediment removal was studied in the full-scale system. The key conclusions drawn from this field investigation are as follows:

1. The cycle time of the SSCS is 65 min on average. The SSCS drains the dry-weather flow accumulating for 50–57 min from the sewer channel to the intercepting system in 10 min. The average velocity in the chamber and its sewer channel can be increased almost five times, and the bed shear stress improved 25 times accordingly after installation of the SSCS.
2. The SSCS removes the near bed solids efficiently. Moreover, it cleans up not only the new sediment layer but also part of the previously captured sediment.
3. The siphon-lift capacity of the SSCS is related to the parameters of siphon head and cross-sectional area, and its relationship should be investigated further.

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