Journal of Zhejiang University SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Optimized operation plan for sewer sediment control*

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Received Apr. 6, 2009; Revision accepted Aug. 7, 2009; Crosschecked Mar. 30, 2010

Abstract: Severe operational problems of sediment deposition have frequently occurred in stormwater sewer systems in Shanghai city due to the flat topography of the area and serious illicit connections. To control sewer sediment and its subsequential problems, optimized operation plans were proposed and an innovative performance assessment method was developed. Simulation results demonstrated that, through changing the way of pump operation and installing necessary actuators in the system, the optimized operations, especially batch intermittent intercept plan, effectively improved the flow velocity in the entire system in dry-weather condition. In conclusion, the optimized operation is an innovative idea for improving the performance and solving the problem of sediment deposition in the sewer system in Shanghai, China.

Key words: Sewer system, Sediment control, Performance assessment, Simulation
doi:10.1631/jzus.A0900082 **Document code:** A **CLC number:** TU992.4

1 Introduction

Combined sewers carry both sanitary and storm flows, which are sized to convey many times the anticipated peak dry-weather wastewater flowrate. Typically, both sanitary and storm flows convey different kinds of solids into the system. In dry-weather conditions the flowrates and associated velocities and shear forces are too low to carry a significant portion of the suspended solids (SS), resulting in their settling. The sediment deposition in the system may cause operational problems, such as loss of hydraulic capacity, in-pipe septicity and contribution to the pollutants in foul flushes (Ashley *et al.*, 2000), and the result of odor and corrosion (Pisano *et al.*, 1998). Moreover, during wet-weather conditions, flowrates are high enough to resuspend these solids and carry them via combined sewer overflows (CSOs) to urban streams causing aesthetic and other pollution (Arthur *et al.*, 1996).

The sewer sediment deposition problem was acknowledged in developed countries in the 19th century (Bertrand-Krajewski, 2003). Initially, manual methods of sediment removal have commonly been employed and these methods are usually involved in moving the sediment to a location for subsequent treatment by mechanical or suction equipments. A number of innovations were also introduced to attempt at ensuring that the solids collected in the drains and sewers could be resuspended and transported to the sewage treatment facility. During the past 15 years, at least three new passive hydraulic-flushing systems have been developed and installed in sewers and/or storage tanks in more than 500 locations in Europe, the USA, and Canada (Pisano *et al.*, 1998; 2003). In addition, some new systems, such as Tipping Flushers®, HYDROSELF® and Hydrass®, have been developed in Switzerland, Germany and France, and widely used in Europe for cleaning accumulated sludge and debris in CSO and stormwater storage-sedimentation tanks (Fan *et al.*, 2003). Moreover, Guo *et al.* (2004) evaluated the performance of a traditional gate-flushing device and a newly designed vacuum flushing device in removing sediment

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* Project (No. 2008ZX07317-001) supported by the Special Grand National Science-Technology Project for Water Pollution Control and Treatment, China

through laboratory testing, and several experimental and numerical analyses were carried out to investigate and optimize the flushing effect (Campisano *et al.*, 2004; Dettmar and Staufer, 2005; Bertrand-Krajewski *et al.*, 2005; 2006). Campisano *et al.* (2007) considered the effect of various values of the dimensionless parameters on deposit removal to obtain indications for the design and positioning of flushing devices in sewer channels. On the other hand, the concept of self-cleansing sewer design was developed, which could keep the sewer clean from sediment deposits (Yao, 1974; Novak and Nalluri, 1975). Conventionally, this method worked at specified minimum 'self-cleansing' flow velocity conditions including certain depth of flow or with a particular frequency of occurrence. More recently, the UK's construction industry research and information association (CIRIA) developed a new self-cleansing design methodology for sewers. This technology took the advantage of the available knowledge on sediment mobility and the effects of sediment deposition on the hydraulic performance of sewers (Butler *et al.*, 2003).

Shanghai is located in the rich, low-lying area of the Yangtze River Delta. Operational problems of sediment deposition have frequently occurred in the stormwater sewer systems in this city, and sometimes were severe due to the flat topography of the area as well as serious illicit connections. Deposited sediment can be scoured and discharged to the receiving water by high flow rates under the wet-weather condition, which has long been recognized as a major contributor to the highly polluted segment or first-flush phenomenon of the CSO. However, the main trunk of stormwater sewer systems is usually under the surcharge condition even in the dry-weather conditions, which makes the physical cleaning methods and automated flushing equipment play a limited role in the sediment removal. In addition, the limited flushing length and flushing volume of automated flushing equipments make it difficult to resolve the problem of sediment deposition in the overall main trunk networks.

This study is aimed to improve the flowrate in the whole stormwater sewer systems in dry-weather by means of optimizing the operation scheme, and preventing the sanitary solids from settling in the sewer. The organic layer, which is the main pollution load in urban stormwater discharges, can be scoured and transported to the wastewater treatment as much as possible. Meanwhile, a new assessment approach was developed in this paper to evaluate the performance improvement of stormwater sewer systems.

2 Methods

2.1 Study site

One of the 4 sub-centers fixed in the general urban plan was the northwest city sub-center, located in the northwest of Shanghai, China. Due to the severe illicit connection, functional problems of sediment deposition have frequently occurred in the stormwater sewer system in this area with the dry-weather. Subsequently, sewer systems suffer from significant CSO pollution, hydraulic restrictions, as well as odor and corrosion problems.

To improve the performance of the sewer system in this region, three old systems, designed to carry 1 in 1 year storm flow without street flooding, were proposed to be reconstructed to form a whole system, the Daguangfu system (DGF system). The DGF system plan is shown in Fig. 1. It is mainly serviced to a residential area of the north bank of Suzhou Creek on the east of sub-center. The pump station of DGF system is equipped with 6 discharge pumps with each capacity of 2.50 m^3/s and 4 intercept pumps with each capacity of 0.41 m^3/s.

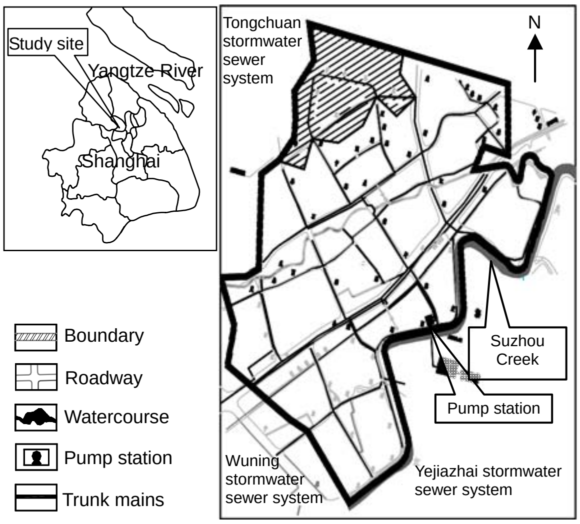


Fig. 1 Plan view of Daguangfu system

2.2 Hydraulic model development

Both current hydraulic model and planed model of the DGF system were built with the InfoWorks CS (Wallingford Software), taking in all nodes and links on the basis of inventory and plan data about pipe diameters and invert levels. The corresponding model tests with both traditional and optimized operations have been conducted for a comparative study.

The parameters of runoff generation, the concentrations of various land uses of the catchments and the roughness coefficient of conduit in the model of current situation were calibrated according to the measured data. After calibration, a few events were used to verify the model results. The events used then were different from the events used for calibration to achieve independent verification. The parameters are adopted in the plan model subsequently to guarantee the accuracy of model tests.

2.3 Assessment methodologies

Two assessment methods, i.e., hourly and overall assessment methods, were developed in this study. Set the duration of an assessment scenario to be T, which can be divided to n time steps, and the velocities of the jth pipe at the ith time step v_i^j can be computed through model tests. The velocities of each pipes in the entire system at the ith time step, $v_i^1,\cdots,v_i^{j-1},v_i^j,v_i^{j+1},\cdots,v_i^m$, can be regarded as a discrete random variable V_i. The hourly assessment method (HAM), which is used to evaluate the velocity condition of pipes in the entire networks at any time in the given scenario, can be expressed as

$$F_i(v)=P\{V_i>v\}=\sum_{v_i^k>v}P\left\{V_i=v_i^k\right\}=\sum_{v_i^k>v}p_i^k=\sum_{v_i^k>v}\frac{l_k}{\sum_{i=1}^{m}l_i}, \tag{1}$$

where $F_i(v)$ is distribution function of velocities at time step i, l_k is the length of the pipe k, and m is the total of the pipes in the entire system.

Moreover, the duration of high velocity is also the main factor to scour the solid deposition. Set the velocities of the jth pipe in each time steps $v_1^j,v_2^j,\cdots,v_n^j$ to be a discrete random variable V^j, then the velocity distribution function of the pipe j can be expressed as

$$F^j(v)=P\{V^j>v\}=\sum_{v_k^j>v}P\{V^j=v_k^j\}, \tag{2}$$

where $F^j(v)$ is the distribution function of velocities of the pipe j. According to Eq. (2) the duration of velocity greater than v can be calculated as

$$t^j\left|V^j>v=F^j(v)\cdot T,\right. \tag{3}$$

where t^j is the duration of velocity greater than v; T is the duration of a given assessment scenario. Therefore, the overall assessment method (OAM), which is used to evaluate the velocity and duration of the systems in the whole given scenario, can be obtained:

$$F(v,t)=P\left\{T>t,V>v\right\}=\sum_{i=1}^{s}L_{vt}^{i}\bigg/\sum_{j=1}^{m}L^j, \tag{4}$$

where L_{vt} and s are the length and total of the pipe with velocity greater than v and duration greater than t, respectively.

3 Results and discussion

3.1 Performance of system with conventional operation

Since the DGF system is still in process, it has not been possible to carry out the field test. Moreover, the model test may be more efficient to find optimized operation plan to solve the sediment deposition problem. In dry-weather, 1 or 2 intercept pumps were run continuously to intercept the dry-weather pollutant or other non-stormwater materials. In this scenario, the hourly velocity performance for the entire network velocity conditions of the system was evaluated by means of HAM and the results are shown in Fig. 2.

The importance of performance assessment has been growing in the planning, design, installation, and operation of sewer systems, which can not only lead to a better knowledge of the utility's activities but also is a suitable basis for the diagnosis, control and selection of solutions for the improvement of technical process and system performance (Cardoso *et al.*,

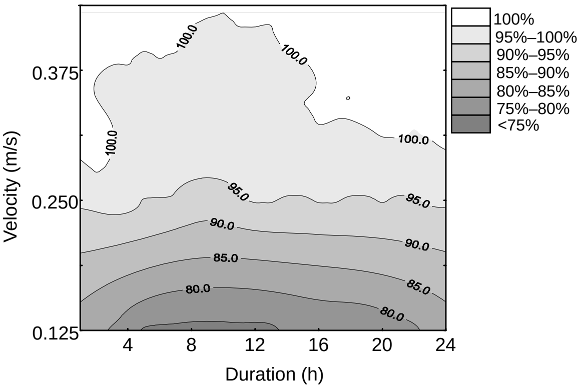


Fig. 2 Velocity condition of the Daguangfu system evaluated by means of the HAM in dry-weather scenario

2005). Low velocities can cause sediment and solids deposition, thus flow velocity is the crucial hydraulic performance variable and selected as the performance indicator to evaluate the deposition risk of sewer systems. For the entire network, the more the proportions of pipes with high-velocity and long-duration are, the less the deposition risk of the system is. In Fig. 2, if (x, y) are the coordinates of a given point in the P% percentile curve, this means that for a certain time of x, the percentage of pipes with velocity performance lower than or equal to y is P%. As shown in Fig. 2, the velocities of 95%–98% pipes of entire system were below 0.250 m/s, and the pipes with velocities greater than 0.375 m/s were accounted for only 1%–2% of the entire system during the peak time of water consumption. Through sewer surveying with closed circuit television (CCTV), Zhu and Wang (2006) proved that such low velocity in whole system led to the production of abundant sediment on the pipes invert. In wet-weather, not only are all of the intercept pumps switched on to intercept the first flush runoff as much as possible, but also the discharge pumps are switched on in succession when the water level of system rises to the pump-on level. According to the design criteria of the DGF system, a short-duration (2 h) design rainfall pattern of 1 in 1 year (Fig. 3) was adopted in the assessment, which was derived from the statistic of Shanghai rainfall information of recent ten years (Ning, 2006).

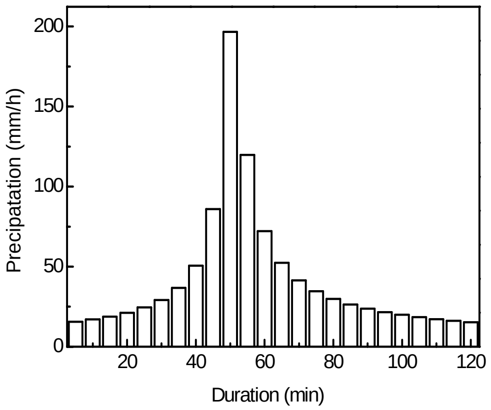
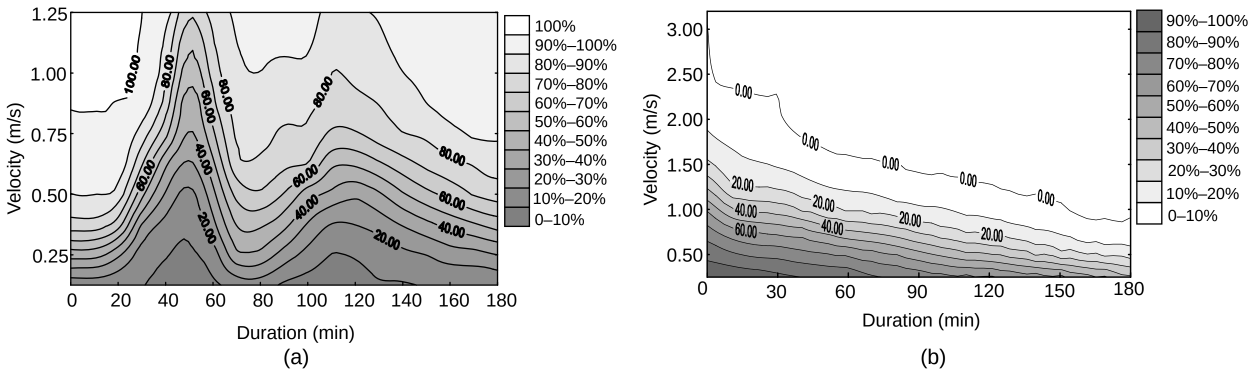


Fig. 3 Pattern of the rainfall of 1 in 1 year

Using the simulation test, the flow velocity conditions of the entire system were evaluated by the HAM and OAM in wet-weather scenario and the results were shown in Fig. 4a and Fig. 4b, respectively.

As shown in Fig. 4a, the velocity performance of the system improved greatly due to the collection and discharge of the stormwater runoff. The results demonstrated that, when rainfall peak appeared and the pipes with flow velocity were greater than 0.75 m/s, the nonsilting velocity regulated by GB 50014-2006 (2006), accounted for about 60% of the entire system. Fig. 4b shows the overall velocity performance for the entire network in the whole



(a)

(b)

Fig. 4 Velocity condition of the Daguangfu system evaluated by means of the HAM (a) and OAM (b) in wet-weather scenario

assessment event computed by means of the OAM. If (x, y) are coordinates at a given point in the P% percentile curve, it means the percentage of pipes with their velocity performance and duration greater than or equal to y and x respectively is P%. As shown in Fig. 4b, the velocity of almost 80% of pipes in the entire system reached 0.75 m/s in the whole assessment scenario. Furthermore, the duration of most pipes, especially the main pipes, reached and/or exceeded 20–30 min. The results suggested that the improvement of the flow velocity made the solid sediment deposited in the dry-weather resuspended, transported and discharged to the receiving water with CSO, and effectively reduced the pollution of the water environment.

3.2 Optimized operation plan for sediment control

To resolve the severe problem of high pollution load in CSO, it is necessary to improve the velocity performance of the system in dry-weather to prevent the occurrence of sediment deposition. Therefore, the optimized operation plan, intermittent intercept plan (IIP), was developed. The IIP changed the continuous running of one or two intercept pumps in the conventional operation mode to intermittent operation of all intercept pumps. In other words, all of the intercept pumps are switched on at the same time when the water of system rises to a certain level with the inflow of non-stormwater materials. After water in the system is intercepted, switch all pumps off and keep them off until the next changing cycle of the water level.

Fig. 5 shows the velocity condition of the entire system in the pump-on cycle under the control of IIP in dry-weather. The velocity performance of the tested system improved greatly compared with the control under the conventional operation. However, only about 20% of the pipes were with a flow velocity greater than or equal to nonsilting velocity. And about 10% of the pipes keep the nonsilting velocity for 10 min. For most of the pipes, the flow velocity was less than 0.5 m/s.

To further improve the velocity performance of the system, the IIP was ameliorated and the batch intermittent intercept plan (BIIP) was proposed. The BIIP can be realized in the DGF system through installing a regulator in the appropriate position of the system, as shown in Fig. 6.

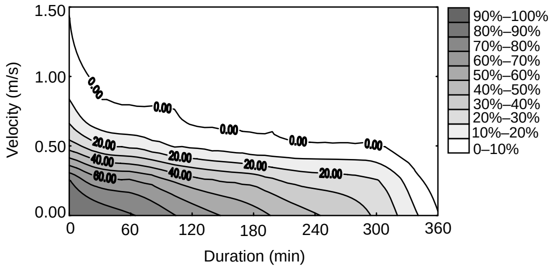


Fig. 5 Velocity condition of the Daguangfu system under control of IIP evaluated by means of the OAM in dry-weather

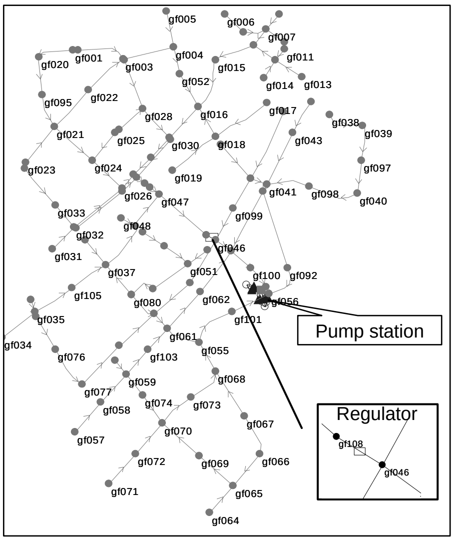


Fig. 6 Regulator in the Daguangfu system

The regulator, which divided the system into two parts as upstream and downstream, responded automatically to the water level of the downstream. When the water level of the downstream rises to a certain level, all of the intercept pumps are switched on, and then the regulator is opened as the water level of downstream decreases to a certain value.

Through the simulation test, the flow velocity condition of the entire system evaluated by the OAM in dry-weather scenario was shown in Fig. 7. Under similar condition of intercept capacity, the flow velocity in pipes of downstream can increase without the inflow from the upstream. Moreover, when the regulator is opened, the releasing discharge from the upstream can not only improve the flow velocity of the upstream greatly but also scour the pipes of the downstream effectively. As shown in Fig. 7, the pipes with flow velocity greater than nonsilting velocity accounted for about 40% of the whole system, and the duration of the same velocity was much longer than that controlled by conventional operation and IIP.

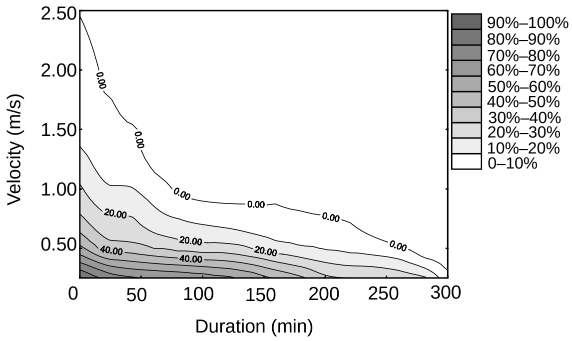


Fig. 7 Velocity condition of the Daguangfu system evaluated by means of the OAM in dry-weather

In the original studies of sewer sediments, a stratification of the deposits was observed at the water-sediment interface with a layer composed of organic matter and paper over the surface of the coarse mineral deposits (Crabtree, 1989). The particles of this organic layer are heavily loaded with pollutants, which was the main contributor to the high pollution load in the CSO. Previous study indicated that the organic layer could be resuspended and transported with the water when the shear stress was greater than 0.1 N/m^2 through the flush experiments, which proved that the layer can be eroded by small rainfall events (Ahyerre *et al.*, 2001). Therefore, the application of BIIP is an effective way not only to prevent the deposition of suspend solid in the pipe but also to flush the organic layer away in the dry-weather, which can eliminate the pollution load in the CSO significantly.

4 Conclusion

Stormwater sewer systems with severe illicit connections, which are oversized to accommodate very infrequent wet-weather events, act as sedimentation unit processes during dry-weather periods. This is due to the low-flow velocities they typically experience. As a result of these low-flow velocities, these over-sized and low-slope sewers fail to maintain settleable solids in suspension. Therefore, low-cost and low structurally intensive controls, e.g., sewer-sediment flushing, must be thoroughly considered in any new CSO control planning effort and sewer systems upgrading plan.

To control sewer sediment and its resulting problems, the optimized operation plans were developed. The optimized operations, especially BIIP, can improve the flow velocity of entire system in the dry-weather condition greatly through changing the way of pump operation and installing necessary actuators in the system. The effectiveness was proved by the simulation test and performance assessment methods. The optimized operation provides an innovative idea for improving the performance and solving the problem of sediment deposition in sewer systems in Shanghai, China.

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