Different erosion characteristics of sediment deposits in combined and storm sewers

Zuxin Xu, Jun Wu, Huaizheng Li, Zhenghua Liu, Keli Chen, Hao Chen and Lijun Xiong

ABSTRACT

To investigate the different erosion patterns of sediments in combined and storm sewers, sediments from three separate sewer systems and two combined sewer systems in urban Shanghai were collected for the flushing experiments. These experiments were conducted with different consolidation periods and shear velocities. As the consolidation period increases, dissolved oxygen exhibits a positive effect on the microbial transformations of organic substrates. Potential structural changes and separations of the surface and bottom layers of sediments are observed. The results also reveal that the organic matter, particle size and moisture have different effects on the erosion resistance of sediments. Furthermore, illicit connections behaved as an important factor affecting the viscosity and static friction force of particles, which directly alter the erosion resistance of sewer sediments.

Key words | erosion, laboratory experiments, organic matters, particle size, sediment, shear stress

Zuxin Xu
Jun Wu
Huaizheng Li (corresponding author)
Zhenghua Liu
Keli Chen
Hao Chen
Lijun Xiong
College of Environmental Science and Engineering,
Tongji University,
Shanghai 200092, China
E-mail: *lihztg@yeah.net*

Huaizheng Li
Keli Chen
Key Laboratory of Yangtze River Water Environment, Ministry of Education,
Tongji University,
Shanghai 200092, China

Zhenghua Liu
Hao Chen
State Key Laboratory of Pollution Control and Resource Reuse,
Tongji University,
Shanghai 200092, China

INTRODUCTION

Urban wet-weather discharges from combined sewer systems to receiving waters alter river hydro-geomorphology, water quality and sanitary quality (Becouze-Lareure *et al.* 2016). In general, a storm drainage system is designed to discharge storm runoff into a receiving water. On dry weather days, however, non-storm water discharges also enter storm drainage systems, resulting in the release of untreated sewage in urban receiving waters, especially in the metropolises of China (Field *et al.* 1994; Li *et al.* 2014). Both combined and storm sewer overflows contribute significant wet weather pollutants to urban rivers. A large fraction of these pollutants are trapped on sediment deposits (Zgheib *et al.* 2011; David *et al.* 2013). Although Field & Struzeski (1972) showed 20–30% of the annual production of wastewater solids settled and were discharged during storm events in Buffalo (NY, USA), it was still unclear as to what type of particles were actually eroded during rain events in combined and storm sewers (SS).

The amounts and types of eroded solids could be affected by many factors during periods of rainfall, particularly in terms of the biochemical and physical properties of deposits, antecedent dry weather period, and rainfall intensity. For instance, Biggs *et al.* (2005) placed real deposits (sediments from Loenen, The Netherlands and Dundee, UK) in the base of an annular flume with varying conditions for consolidation. However, the transport and amount of eroded sediments also play an important role in this research field, but are rarely assessed. In addition, Banasiak *et al.* (2005) made use of sewer sediment (from a combined sewer system in the city of Dendermonde, Belgium), observing strong biochemical reactions during the deposit formation period. Unfortunately, these researchers did not discuss the differences between sediments from combined and SS. Different combined and SS systems may have different dimensions of illicit connection, which may result in differences in the types of sediments.

doi: 10.2166/wst.2017.076

The aim of this project is to investigate the different erosion patterns and initial effects of combined sewer sediments (CSSD) and storm sewer sediments (SSSD) under different consolidation periods. The flux on eroded particle size and flush pollutants are determined by continuous monitoring. We hypothesize discovering some differences in the initial effects between CSSD and SSSD. This study seeks to determine the parameters of flushing gates or weirs in different combined and SS, leading to a decrease in pollution from wet weather discharges.

MATERIALS AND METHODS

Study areas

Between 2008 and 2012, according to the local government, the length of pipe for dredging the urban drainage system in Shanghai was much longer than in rural areas, and the amount of siltation in urban drainage systems was also higher than in rural areas (0.02–0.04 t/m pipe >0.006–0.027 t/m pipe). This finding indicates that the sedimentation in urban areas is heavier than in rural areas. Thus, the local government made urban drainage systems focus on serious sedimentation. Therefore, it is more reasonable for us to select urban drainage systems as a research project.

Hongkou District is located in the northeast of Shanghai City, with a total area of 23.45 km^2. The population density is approximately 36,000 per square kilometre, which is the highest in Shanghai. There are a total of 13 drainage systems in the Hongkou District (see Figure 1). Hongzheng, Liyang and Guangzhong are typical combined drainage systems. Quyang and East Tiyu are typical separated drainage systems, which rarely interfere with domestic sewerage. Considering a representative sample, the above five drainage systems were chosen as the sampling area.

Sampling procedure

To avoid the destruction of the structure of the sewer sediments, deposit samples were pumped with a suction device, consisting of a peristaltic pump and a polyethylene tube (see Figure S1, Supplementary material, available with the online version of this paper). The tube was sunk into the sediment using a mallet to the depth required (15 cm in this study). The peristaltic pump was used to create a vacuum that sucked the sediment. A new tube was used for each sample. All used tubes were carefully transferred to polypropylene containers and stored on ice until arrival in the laboratory.

To avoid the influence of overlying water on samples, a period of consolidation was set in the laboratory. After several hours, the overlying water was excluded, and the sediments were ready for the following tests. Wei (2012) found that the water-solid interface would be stable after a consolidation of approximately 4 h (see Figure S2, Supplementary material, available with the online version of this paper). Twenty samples were collected in separated drainage systems (ID400, No.1–4; ID600, No.1–4; ID800, No.1–4; ID1000, No.1–4; ID1200, No.1–4, here ID400 means internal diameter of 400 mm). Twenty samples were also collected in combined sewer systems (ID400, No.1–4; ID600, No.1–4; ID800, No.1–4; ID1000, No.1–4; ID1200, No.1–4).

Experimental setup

Hydraulic flushing device

A flush model was designed for the erosion test (see Figure S3, Supplementary material, available with the online version of this paper). The pipe diameter (outside diameter) was 200 mm, and the inside diameter was 190 mm. The length of the pipe was 7.0 m, and the pipe material was un-plasticized polyvinyl chloride. The pipe slope was 8.03‰. The roughness of the inside pipe wall was $n = 0.018$ (n is the Manning coefficient. Units for values of n are often left off; however it is not dimensionless, having a unit of $\mathrm{s}/[\mathrm{m}^{1/3}]$). The pipeline was divided into two parts. The length of one section was 6.8 m, and the top 7 cm part was cut off, primarily for the convenience of such parameters as placing sediments and calibrating the flow. The rest of the pipe remained intact, and its length was 0.2 m. The diameter of the return pipe was 50 mm; it was made of PVC, and was used for adjusting flow. The flush pipe and the return pipe were connected with a PVC bucket (volume = 685 L). An agitator was installed in the bucket, and the distance was 30 cm from the blades to the bottom of the bucket. An online particle test probe was also set in the bucket for testing turbidity every 20 s. A single-stage vertical centrifugal pump (Rated Power = 21 m^3/h) and the bucket were connected by a PVC pipe. To regulate the flow, a butterfly valve and a Holykell electromagnetic flowmeter were sequentially arranged behind the centrifugal pump. The control process can be seen in the Supplementary material.

Laboratory tests

Consolidation period and scouring experiment. Biggs *et al.* (2005) suggested that the degree of consolidation

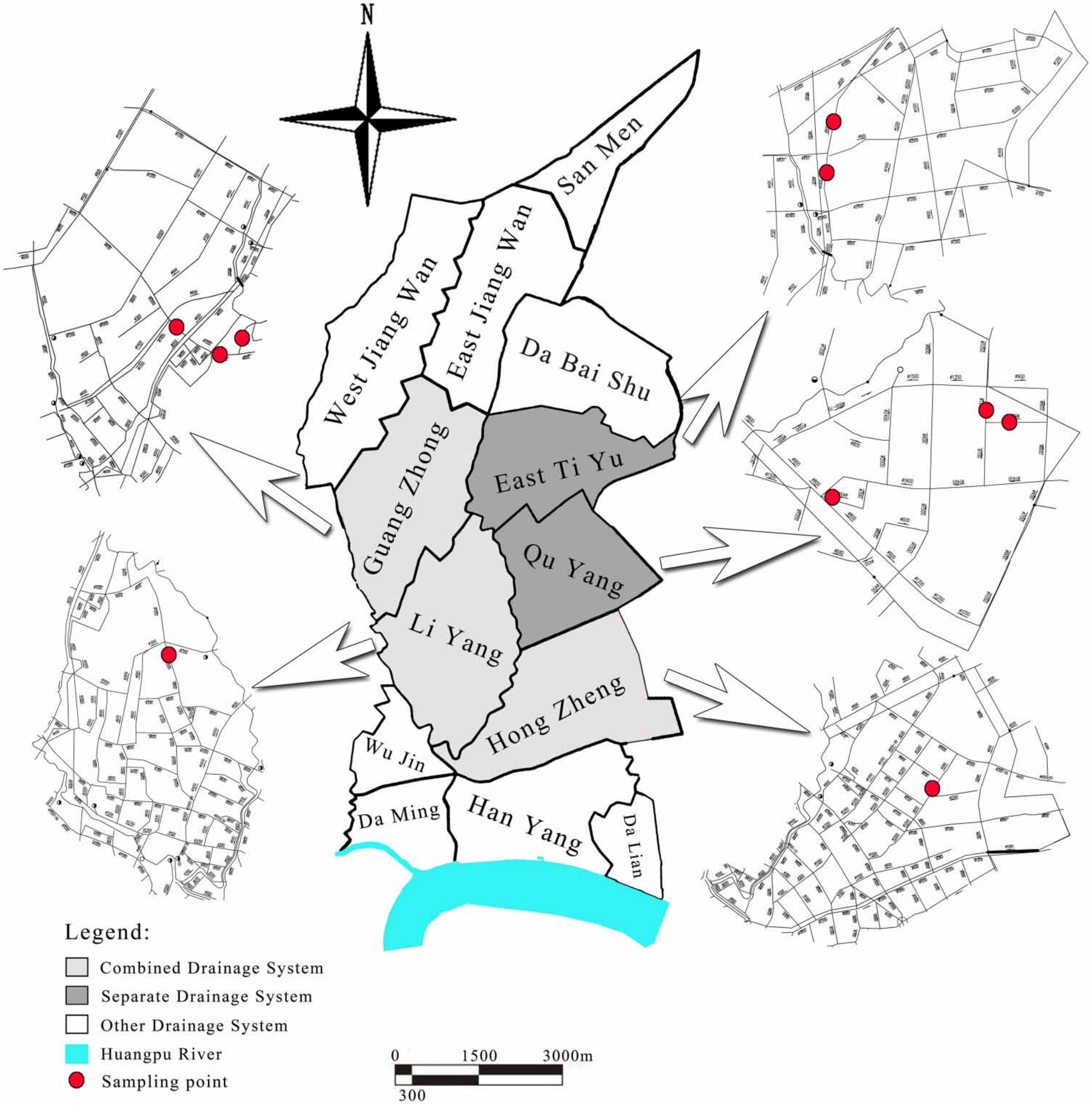

Figure 1 | Distribution map of drainage system in Hongkou District.

in a cohesive sediment bed is strongly influenced by the length of the consolidation period and biological activity. In gravity sewers, biofilms may also affect the friction of sediments, resulting in different hydraulic conditions (Characklis & Marshall 1990). Biofilms in sewers are usually related to 'slimes', which consist of the following two major fractions (Hvitved-Jacobsen *et al.* 2013): (1) microorganisms and (2) extracellular polymers, EPS, which are always produced by microorganisms outside their cells in unfavourable environments, and comprise the largest (up to 90% of total organic matters) organic fraction of sewer biofilms. Hvitved-Jacobsen *et al.* (2013) have concluded that the daily production of biomass in biofilm of gravity sewers consists of two parts, as follows:

$$M_B = M_{ae} + M_{an} \tag{1}$$

where M_B is the daily production of biomass, M_{ae} is the daily production of aerobic microorganisms, M_{an} is the daily production of anaerobic microorganisms.

$$M_{ae} = \frac{Y_{gr}}{1 - Y_{gr}} \cdot r_{re} \cdot K \cdot kg\ COD \tag{2}$$

where Y_{gr} is the biofilm yield constant of the heterotrophic biomass, which was estimated as $Y_{gr} = 0.55$ g chemical oxygen demand (COD), r_{re} is the dissolved oxygen (DO) consumption rate of sewer biofilm, K (>1) is a conditional constant.

The value of M_{an} is in the order of 0.05–0.1 g COD in the gravity sewer, which is far lower than that in the aerobic microbial process. Therefore, M_B is approximately equal to M_{ae}, which is as follows:

$$\begin{aligned} M_B &\approx \frac{Y_{gr}}{1 - Y_{gr}} \cdot r_{re} \cdot K \cdot kg\ COD \\ &= 0.55 \cdot r_{re} \cdot K \cdot kg\ COD \end{aligned} \tag{3}$$

Two different consolidation periods of 0 and 30 days were used to simulate dry-weather periods. During these consolidation periods, the sediment bed was subjected to a constant and relatively low shear stress. The five types of samples (Storm sewer ID400, ID800, ID1000 and Combined sewer ID800, ID1000) were exposed to the same oxygen levels during consolidation for comparing the erosion characteristic between deposits from combined and SS. Each type had four parallel samples.

After consolidation, the sediments were laid on the flush pipe. Two different flows (1.30 L/s and 5.95 L/s) were set in these tests. An online particle test probe (Range: 0–10 g/L; Resolution: 0.1 mg/L; Model: SYCAMIN 7200 Germany) was set in the bucket for testing turbidity every 20 s. Simultaneously, aqueous samples were collected for analysing particle size by a Mastersizer 3000 laser diffraction grain size analyser (Range: 0.01–3,500 μm). The volume of every sample was 200 mL. DO was measured *in situ* using a Hydrolab DS5X multi-probe sonde (Hach, USA).

Critical shear stress was measured to analyse how it is affected by particle size, moisture, relative density and organic matters. Five sources (Storm sewer ID400, ID800, ID1000 and Combined sewer ID800, ID1000) of original sediments were measured. Critical shear stress was defined as the value of the shear stress that would yield a zero transport rate (Vanoni 1964). Different methods of detecting critical shear stress exist and can produce different values. The method for measuring critical shear stress was described by Seco *et al.* (2014). Moisture and organic content of sediments (volatile suspended solids/total suspended solids, VSS/TSS) were measured according to the Chinese standard method (CJ/T 221–2005). Oxygen uptake rates (OUR) of sediments were determined and modeled according to the description by Vollertsen *et al.* (1999). Relative density was measured by a densitometer (SARTORIUS BSA-DS3). In addition, redundancy analysis was used for correlation analysis by *R* language.

Stratified sampling experiment. To compare the erosion characteristics between combined and SS, parts of samples (Storm sewer ID400, ID800 and Combined sewer ID800) were stratified for particle size and moisture analysis.

RESULTS AND DISCUSSION

Sediment characterization

Median particle size (D50) of both CSSD and SSSD decrease with increasing pipe diameter. This finding illustrates that the proportion of small particles in large diameter pipes is higher than in small diameter pipes. There are two potential reasons: first, from the perspective of hydraulics and practical design calculations (Wei 2006), in a certain area, the flow rate in large diameter pipe is less than in a small diameter pipe. Therefore, small particles in large diameter pipes are less easily swept up than in small diameter pipes. In addition, sediments in small diameter pipes are washed into large diameter pipes, bringing together more small particles into large diameter pipes. Particle size of CSSD decreases (from ID400 to ID1200) are greater than in SSSD (Figure 2(a)). This finding is observed primarily because of sediments of higher particle size in small diameter combined sewers (CS). On a clear day, combined sewer systems are mainly used for transferring domestic sewage, the equivalent viscosity of which is two or three times the viscosity of water at the same temperature (Xu *et al.* 2014), which may promote the agglomeration of particles. The VSS content of CSSD, which is also affected by domestic sewage, is significantly higher than that of SSSD, but the difference between pipes of different diameters is not obvious (Figure 2(d)). Both the relative density of SSSD and CSSD from large size pipes (ID1000 and ID1200) are significantly lower than that from pipes of

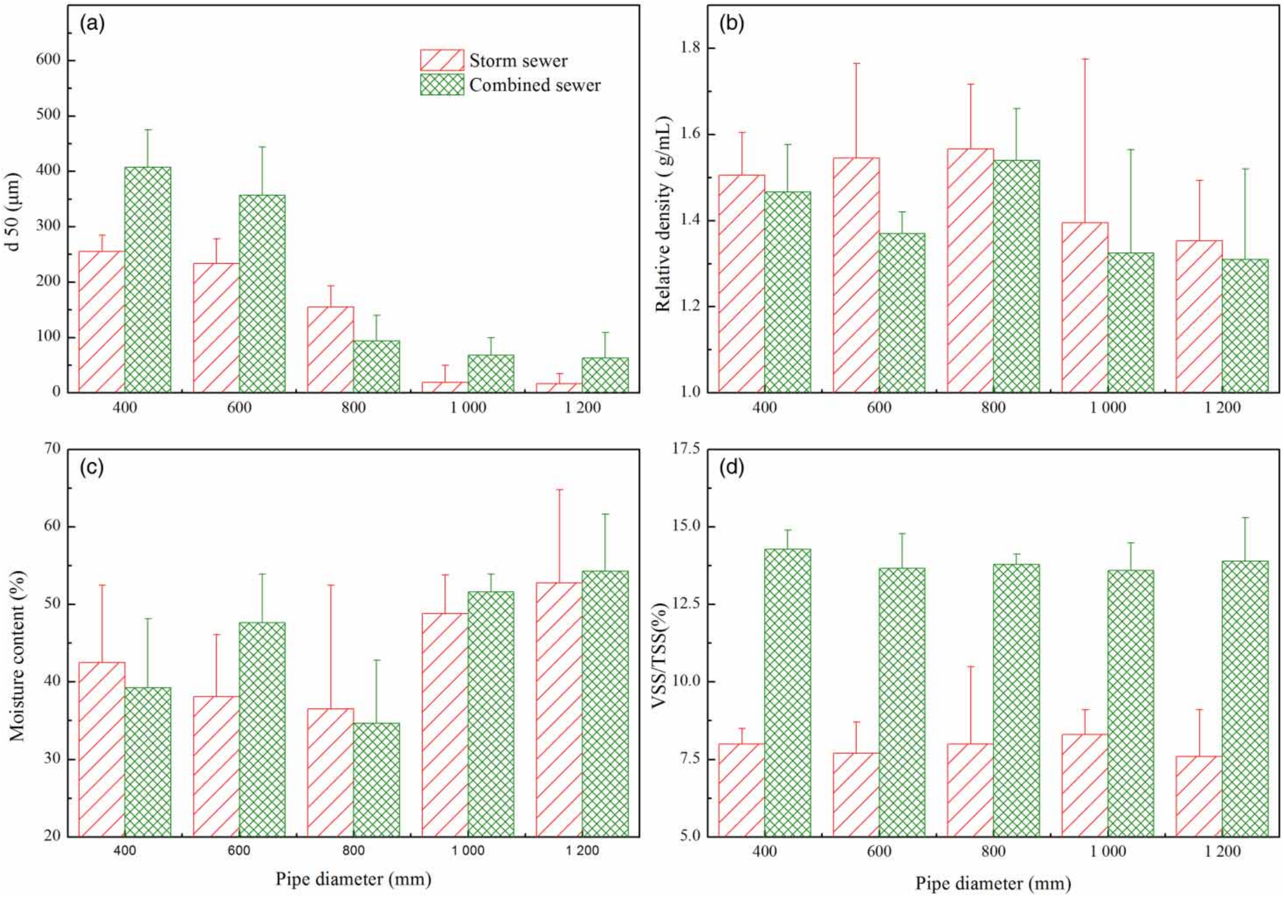

Figure 2 | Characteristics of sediments captured from the SS and the CS of different pipe diameters.

ID400 to ID800 (Figure 2(b)). Obviously, particle size shows a positive effect on this phenomenon. Additionally, the water content of SSSD and CSSD increases with large size pipes (Figure 2(c)).

Effects of consolidation period

The change in turbidity for the different consolidation times can be seen in Figure 3. In each case, the flow rate was given to provide a description of the shear stress acting on the bed. D50 and turbidity of the discrete samples were also given for each test to describe the quantity and characteristic (particle size) of deposits being eroded.

The turbidity value significantly increases under the higher flow condition (Q = 5.95 L/s), and the value of SS (ID1000) reaches its peak relatively later than other samples (Figure 3 (a)). Under the higher flow condition, the turbidity value of CSSD after consolidation of 30 days increases more than without consolidation; thus, it reaches its peak in a shorter time. This may suggest that its sub-layer is exposed earlier to a higher flow rate. In addition, the consolidation process may cause structural changes in the deposits and results in a separation between the surface layer and the bottom layer. Our results are consistent with the findings of Ristenpart (1995) and De Sutter *et al.* (2003) that the consolidation process could result in an increase of erosional strength with depth.

In field research, Gromaire-Mertz *et al.* (1998) and Ahyerre *et al.* (2001) found that the deposits grew regularly in the surface layer during dry weather periods, contributing to a large extent to the pollution (TSS and organic matters) of combined sewer overflows (CSOs). In drainage systems, the biofilm, the organic layer (OL) and the gross bed sediment are the three kinds of deposits (Ahyerre *et al.* 2000). Ahyerre *et al.* (2000) has established that the main pollution to be eroded was from the OL. In this study, the reduction ratio of organic matter is the lowest at the surface layer of sediment and increases continuously with increasing sediment depth after 30 days' consolidation (Figure S4, Supplementary material, available with the online version of this paper). The reduction ratio of the bottom layer is

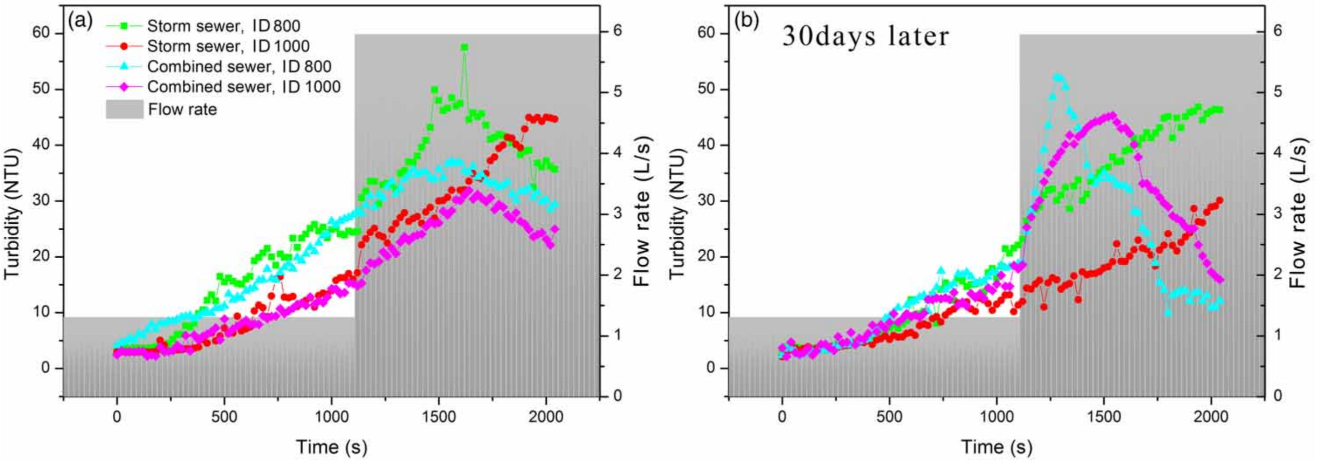

Figure 3 | Water turbidity changes against time under four conditions (SS: ID800, ID1000; CS: ID800, ID1000) with two different flow rates (1.30 L/s, 0–1,100 s and 5.95 L/s, 1,100–2,040 s), (a) 0 day consolidation, (b) 30 days' consolidation.

two times that of the surface layer, which leads fewer particles to be eroded from the deposits before shear stress increases (Figure 3(b)). VSS shows great positive effects on the critical shear stress of original sediments from CS-ID1000 and CS-ID800 (Figure 4). As shear stress increases, the turbidity value starts to increase rapidly (Figure 3(b)), when the surface layer no longer covers the whole surface and releases the material below itself. Thus, VSS is a key factor for the stability of deposits from CS. It is one of the reasons for sediment differentiation. Recent works have concluded that organic cohesion in sewer sediments can develop strong bonding forces between particles, which affects the behaviour of sewer deposits regarding their resistance to erosion (Seco *et al.* 2014). To a certain extent, polysaccharide and humus compounds can affect the viscosity of organic matter.

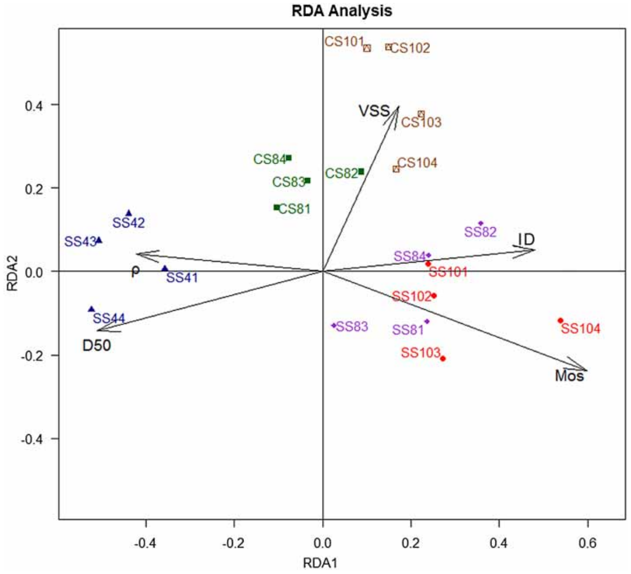

Figure 4 | Redundancy analysis regresses a response variable (shear stress, τ) on multiple explanatory variables (D50, VSS, Pipe ID, Moisture (Mos), relative density (ρ)), SS41–44: storm sewer, ID400, parallel samples NO.1 to 4; SS81–84: storm sewer, ID800, parallel samples NO.1 to 4; SS101–104: storm sewer, ID1000, parallel samples NO.1 to 4; CS81–84: Combined sewer, ID800, parallel samples NO.1 to 4; CS101–104: Combined sewer, ID1000, parallel samples NO.1 to 4.

Microbial biomass in sediments is positive to the rate of oxygen consumption in Equation (3). In this study, the sediment bed is subjected to a constant and relatively low shear stress before erosion experiments for consolidation. Thus, the surface layer of the sediment is in an aerobic environment, which promotes the growth of microorganisms. This finding further illustrates that with an increasing consolidation period, DO shows positive effects on microbial transformations of organic substrates (Vollertsen *et al.* 1999), and it is one of the reasons for the lowest reduction ratio of organic content in the surface layer of the sediments. Typical curves of OUR vs DO could be simulated in the following equation:

$$Y = \frac{Y_{\max} X}{A + X} \tag{4}$$

where Y is OUR ($gO_2\ m^{-3}\ h^{-1}$), $Y_{\max}$ is the maximum OUR of one sample, X is the DO concentration ($gO_2\ m^{-3}$), and A is a constant.

The results of the OUR determination show that the OUR of SSSD is lower than that of CSSD and higher from the large diameter pipes than from the small diameter pipes (Figure 5(a)). The significant amount of biomass in the CS could facilitate the growth of biofilms in the surface layer of sediments. The amount of biofilm is highest at the

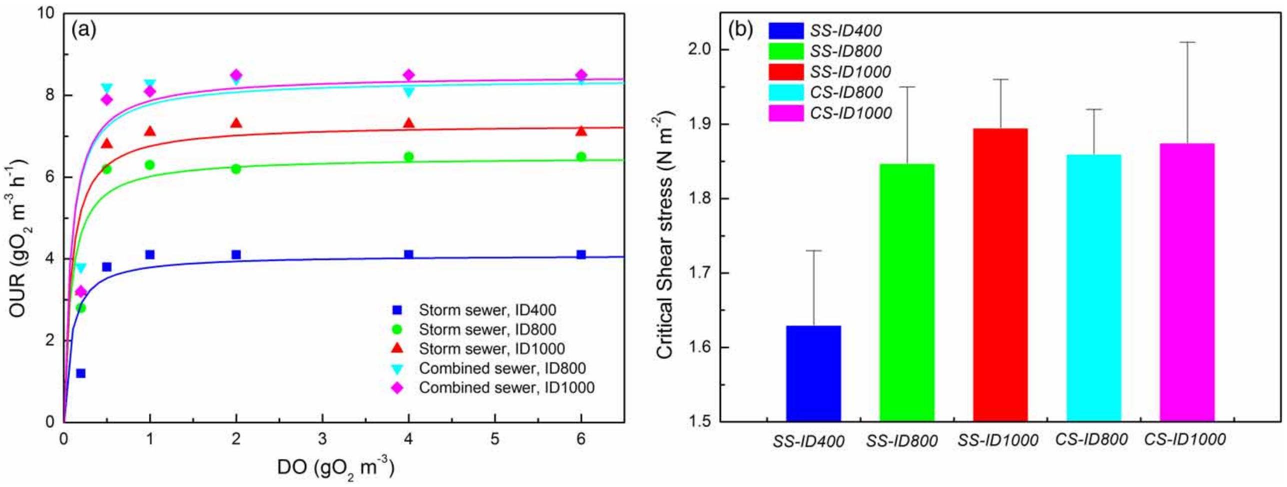

Figure 5 | (a) Typical curves of OUR vs DO concentration and simulations based on equation; (b) critical shear stress of sediments from five different types of sewers (SS-ID400, SS-ID800, SS-ID1000, CS-ID800, CS-ID1000).

surface layer of the sediments and decreases continuously with increasing sediment depth (Rocher *et al.* 2003). However, different studies have posited that bio-processes may weaken or enhance the strength of the in-pipe sediment deposits (Banasiak *et al.* 2005; Fang *et al.* 2014). However, there is no significant difference in the critical shear stress between SS and CS of large diameter (Figure 5(b)).

After 30 days' consolidation, the turbidity variation trend of the SSSD is steadier than that of CSSD (Figure 3(b)). The moisture content of SSSD regulated by different rainfall conditions has a positive effect on the erosion resistance of SSSD (ID800, ID1000) (Figure 4). Nevertheless the effects of VSS on these two types of sediments are not significant (Figure 4). A high proportion of illicit connections could cause an increase in organic matter in CSOs (Li *et al.* 2010). Therefore, this may imply few illicit connections remained in the study sewer networks, which is consistent with the previous perambulation. The particle size of the SSSD is less than that of the CSSD on average (Figure S5, Supplementary material, available with the online version of this paper). A smaller particle has a larger specific surface area; therefore, the static friction between particles of small size is greater than that of large size particles. In addition, organic matter in the sediment could also produce viscosity between particles. The critical shear stresses of sediments from SS-ID1000 and SS-ID800 are observed to be negatively affected by their particle size (Figure 4). Thus, the small size may improve the erosion resistance of the sediment from the above two types of pipelines. It could further illustrate that the viscosity was considerably smaller than the static friction force between the particles in this study. Because VSS of SSSD is less than that of CSS (Figure 2(d)), VSS content may have little effect on the erosion resistance of SSSD according to the above analysis. Therefore, after 30 days of consolidation, the variation of turbidity of the SS is not significant to some extent (Figure 3(b)). In the urban areas of Shanghai, SS of ID400 are typically used to connect rain grates and main pipes, which causes the characteristic differences between the sediments from a branch pipe (ID400) and main pipes (ID1000 or ID800). Simultaneously, water gushing occurs much more frequently in rain grates and branch pipes, where rainwater accumulates severely. Thus, on rainy days in urban areas, a significant amount of sediments frequently accumulate with high water content. This finding is consistent with the results shown in Figure 2(c). Overall, these findings indicate that the grain size and relative density of sediments are both important factors that affect the erosion resistance of sediments from the storm sewer of ID400 (Figure 4).

The variation of particle size against time is not as regular as the turbidity. Therefore, values of particle size are sorted from small to large order (Figure S5a, b, Supplementary material). The results show that CS-ID800 > CS-ID1000 > SS-ID800 > SS-ID1000 (Figure S5a, b, Supplementary material), but this is opposite to the peak time of turbidity (CS-ID800 < CS-ID1000 < SS-ID800 < SS-ID1000, Figure 3(b)). Therefore, the particle size of sediments may affect the interaction between the particles, thus modifying the erosion resistance of sediments. The effect of particle size on the interaction between particles may exist in the following two aspects: (1) small particles size leads to large specific area, which increases the friction between particles; (2) particles with large specific area could attach larger amounts of viscous organic matter (e.g., humic acid), which may increase the amount of microorganisms that inhabit their surface. Both microorganisms themselves and the EPS they secrete exhibit stickiness under adverse conditions, which will increase the viscosity of particles. In addition, after a consolidation of 30 days, it was found that the particle size was higher under the condition of large flow than under small flow (Figure S5a, b, Supplementary material). Therefore, it can be concluded that the distribution of particles has been changed to a certain extent after a period of consolidation, which is consistent with the conclusion drawn from the change of turbidity. This change may be related to the increase of particle size, caused by the aggregation of organic matter and the consolidation of inorganic particles.

Growth rate of particle size (D50) and moisture from bottom to surface of the sediments

Stratified analysis was carried out on the variation of the characteristic of sediments from the bottom to the surface (five layers) over the 30 days. After consolidation of 30 days, the D50 of each layer of sediment from all sources (except surface sediments from the storm sewer of ID400) had increased (Figure S6a, b, c, Supplementary material). In contrast, the water contents of each layer had a different degree of reduction (Figure S6d, e, f, Supplementary material). The bottom water content decreased more rapidly than the surface for both SSSD and CSSD (Figure S6d, e, f, Supplementary material). Thus, it can be concluded that the surface layer has a relatively higher water-holding capacity than that of the sub-layer, though the surface layer is always considered to be prone to losing water on account of its regular exposure to air. Cells and EPS from a biofilm layer are related to the particle concentration, which might be explained by the water holding capacity of cells and EPS (Cetin & Erdincler 2004). Actually, Chen *et al.* (2003) confirmed that a biofilm layer was present at the sediment surface in a sanitary gravity sewer. The water contents of 1–4 layer sediments from SS-ID400 all decreased significantly, but their growth rates of D50 all increased (Figure S6a, d, Supplementary material). This finding implies that most of the surface particles may settle into the lower space in the deposition process of sediments from SS-ID400. This is probably due to the lack of viscous organic matter in the storm sewer.

Overall, the growth rates of D50 and the water content in each layer of the combined sewer are lower than those of the storm sewer. Water content is a good reflection of the living state of microbial life (Erdincier & Vesilind 2000). Microorganisms can grow well under the condition of sufficient organic matter, which helps to maintain moisture. Under adverse conditions, microbials could produce EPS, which could form aggregate structures for adhesion around the particles, thereby increasing the particle size. This finding may be the reason for the increasing particle size of SSSD. Additionally, water loss in the sediment (especially in bottom sediments) accelerates the mineralization rate, which promotes the consolidation of the bottom layer. Thus, in the scour process, the turbidity has a gentle change of storm sewer (Figure 3(b)).

CONCLUSIONS

- CSSD and SSSD have different erosion patterns, which are affected by the consolidation period, pipe types, organic matter, particle size, moisture and relative density. Additionally, illicit connection is an important factor affecting the viscosity and static friction force of particles, altering the erosion resistance of sewer sediments.
- In the flux experiment, the quantity of eroded samples was determined by continuous monitoring. Under the higher flow condition, the turbidity values of CSS after 30 days of consolidation showed a greater increase than without consolidation. Additionally, the sub-layer is exposed earlier to the higher flow rate. As the shear stress increases, the surface layer no longer covers the whole surface and releases the material beneath itself. After consolidation, the reduction ratio of organic matter is lowest at the surface layer of the sediment and increases continuously with the increase in sediment depth after 30 days of consolidation. This ratio is one of the reasons for the differentiation of sediments, leading fewer particles to be eroded from the deposits before the shear stress increases. Based on previous researches, it is assumed that the consolidation process will result in an increase in erosional strength with depth (Ristenpart 1995; De Sutter *et al.* 2003). In contrast, this phenomenon is not obvious for SSSD. The VSS content of CSSD is higher than that of SSSD.
- The results of the variation in particle size show that CS-ID800 > CS-ID1000 > SS-ID800 > SS-ID1000; this finding is the opposite of the peak time of the turbidity. Therefore, the particle size of sediments may have some relationship with the interaction between the particles, thus affecting the erosion resistance of the sediments.

Under adverse conditions, microbials can produce EPS, which could form aggregate structures for adhesion around the particles, thereby increasing the particle size. This could be the reason for the increasing particle size of SSSD. Additionally, water loss of the sediment (especially in bottom sediments) accelerates the mineralization rate, which makes the bottom consolidation.

- The OUR of SSSD is lower than that from CSSD, which has a relationship with critical shear stress of sediments. However, there is no significant difference between the storm and CS of large diameter. Therefore, understanding quantitatively the direct impacts of microorganisms on the critical shear stress requires further analysis.
- The different illicit connection ratio causes the difference between CSSD and SSSD, which has strong effects on the CSOs and SSOs with different rainfall intensities. Elucidating the differences of time-varying pollutant loads between combined and SS can help to control overflows. Future laboratory investigation is needed, considering the influence of types of organic matters and microbial populations on erosion. In addition, a larger number of tests are needed to confirm the influence on critical shear stresses.
- Overall, this study will help to determine the parameters of flushing gates or weirs, based on different characteristics of sediments, in different combined and SS, which reduces the sedimentation in dry weather, and finally leads to a decrease in pollution from wet weather discharges.

ACKNOWLEDGEMENTS

These studies were financially supported by national water pollution control and management technology major projects (2014ZX07303-003). The authors would like to extend their appreciation to research team members for their help. We also appreciate Hong Kou Municipal Sewerage Co. Ltd for great help.

REFERENCES

Ahyerre, M., Chebbo, G. & Saad, M. 2000 Sources and erosion of organic solids in a combined sewer. *Urban Water* **2** (4), 305–315.

Ahyerre, M., Oms, C. & Chebbo, G. 2001 The erosion of organic solids in combined sewers. *Water Science and Technology* **43** (5), 95–102.

Banasiak, R., Verhoeven, R., De Sutter, R. & Tait, S. 2005 The erosion behaviour of biologically active sewer sediment deposits: observations from a laboratory study. *Water Research* **39** (20), 5221–5231.

Becouze-Lareure, C., Thiebaud, L., Bazin, C., Namour, P., Breil, P. & Perrodin, Y. 2016 Dynamics of toxicity within different compartments of a peri-urban river subject to combined sewer overflow discharges. *Science of the Total Environment* **539**, 503–514.

Biggs, C. A., Prall, C., Tait, S. & Ashley, R. 2005 Investigating the effect of storm events on the particle size distribution in a combined sewer simulator. *Water Science and Technology* **52** (3), 129–136.

Cetin, S. & Erdincler, A. 2004 The role of carbohydrate and protein parts of extracellular polymeric substances on the dewaterability of biological sludges. *Water Science and Technology* **50** (9), 49–56.

Characklis, W. G. & Marshall, K. C. 1990 *Biofilms*. Wiley, New York, NY, USA.

Chen, G., Leung, D. H. W. & Hung, J. 2003 Biofilm in the sediment phase of a sanitary gravity sewer. *Water Research* **37** (11), 2784–2788.

David, T., Borchardt, D., von Tümpling, W. & Krebs, P. 2013 Combined sewer overflows, sediment accumulation and element patterns of river bed sediments: a quantitative study based on mixing models of composite fingerprints. *Environmental Earth Sciences* **69** (2), 479–489.

De Sutter, R., Rushforth, P., Tait, S., Huygens, M., Verhoeven, R. & Saul, A. 2003 Validation of existing bed load transport formulas using in-sewer sediment. *Journal of Hydraulic Engineering* **129** (4), 325–333.

Erdincier, A. & Vesilind, P. A. 2000 Effect of sludge cell disruption on compactibility of biological sludges. *Water Science and Technology* **42** (9), 119–126.

Fang, H., Shang, Q., Chen, M. & He, G. 2014 Changes in the critical erosion velocity for sediment colonized by biofilm. *Sedimentology* **61** (3), 648–659.

Field, R. & Struzeski, E. J. 1972 Management and control of combined sewer overflows. *Journal (Water Pollution Control Federation)* **44** (7), 1393–1415.

Field, R., Pitt, R., Lalor, M., Brown, M., Vilkelis, W. & Phackston, E. 1994 Investigation of dry-weather pollutant entries into storm-drainage systems. *Journal of Environmental Engineering* **120** (5), 1044–1066.

Gromaire-Mertz, M., Chebbo, G. & Saad, M. 1998 Origins and characteristics of urban wet weather pollution in combined sewer systems: the experimental urban catchment "Le Marais" in Paris. *Water Science and Technology* **37** (1), 35–43.

Hvitved-Jacobsen, T., Vollertsen, J. & Nielsen, A. H. 2013 *Sewer Processes, Microbial and Chemical Process Engineering of Sewer Networks*, 2nd edn. CRC Press, Boca Raton, FL, USA.

Li, T., Tan, Q. & Zhu, S. 2010 Characteristics of combined sewer overflows in Shanghai and selection of drainage systems. *Water and Environment Journal* **24** (1), 74–82.

Li, T., Zhang, W., Feng, C. & Shen, J. 2014 Performance assessment of separate and combined sewer systems in metropolitan areas in southern China. *Water Science and Technology* **69** (2), 422.

Ristenpart, E. 1995 Sediment properties and their changes in a sewer. *Water Science and Technology* **31** (7), 77–83.

Rocher, V., Azimi, S., Moilleron, R. & Chebbo, G. 2003 Biofilm in combined sewers: wet weather pollution source and/or dry weather pollution indicator? *Water Science and Technology* **47** (4), 35–43.

Seco, I., Gómez Valentín, M., Schellart, A. & Tait, S. 2014 Erosion resistance and behaviour of highly organic in-sewer sediment. *Water Science and Technology* **69** (3), 672.

Vanoni, V. A. 1964 *Measurements of Critical Shear Stress for Entraining Fine Sediments in a Boundary Layer*, *W. M. Keck Laboratory of Hydraulics and Water Resources Report, 7*. California Institute of Technology, Pasadena, CA.

Vollertsen, J., Almeida, M. D. C. & Hvitved-Jacobsen, T. 1999 Effects of temperature and dissolved oxygen on hydrolysis of sewer solids. *Water Research* **33** (14), 3119–3126.

Wei, L. 2006 *User's Manual for Hydraulics Calculation, Code of Practice for Design and Construction.* Water Conservancy and Hydropower Press (in Chinese), Beijing (Reprinted).

Wei, B. 2012 *Analysis of Sewer Sludge Characteristics and Study on Sewer Sludge Thickness Measurement.* Master degree, Tongji University, Shanghai.

Xu, Y., Wu, Y. & Sun, Q. 2014 Flow characteristics of the raw sewage for the design of sewage-source heat pump systems. *The Scientific World Journal* **2014**, 503624.

Zgheib, S., Moilleron, R., Saad, M. & Chebbo, G. 2011 Partition of pollution between dissolved and particulate phases: what about emerging substances in urban stormwater catchments? *Water Research* **45** (2), 913–925.

First received 11 December 2016; accepted in revised form 25 January 2017. Available online 8 February 2017