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A Study on the Installation of a Sewage Separator Pipe inside an Existing Combined Sewer System for CSO Control

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기존 합류식 하수관거에 CSO 제어를 위한 하수분리관의 설치에 관한 연구

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Abstract

Sewage separation which often involves installing a new pipe to separate wastewater flow from stormwater runoff flow can be costly and depends highly on its feasibility in a site. To be able to develop a potentially more economical alternative that can also lessen major road traffic disturbance during this process, a different approach where a smaller sewage separator pipe is installed inside an existing combined sewer pipe was investigated. A small-scale of a box sewer and the proposed sewage separator pipe was constructed in the laboratory to observe and compare the deposition of solids and other solid-associated major pollutants at different flow rates. In addition, three-dimensional flow simulations considering five different scenarios were conducted using Ansys Fluent to observe the effect of the proposed sewage separator pipe to the hydraulic flow if installed inside the combined sewer pipe. Results revealed that the deposition of TSS, TCOD, TN, and TP were reduced by at least 60% when the wastewater was conveyed by the sewage separator pipe instead of the combined sewer pipe. Moreover, the flow simulations conducted showed that there was little to no major disturbance in hydraulic flow and velocity distribution when the sewage separator was installed inside a straight pipe and even at pipe transitions such as intersections, turns, and drop in elevation. Considering the pipe dimensions and the results of the study, the proposed approach can be promising in terms of reduction in pollutant deposition without a major effect on the hydraulic flow. Further investigation and cost-analysis should be done in the future to support these preliminary findings and help alleviate the problems caused by combined sewer overflows by introducing an alternative approach.

Key words : combined sewer system, nonpoint source pollution, sewage separation, stormwater runoff

요 약

유역으로부터 발생되는 강우유출수가 하수관거로 유입되는 것을 방지하기 위하여 별도의 우수전용관을 설치하는 것은 많은 비용이 수반되며 현장 시공여건에 따라 대단히 어려운 경우가 있다. 본 논문에서는 교통 및 도로 여건상 시공이 어려운 곳에 경제적인 접근방법으로 기존의 하수관거에 별도의 하수분리관을 설치하는 단순하면서 혁신적인 방안에 관한 연구결과를 제시하였다. 실험실 규모의 하수관거 실험장치를 통하여 얻은 결과에 따르면 기존의 관거를 하수 및 우수전용 공간으로 분리할 경우 관내유속을 증가시켜TSS, TCOD, TN, TP 퇴적율을 각각 74-88%, 79-90%, 75%, and 67-90%, 정도 감소시킬 수 있는 것으로 나타났다. 또한 3차원 수리유동 모의결과 하수분리관의 설치가 직선구간, 접속구간, 곡선 및 낙차구간에서 하수의 흐름 및 유속분포에 미치는 영향이 미미한 것으로 분석되었다. 그러나 접속구간에 분리관을 설치할 경우 접속면 지역은 유입되는 강우유출수의 운동에너지에 의한 구조물 훼손을 방지하기 위하여 보강해야 할 것으로 판단된다. 또한 곡선부에서 분리관은 곡선부의 안쪽보다는 외곽쪽에 설치하는 것이 구조적으로 안정 적인 것으로 분석된다. 이와 같은 연구결과를 바탕으로 폭 3 m 제원을 갖는 하수관거에는 약 0.4 m × 0.4 m 분리관 설치가 적합한 것으로 나타났다.

핵심용어 : 강우유출수, 합류식 하수관거 시스템,하수분리, 비점오염

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1. Introduction

A combined sewer system (CSS) can be defined as a single pipe system which transports sanitary sewage on dry days and a mix of sewage and stormwater runoff on rainy days. The cross-sectional area of the combined sewage pipe has to be large because sewage and rainwater must be treated simultaneously in a single pipe. However, during the dry season, the flow of wastewater is small as compared to stormwater runoff. This results to low flow rate and velocity where suspended solids can settle and be deposited to the bottom of the pipe (Lange and Wichern, 2013; Silvagni et al., 2014).

Combined sewers have been reported to pose several disadvantages (Dittmer et al., 2020; Tibbetts, 2005;). Since suspended solids and other solid-associated contaminants in wastewater are deposited to the bottom of the combined sewers before reaching the sewage treatment plant, the concentration of pollutants reaching these plants is lower than the design concentration resulting to wasted treatment capacity. Moreover, in cases where the dissolved oxygen levels become low, odor-causing gases such as NH_3, CH_4, and H_2S are generated by biological reduction processes that occur under anaerobic conditions. This poses health risks and lowers the quality of the life of the community in the vicinity of the pipeline. When heavy rainfall occurs after a period of dry days, a mixture of untreated stormwater runoff and wastewater flows through the combined sewer at a rapid rate and washing off the sediments and other pollutants that have accumulated at the bottom of the pipe. When the capacity of the CSS is exceeded, combined sewer overflow (CSO) can occur. For example, 86% of Seoul is serviced by combined sewers and the inflow of water to treatment plants can reach 5.09 million m^3/day which exceeds the city's treatment capacity of 3.71 million m^3/day (Kim, 2018). To prevent flooding and public health risks, CSOs are traditionally discharged directly into receiving waters through CSS outfalls. The untreated discharge causes another problem because the combined sewage potentially includes high concentrations of nonpoint source pollutants that has caused many receiving waters to exceed water quality standards resulting in threats to public health and aquatic species and may also compromise the aesthetics and limit recreational uses of water bodies (USEPA, 1999). Even on dry seasons, in cases where the CSS is connected to permeable areas such as parks and urban landscapes, the infiltration flow generated from these areas will go to the wastewater treatment plants instead of the rivers which causes drying water bodies while there is uneconomical operation of wastewater treatment plants.

In order to alleviate the problems caused by combined sewage systems, the Korean government has been promoting extensive sewage pipe maintenance projects with the help of private institutions. Another solution is sewer separation where the combined sewer systems are converted to separate sewer systems so that wastewater and stormwater runoff can be treated separately (Abaas et al., 2019; Mannina and Viviani, 2009; Schaarup-Jensen et al., 2011). This is more efficient since the two has different pollutant concentrations and stormwater tends to have varying flow rates while wastewater flow is relatively steady. The stormwater runoff will also be discharged in their natural receiving waters while a better treatment will be provided for wastewater and will avoid CSOs (Thorndahl et al., 2013). However, they can be costly and will create a huge disturbance to traffic during construction. Conventional sewer separation process basically involves either constructing new storm drains and using the existing combined sewers as sanitary sewers or constructing new sanitary sewers and using the existing combined sewers as storm drains. It can also be a combination of the two. Either way, the process will require disconnecting existing pipes including the ones connected to public and private properties and more excavation works for the laying of the new pipe system. Therefore, most of these projects are concentrated on smaller cities where the disturbance by maintenance and construction is minimal.

Therefore in this study, a different approach to sewage separation was investigated. A lab-scale of the proposed design was constructed and laboratory experiments were conducted to compare the changes in the deposition of major pollutants such as sediments, organic matter, and nutrients during dry days. In addition, 3D hydraulic flow modeling was also conducted to simulate the changes in flow and velocity distribution inside the proposed design considering different scenarios during storm days. The proposed design can potentially be more economical, is expected to require less space and excavation works, and might cause less disturbance in traffic during installation. However, the focus of this study is limited to comparative analysis of the deposition of major pollutants as well as hydraulic flow. It aims to provide preliminary results which can contribute to developing an alternative to the conventional sewage separation process. A cost-analysis or a feasibility study is outside the scope of this research but should be done in the future.

2. Materials and Methods

2.1 Proposed retrofit design

In order to solve the problems related to the existing combined sewer systems in Korea, an internal sewage separation pipe that can be assembled and installed inside a box-type combined sewer pipe as shown in Fig.1 was investigated. The separation

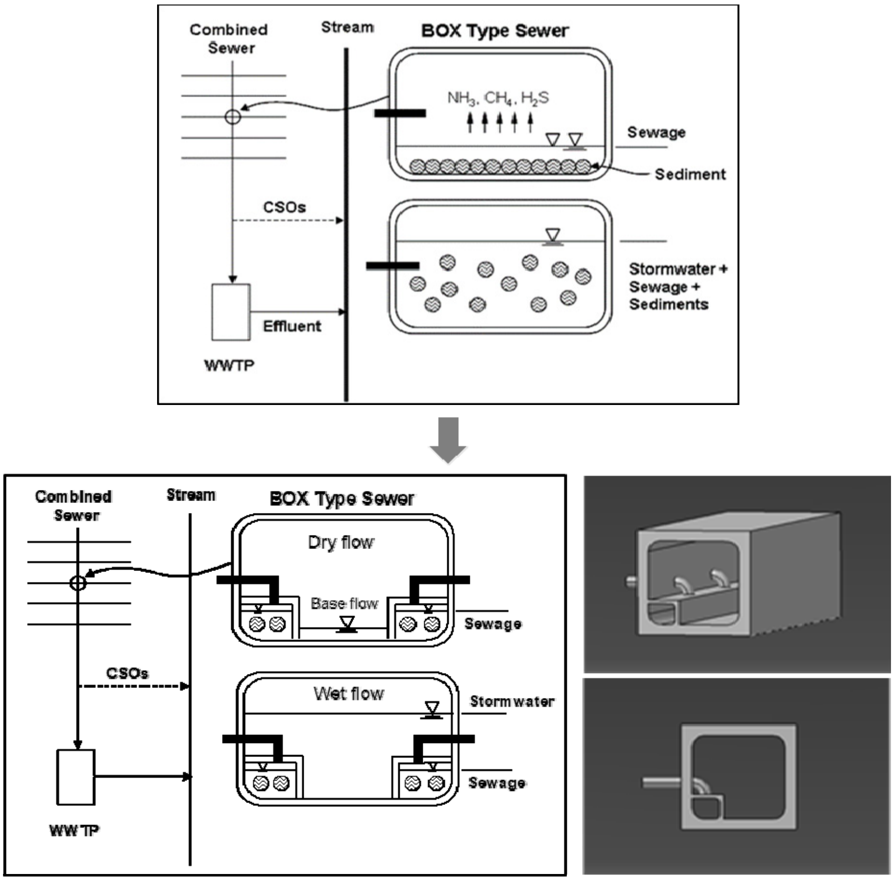

Fig. 1. Conventional combined sewage system and the proposed retrofit design with separator pipe.

pipe can be installed on one side or two sides of the box pipe depending on the required capacity and will be connected to the community sewage pipes to be able to collect wastewater during dry days. On rainy days, it will continuously collect sewage while the rest of the space inside the combined box sewer pipe will collect the stormwater runoff. With this proposed design, the excessive costs and traffic disturbance related to converting combined sewer systems to separate sewer systems may be avoided. To investigate the feasibility of this design in terms of hydraulic flow and pollutant concentrations, laboratory experiments as well as hydraulic simulations were conducted.

2.2 Experimental setup and analysis

A model of a combined sewage system was constructed in the laboratory at a scale of 1:10 to 1:15 as shown in Fig. 2. It consists of a 0.5 m × 0.3 m × 0.2 m (L × W × H) flow distribution tank, a 0.8 m × 0.8 m × 0.8 m mixing tank, a combined sewer pipe (CSP), a sewage separator pipe (SSP), connectors, and a circulation pump. The device was made of plastic and polyvinyl chloride (PVC) pipes with valves to control the flow. The pipes were mounted on a metal support for stability. The CSP has dimensions of 0.2 × 0.2 × 5 m (WxHxL) while the SSP was 0.03x0.03x5 m which makes the cross-sectional are of SSP 15% of that of CSP.

The inflow for the experiments was sewage collected from a combined sewer in Seosan City, Korea. Major pollutant concentrations in the samples were measured as 540 mg/L total suspended solids (TSS), 168 mg/L total chemical oxygen demand (TCOD), 18.0 mg/L total nitrogen (TN), and 1.83 mg/L total phosphorus (TP). These are typical pollutant concentrations for wastewater in Korea. The sewage was allowed to flow to both CSP and SSP at three different target flow rates of 5, 10, and 15 m^3/day. Each experiment was conducted for 3 hours after which tapwater was fed to each pipe to be able to collect the solids that have settled at the bottom. The wash water resulting from this final step was analyzed for total suspended solids concentration and to be able to compare the amount of deposited solids under each pipe. Concentrations of TSS, TCOD, TN, and TP were determined using the Standards Methods for the Examination of Water and Wastewater (APHA et al., 1995). Furthermore, the pollutant depositions were measured from the sediments that were collected in the pipe at the end of each experiment. Pollutant deposition rates were determined by dividing the mass of the deposited sediments by the length of the pipe and the

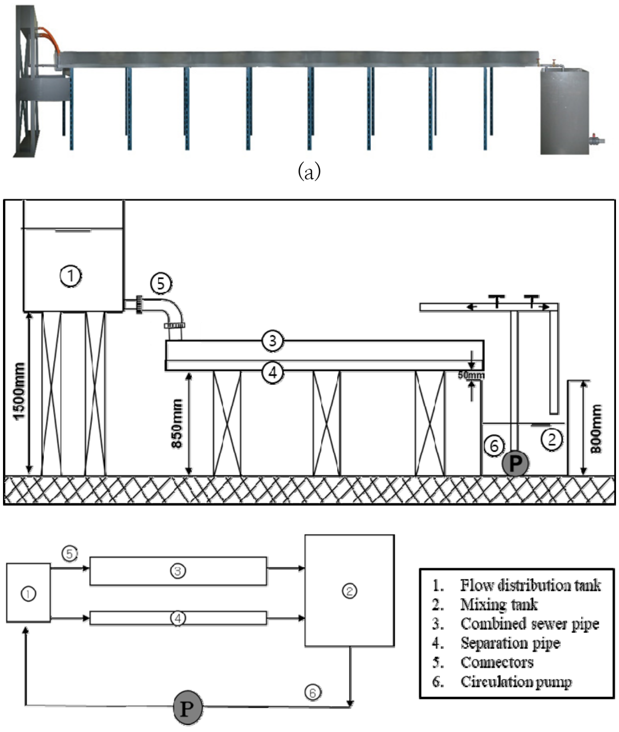

Fig. 2. (a) Photo and (b) schematic diagram of the lab-scale combined sewer system with the proposed retrofit design.

duration of the flow which was 3 hours. Since the flow was maintained at steady-state, it was assumed that the deposition rates were uniform throughout the experiment. The decrease or increase in deposition rates were from the comparison of values calculated based on the collected sediments in the two pipes (CSP and SSP).

2.3 Hydraulic simulation

Hydraulic flow analysis was conducted using a three-dimensional (3D) flow model in Fluent. Fluent is a fluid simulation software that can be used to predict flow, heat, and mass transfer using the finite volume method. It was used to simulate five scenarios: (1) CSP and SSP (2) CSP and CSP+SSP (3) CSP and CSP+SSP with a right angle intersection (4) CSP and CSP+SSP with 45° turn (5) CSP and CSP+SSP with 11.3 slope. These are based on typical pipe conditions that can be expected in a sewer network. The details of the simulations are summarized in Table 1. Scenario 1 was simulated for dry days to compare the hydraulic behavior of wastewater between the two pipes. Scenarios 2 to 5 were simulated for storm days where CSP is compared with another CSP installed with an SSP to compare the effect of adding the SSP to the hydraulic flow. Scenarios 3 to 5 were simulated to investigate the effect of different potential disturbances in flow such as an intersection, a bend, and a steeper slope. Moreover, the slope of the pipes from inlet to outlet were set at 1° and the inlet velocities were set at 2 m/s at 1 m water depth except for scenario 1. The pipes used for the different scenarios for the hydraulic flow simulations are shown in Fig. 3.

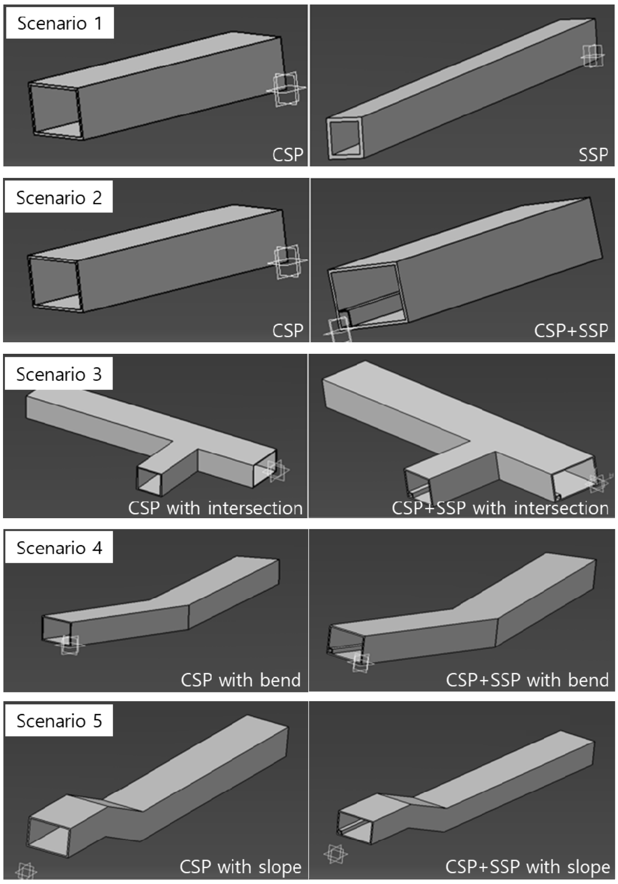

Fig. 3. Different scenarios used in the hydraulic flow simulations.

Table 1. Details of the different scenarios used in the hydraulic flow simulations

Scenario	Description	Dimensions (WxHxL), m		Water depth at inlet, m	
		CSP1	SSP2	Inlet velocity, 0.4 m/s	Inlet velocity, 2 m/s
1	CSP and SSP, dry day	3 × 0.4 × 10	0.4 × 0.6 × 10	0.2	0.3
2	CSP and CSP+SSP, storm day	3 × 2 × 30	0.4 × 0.4 × 30	-	1
3	CSP and CSP+SSP with intersection, storm day	3 × 2 × 30	0.4 × 0.4 × 30	-	1
4	CSP and CSP+SSP with 45° turn, storm day	3 × 2 × 30	0.4 × 0.4 × 30	-	1
5	CSP and CSP+SSP with 11.3° slope, storm day	3 × 2 × 30	0.4 × 0.4 × 30	-	1

[1]CSP = combined sewer pipe, [2]SSP = sewage separator pipe

3. Results and Discussion

3.1 Pollutant deposition

Fig. 4 shows the variation of wastewater flow through CSP and SSP during the experiments. It was clear that the flow in both pipes were similar during each 3-hour experiment and that the flow rates were maintained constant throughout the experiments. It should be noted that the experiment was conducted in such a way that wastewater was allowed to flow through both pipes simultaneously. The similarity in flow in both pipes is essential to be able to compare the pollutant deposition rate between them without having to consider the flow rate as a varying factor. Average flows in CSP were 4.8, 9.5, and 13.8 m^3/day in three separate runs while the corresponding flow in SSP were 4.2, 9.2, and 13.4 m^3/day, respectively. This resulted to flow velocities of 15, 18, and 20 cm/s in CSP and 17, 24, and 26 cm/s in SSP. The flow velocities in SSP ended up higher than those in CSP due to its smaller cross-section.

The effect of higher flow velocities in SSP resulted to substantial changes in pollutant deposition which can be seen in Fig. 5. In CSP, the measured deposition rates were 1.36-2.81 kg/km-hr for TSS, 0.63-0.87 kg/km-hr for TCOD, 0.025-0.027 kg/km-hr for TN, and 0.006-0.01 kg/km-hr for TP. Meanwhile, the corresponding deposition rates measured in SSP were 0.26-0.35 kg/km-hr for TSS, 0.09-0.13 kg/km-hr for TCOD, 0.006-0.007 kg/km-hr for TN, and 0.001-0.002 kg/km-hr for TP. This results to a decrease in deposition of 74-88% TSS, 79-90% TCOD, 75%TN, and 67-90% TP. The smaller cross-section of CSP that led to higher flow velocities improved the transport of sediments and other sediment-associated pollutants. In addition, the higher flow rates in CSP seemed to lead to higher pollutant deposition rates whereas it didn't affect the deposition in SSP. Because of the larger cross-section and lower flow velocities in CSP, the amount of pollutants that can settle at the bottom of the pipe increases with increasing flow rates. On the other hand, the increasing flow rates will not affect the settling in of pollutants in SSP because the higher flow velocities and water levels will

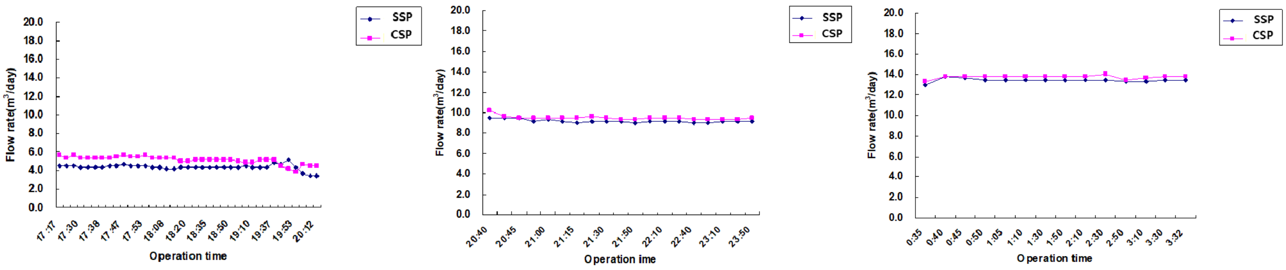

Fig. 4. Varation of flow rate during the experiments.

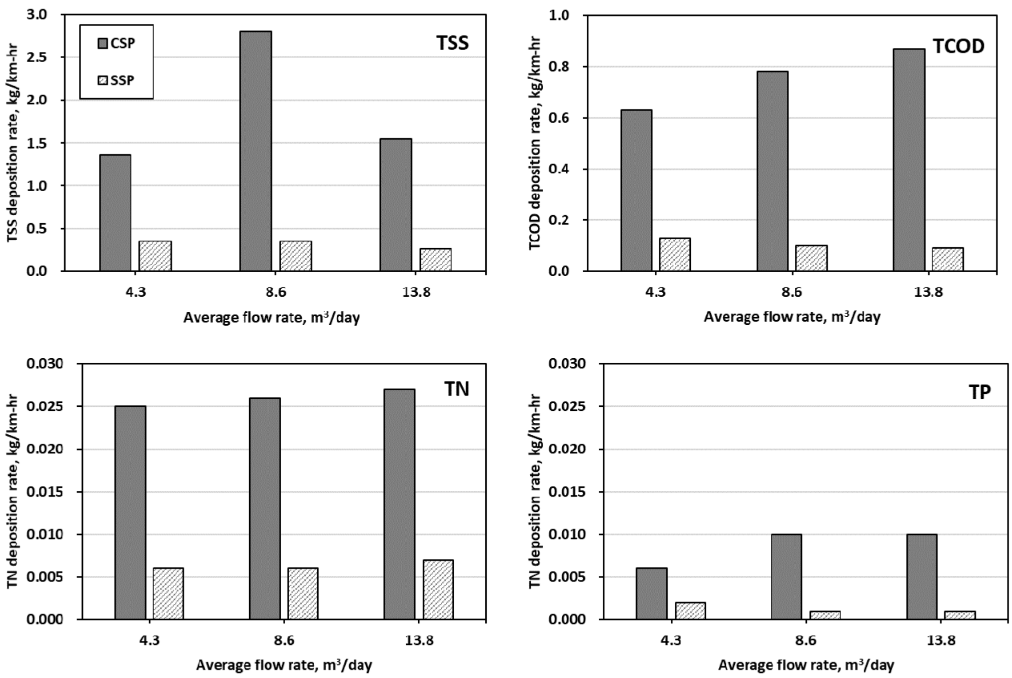

Fig. 5. Deposition of major pollutants at the bottom of CSP and SSP.

not give them a chance to settle at the bottom of the pipe. Therefore, the addition of a sewage separator pipe inside the combined sewer pipe for wastewater flow during dry days is an effective retrofit to combined sewer systems in terms of decreasing pollutant deposition.

3.2 Hydraulic simulation and comparison of flows between the combined sewer and sewage separator

The results of the flow simulation using scenario 1 in terms of flow velocity distribution along the length of both CSP and SSP during dry days can be seen in Fig. 6. Assuming that the flow rates in the two pipes were the same, the flow velocity along the length (x-z plane) was in the range 0.4-2.5 m/s. Meanwhile, the flow velocity in SSP was 2.0-3.5 m/s. This shows that the increase in velocity if the wastewater is made to flow through the sewage separator instead of the combined sewer could be as high as 1.6 m/s more. Meanwhile, there was no visible difference between the distributions of flow along the length of both pipes based on the figure. The same can be said in terms of the cross-section (y-z plane, not shown in the figure) where the flow velocities in CSP ranges at 0.025-0.05 m/s and while that in SSP ranges at 0.04-0.08 m/s. Note that the velocities are expressed in terms of the movement in the described plane. Therefore the velocities measured along the cross-section was slower than that along the length of the pipes. This finding supports the result of the experiments where the wastewater flow velocity will increase if made to flow inside the sewage separator instead of the bigger combined sewer during dry days. This increase in flow will affect the settling of solids and the deposition of solid-associated pollutants at the bottom of the pipe.

3.3 The effect of adding a sewage separator to hydraulic flow

Installing an SSP inside an existing CSP can potentially affect the hydraulic behavior of stormwater runoff because the SSP can be an obstacle to the water flow. Thus, a comparison between CSP with and without SSP was conducted. The result of the simulation under scenario 2 (storm day) in terms of the flow velocity of the stormwater runoff is shown in Fig. 7. Contrary to the expected result, there was no major disturbance in flow due to the added SSP inside the CSP. As seen in the figure, the distribution of velocity along the length of both pipes were similar at long sections y = 0.3 m, y = 1.5 m, and y = 2.5 m. There was a difference in velocity of about 0.5 m/s between the section at y = 0.3 m, where the SSP was installed and the section at y = 2.5 m near the opposite wall where no SSP was installed. Considering the cross-sections at × = 15 m and × = 25 m from the inlet, it was observed that the flow of water on the side where no SSP was installed tend to be higher than that on the side where there was an

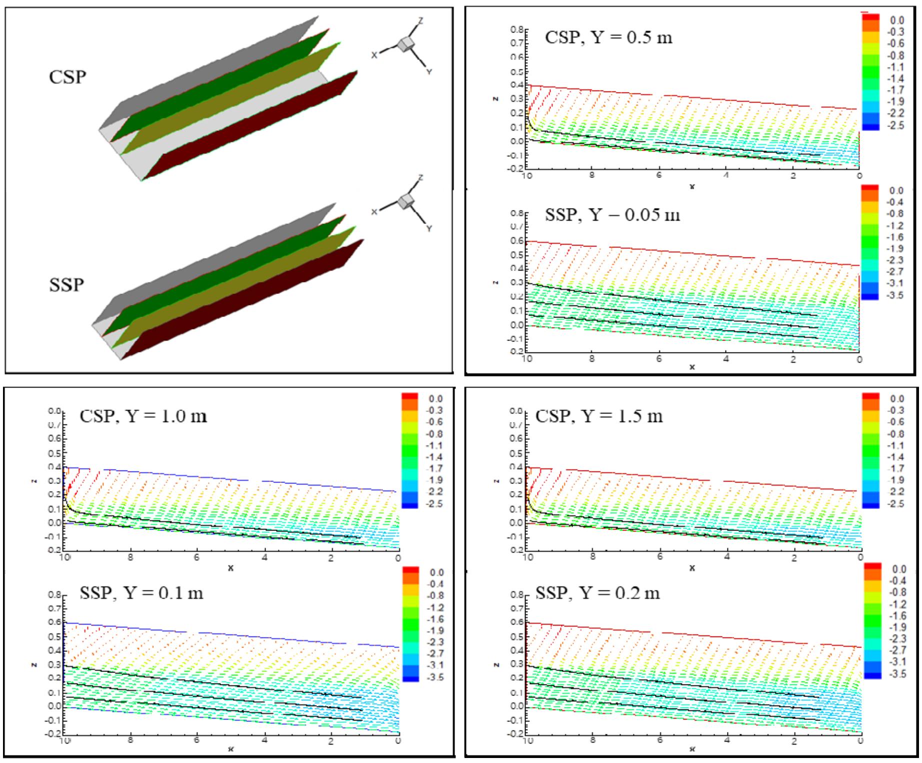

Fig. 6. Distribution of flow velocities along the length of the combined sewer and sewage separator pipes (Scenario 1).

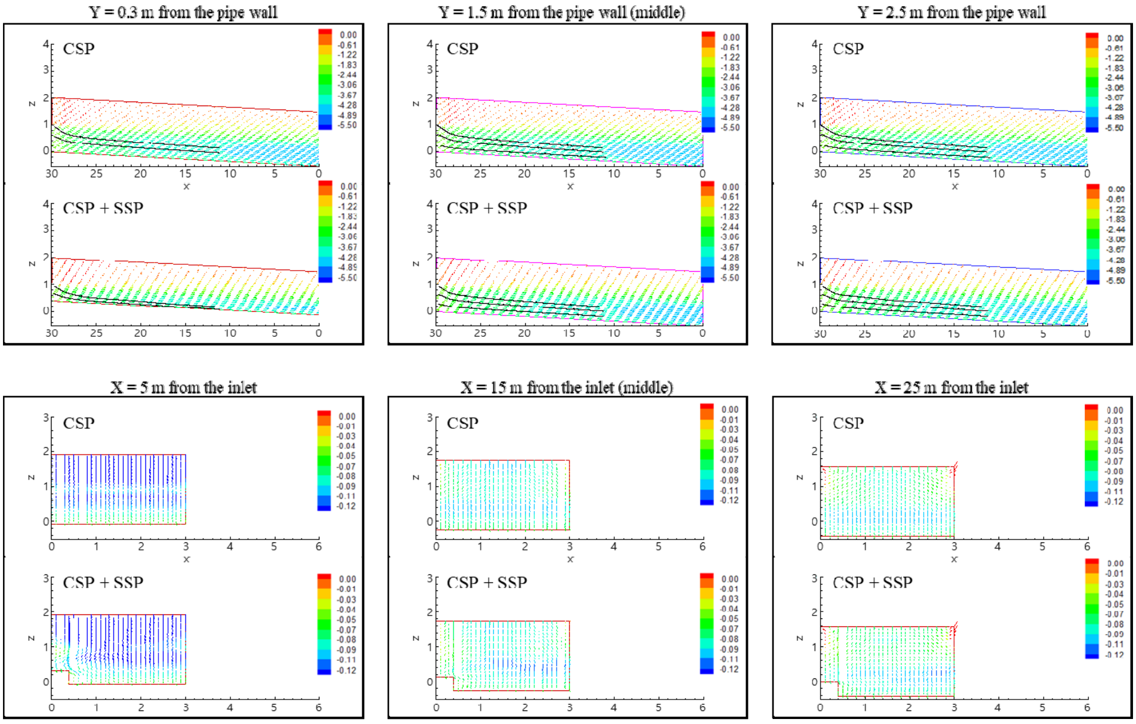

Fig. 7. Distribution of flow velocities along the length and cross-section of the combined sewer and combined sewer with sewage separator pipe (Scenario 2).

SSP which was expected. However, the difference in velocities where not that high (~0.05 m/s). Considering the results from scenario 2 using a straight CSP with SSP on a storm day, installation of a 0.4 × 0.4 m separator pipe along a 3.0 m width box sewer and considering a water level of 1 m, the SSP did not cause a major hydraulic flow disturbance.

3.4 The effect of adding a sewage separator to the hydraulic flow in pipe transitions

More simulations comparing CSP with and without SSP were conducted, this time considering piper transitions namely a right angle or 90° intersection, a 45° turn, and a 11.3° slope (1 m drop over a 5 m pipe length). First, the results of the simulations with a right angle intersection can be seen in Fig. 8 where it clearly shows the change in the shape of flow at the point of intersection. In the case where there was no SSP installed, the flow velocity in the main pipe along the x-axis was much lower than that in the intersecting pipe along the y-axis and the combined flow was less disturbed. A rise in water level was also observed due to the force of the incoming flow from the intersecting pipe. On the other hand, in the case where there was an SSP installed, the energy from the intersecting flow was dissipated and did not cause a rise in water level. However, turbulence and eddy currents occurred at the area after crossing the SSP and the combined flow had a higher velocity. This means that if installing an SSP inside a CSP to separate the wastewater and stormwater, the part around the area of intersections should be reinforced or made stronger during the retrofit process. Alternatively, flow dissipation mechanisms can be employed to reduce the resulting turbulence

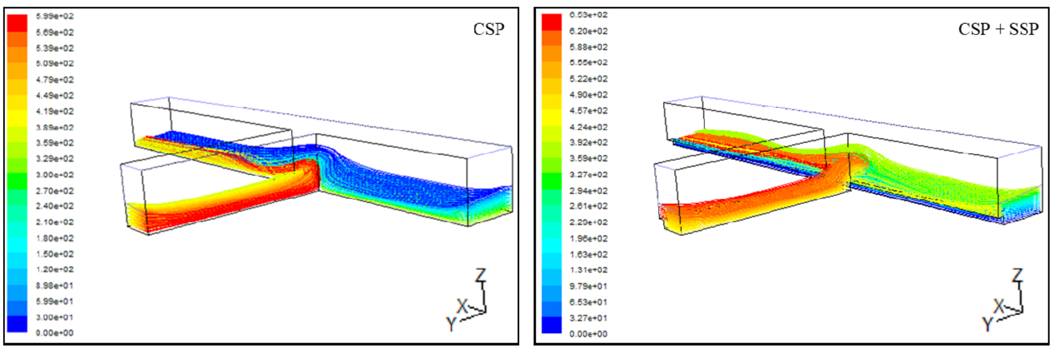

Fig. 8. Path lines and flow velocity distributions in a pipe with a right angle intersection (Scenario 3).

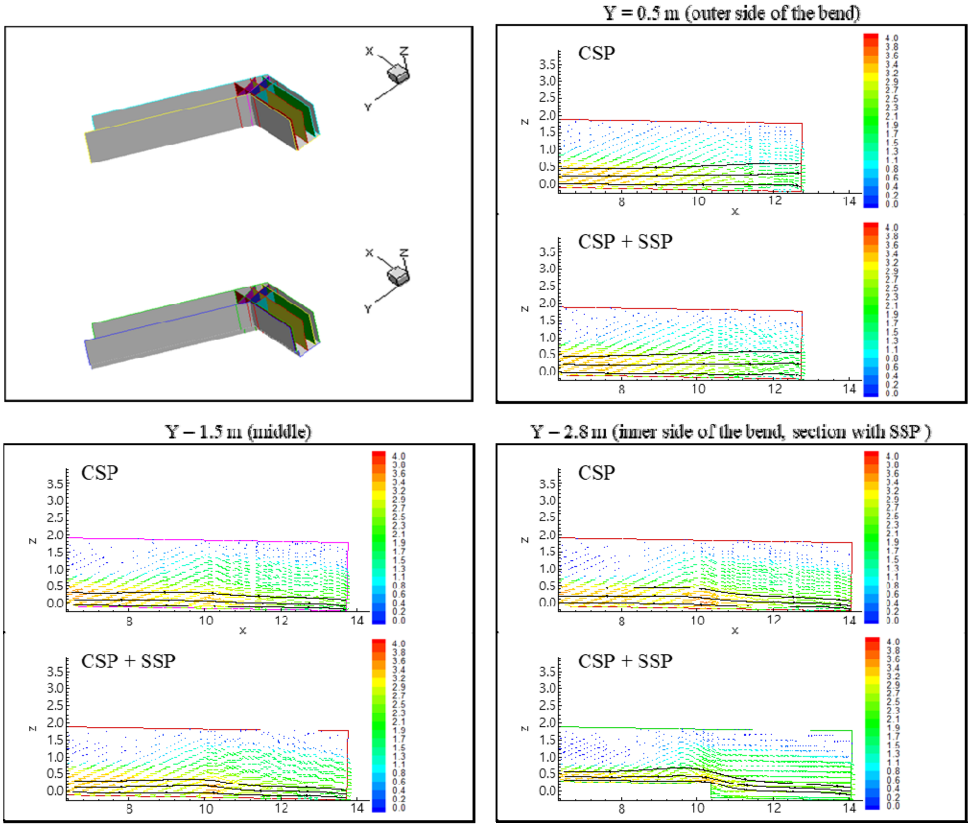

Fig. 9. Distribution of flow velocities along the length of the combined sewer and combined sewer with sewage separator pipe considering a 45° turn (Scenario 4).

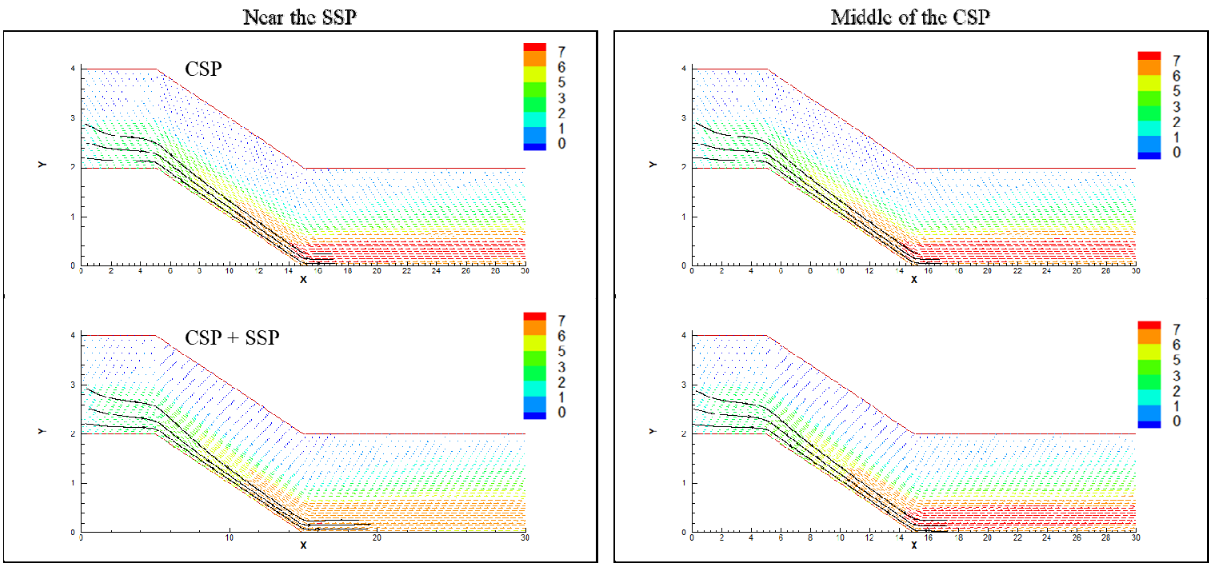

Fig. 10. Distribution of flow along the length of the combined sewer and combined sewer with sewage separator pipe considering a 11.3° slope (Scenario 5)

caused by any SSPs perpendicular to any intersecting flows.

Meanwhile, the results from Scenario 4 where a bend or turn was considered is shown in Fig. 9. From the distribution of flow at long sections y = 0.5 m, y = 1.5 m, and y = 2.8 m, it can be seen that the installation of SSP inside a CSP has no huge impact on the hydraulic flow where bends occur. This is because the direction of the bend is the same for both pipes. However, the bend itself caused a headloss that resulted to the decrease in flow rate after the water passes through it. This was observed in both pipes. In addition, a rise in water level was observed in the outer part of the bend (y = 0.5 m) causing a jump in the area (between × = 10 m and x= 11 m). This means that when installing an SSP inside a CSP with a bend, the SSP should be positioned on the outside part of the bend to make it more structurally stable since the CSP will act as a support for the SSP when the water hits the bend.

In the case where the pipe drops 1 m over a 5-m length resulting to a steep slope of 11.3° , there was also no remarkable change in hydraulic behavior between the CSP without SSP and with SSP. However, in both pipes, the flow accelerated through the slope resulting to a lower water level which increased as stormwater goes further down the length of pipe after the drop (Fig. 10).

4. Conclusions

For the purpose of developing a potential alternative to converting combined sewage systems to separate sewage systems, a different approach was introduced and investigated using lab-scale experiments as well as 3D modeling. Experimental results revealed that installing a smaller SSP inside an existing box-type CSP to accommodate the flow of wastewater during dry and storm days results to higher flow velocities which resulted to a decrease in the deposition of major pollutants between 67-90%. The increase in flow velocities was corroborated by the results of the 3D flow modeling simulated in Fluent where the same amount of water was made to flow through CSP and SSP. The results of the simulation showed that the velocity of wastewater could be increased by 1.6 m/s if made to flow through the SSP instead of the CSP. Moreover, there was no major difference observed between the flow path and velocity distribution along the length and cross-sections of CSP and CSP+SSP under different scenarios considering pipe intersections, turns or bends, and steep slopes or drops. Minor flow disturbances that were observed and possible pipe damage, if there is any, were believed to be easily avoided by reinforcing certain portions of the pipe itself.

These findings suggest that in terms of pollutant deposition and hydraulic flow, a single and smaller pipe installed inside a combined sewer pipe to convert it to a separate sewer system has a potential to be an alternative approach to separating combined sewer systems. These findings are preliminary and needs support from further investigation, cost-analysis, and feasibility studies. Nonetheless, the development of a more economical process of sewer separation can alleviate numerous hindrances to the control of CSOs especially in Korea.

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References

Abbas, A, Carnacina, I, Ruddock, F, Alkhaddar, R, Rothwell, G, Andoh, R (2019). An Innovative Method for Installing a Separate Sewer System in Narrow Streets, J. Water Manag. Model., 27: C467. [DOI: 10.14796/JWMM.C467]

APHA, AWWA & WEF (1995). *Standard Methods for the Examination of Water and Wastewater. 19th ed.*, American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, USA.

Dittmer, U, Bachmann-Machnik, A, Launay, MA (2020). Impact of Combined Sewer Systems on the Quality of Urban Streams: Frequency and Duration of Elevated Micropollutant Concentrations, *Water*, 12, pp. 1-18. [DOI: 10.3390/w12030850]

Mannina, G. and Viviani, G (2009). Separate and combined sewer systems: a long-term modelling approach, *Water Sci. Technol.*, 60(3), pp. 555-565. [DOI: 10.2166/wst.2009.376]

Kim, YR (2018). The Sewerage System of Seoul. https://www.seoulsolution.kr/en/content/2373

Lange, RL and Wichern, M (2013). Sedimentation dynamics in combined sewer systems. *Water Sci. Technol.*, 68(4), 756 - 762. [DOI:10.2166/wst.2013.278]

Schaarup-Jensen, K, Rasmussen, MR, Thorndahl, SL (2011). The Effect of Converting Combined Sewer Catchments to Separate Sewer Catchments, *Proceedings of the 12th International Conference on Urban Drainage*, Brazil, September 11-16, 2011, pp. 1-8.

Silvagni, G, Volpi, F, Celestini, R (2014). Sediment Transport in Sewers, *WIT Trans. Ecol. Environ.*, 182. [DOI: doi:10.2495/WP140251]

Tibbetts (2005). Combined Sewer Systems: Down, Dirty, and Out of Date, *Environ Health Perpect*, 113(7), pp. A464-A467. [DOI: 10.1289/ehp.113-a464]

Thorndahl, S, Schaarup-Jensen, K, Rasmussen, MR (2013). On hydraulic and pollution effects of converting combined sewer catchments to separate sewer catchments, *Urban Water J.*, 12(2), pp. 120-130. [DOI: 10.1080/1573062X.2013.831915

US Environmental Protection Agency (USEPA) (1999). *Combined Sewer Overflow Management Fact Sheet: Sewer Separation*, EPA 832-F-99-041, USEnvironmental Protection Agency, Washington D.C.