# Improvement of the carrying capacity of Drainage System using Sediment Trapping Effect of Seoul Vortex Tube

Yong Jun Cho[1]

***Abstract*—**The flooding problem due to the extremely localized heavy rainfalls (as observed in Seoul in 2012) has been addressed by installing emergency relief facilities such as an underground storm water storage system. In addition to this expensive conventional approach, it would be very helpful to better utilize the present drainage system by preventing the reduction of carrying capacity caused by factors such as blockage by debris and other pollutants. In doing so, we can also reduce the volume requirements for new storm water storage systems.

Following this rationale, we proposed a debris separating system called the Seoul Vortex Tube consisting of a cylindrical reservoir, entrance and exit channels, and an accelerator. The debris trapping effect of the Seoul Vortex Tube utilizes the same mechanism as that underlying the formation of cross stream circulation cells as found in curved river reaches.

We induced a forced vortex flow by placing the entrance channel eccentrically to the cylindrical reservoir. Once the forced vortex flow reaches an equilibrium state, two counter rotating vortex cells gradually develop across the cylindrical reservoir by centrifugal force, causing sediments to drift toward the center.

In order to verify the sediment trapping effect of the Seoul Vortex Tube, we carried out the numerical simulation based on the mass balance and 3-D Navier-Stokes equation, the numerical integration of which is implemented using Volume of Fluid (VOF) method. Numerical results show that the sediment trapping effect of the Seoul Vortex Tube depends on the strength of incoming flow and the location of the exit channel, which together dictate the residence time of the storm water within the Seoul Vortex Tube. Based on these results, we modify the Seoul Vortex Tube by adding an accelerator at its entrance, which leads to remarkable improvements in the sediment trapping effects of the Seoul Vortex Tube.

***Keywords*—** Seoul Vortex tube, two counter rotating circulation cells, sediment trapping effect, forced vortex flow, centrifugal force.

## I. Introduction

WITH global warming becoming progressively worse, the Korean Peninsula is frequently exposed to super typhoons and extremely localized heavy rainfalls previously not experienced in Korea. If we do not take any measures in the near future, this trend will continue. In order to mitigate the climate change by global warming, we need to replace fossil energy with renewable energy such as solar, wind, and tide; dedicated efforts need to be made to reduce the emission of carbon dioxide. However, since developing renewable energy activated power plants such as tidal power plants and offshore wind farms involves enormous cost, significant improvements in the near future are unlikely.

Recently, we helplessly witnessed the flooding of the Gwang Whamun and Gangnam station districts in downtown Seoul, symbol of the Korean economic development, caused by the aforementioned localized heavy torrential rainfall.

In the water resources community of South Korea, there is a growing consensus that these floods were triggered by increased rainfall intensity due to global warming and the increase of impermeable surface areas due to urbanization. This urbanization has led to an increase in storm water runoff rates in urbanized areas, subsequently increasing the peak discharge and causing the flood wave to arrive faster than it would otherwise. Following this rationale, the municipal government of Seoul considers the construction of new remedial measures to mitigate the flooding problem such as rain gardens and an underground storm water storage system. Considering the facts that rain gardens provide additional permeable areas in downtown Seoul, and an underground storm water storage system can replace detention ponds, these measures could be helpful in alleviating the flooding problem. However, such measures are too expensive to consider.

The reason why the current drainage system in service cannot accomplish the intended purpose has recently been revealed; the flows within the drainage system that are hampered by the debris and other pollutants carried by the surface run off actually exceed the design value. Hence, it can be deduced that partial blockage of the drainage system by the debris would worsen the flooding problem to some extent.

Considering this, along with the extension of the drainage system using an underground storage system, the development of a number of measures to better utilize the present drainage system by preventing blockages caused by debris is worth pursuing.

Once a measure can be successfully materialized (such as a separating system which can effectively separate the sediments and other pollutants carried by the runoff from the storm water entering the street ditch), the effectiveness of the storm drainage system can be greatly improved without any further extension. Hence, this separating system has an economic edge over other measures such as rain gardens and underground storm water storage systems [1].

However, the architecture of most separating systems now

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available has not evolved any further from that of the inefficient classical sediment basin, which relies heavily on settling due to gravity [2].

In a separating system in line with a conventional sediment basin, the flow velocity should be lowered to boost the deposition of sediments and other pollutants; as a result, the carrying capacity of the drainage system will inevitably be greatly reduced. However, the hydraulic environment surrounding the street ditch during storm water flow is very energetic and storm water does not reside long enough for sediments and other pollutants from the surface runoff to settle, which eventually leads to the inefficient operation of the separating system in line with the conventional sedimentation basin.

In light of the above, the aim of this study is to propose a sediment separation system called Seoul Vortex Tube utilizing the mechanism of the secondary circulation cells that can be found in curved river reaches. The Seoul Vortex Tube consists of a cylindrical reservoir and entrance and exit channels. The sediment trapping effect of the Seoul Vortex Tube utilizes the forced vortex flow developed within the cylindrical reservoir. The forced vortex flow within the cylindrical reservoir is induced by placing the entrance channel eccentrically to the cylindrical reservoir. Once the forced vortex flow reaches an equilibrium state, two counter rotating vortex tubes gradually develop across the main flow direction within a cylindrical reservoir by centrifugal force, which eventually causes sediments to drift toward the center of the cylindrical reservoir.

Considering the facts that secondary circulation cells as well as gravity are utilized in trapping the sediment, the Seoul Vortex Tube is more effective than the separating system in line with the conventional sediment basin.

The sediment trapping effect of the Seoul Vortex Tube depends on the strength of the incoming flow and the location of the exit channel, which dictate the residence time of the storm water within the Seoul Vortex Tube.

Following this rationale, a great deal of effort has been made to find the optimized location of the exit channel to secure the sufficient residence time required for sediments to be effectively trapped.

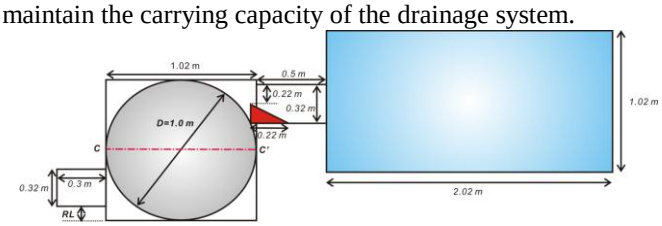
In order to fully utilize the potential of the Seoul Vortex Tube (such as being able to self adaptively adjust its vortex tube strength with incoming flow without any mechanical device), we also attempted to improve the Seoul Vortex Tube by installing a flow accelerator at the entrance channel to the cylindrical reservoir that accelerates the incoming flow by gradually narrowing the flow area of the entrance channel by as much as 25% without causing any backwater.

In this study, we first carried out the hydraulic model test of the separating system in line with the conventional sediment basin to provide data for the verification of the numerical model. We then numerically simulated the flow via the Seoul Vortex Tube by varying the flow rate to show the sediment trapping effect of the Seoul Vortex Tube. We developed the numerical model using the mass balance and Navier-Stokes equation and the sediment transport equation, the numerical integration of which was carried out using VOF.

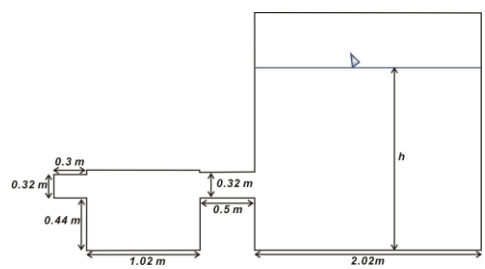
## II. Physical background of Seoul Vortex Tube

The driving mechanism of the helical flows (center region circulation cell) as found in curved river reaches forms the basis of the debris trapping effect of the Seoul Vortex Tube. Seoul Vortex Tube

In order to materialize the sediment trapping effect using the generation mechanism of secondary flow in the curved channel discussed in 2.1, we first induce a forced vortex flow in a cylindrical reservoir. The forced vortex was induced by placing the entrance channel to the Seoul Vortex Tube eccentrically (see Fig.1). Once the forced vortex flow is formed within the cylindrical reservoir, two counter rotating circulating vortex tubes begin to develop across the flow direction of the forced vortex within a cylindrical reservoir due to the aforementioned centrifugal force. As a result, the sediments carried by the runoff from the storm water entering the street ditch will drift toward the center of the cylindrical reservoir. As rain fall ceases, the sediments trapped within the cylindrical reservoir settle on the bed; these sediments can be easily removed on a regular basis to maintain the carrying capacity of the drainage system.




(a) Plan view




(b) Side view

Fig.1 Definition sketch of the Seoul Vortex-Tube.

## III. Numerical model

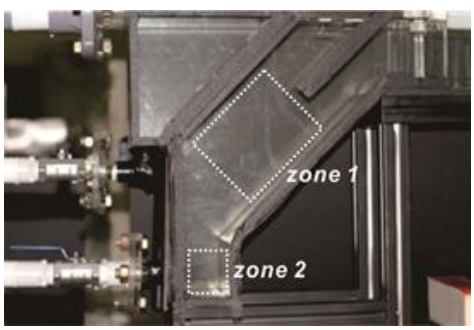
A numerical simulation was carried out in order to verify the sediment trapping effect of the Seoul Vortex Tube proposed in this study. We used the mass balance and the Navier-Stokes equation as a hydrodynamic model, the numerical integration of which was implemented using the VOF method. The VOF method was also utilized in order to track the free surface and the Factional Area/Volume Obstacle Representation (FAVOR) method was used to represent the complicated boundaries between the fluid and solid objects.

## IV. Verification of Numerical Model

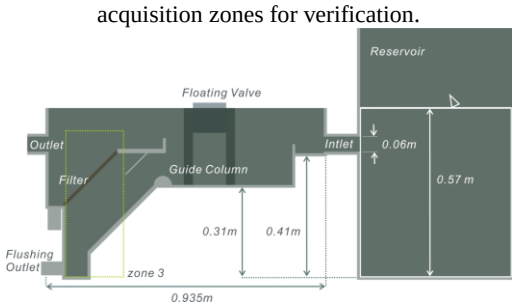
For the verification of the numerical model proposed in this study, we first carried out a hydraulic model test of the sediment

separating system in line with the conventional sediment basin, and implemented the numerical simulation. Verification of the numerical model was performed using the velocity data from the hydraulic model test. In Fig. 2, we plot the hydraulic model of the sediment separating system, velocity data acquisition zones, and computational domain. The depicted computational domain is discretized by 1,157,632 nodal points. A hydraulic model test was performed for flow rates of 0.8m$^3$/hr and 1.0m$^3$/hr. Fig. 4 shows the vector plot of instantaneous flow velocities measured using the particle image velocimetry (PIV) in the hydraulic model test. Vector and contour plots of numerically simulated flow velocities are depicted in Fig. 4.

In the hydraulic model test, swirling currents toward the outlet can be observed in front of the filter, and the strength of these swirling currents increases as the flow rate increases. However, these swirling currents cannot be found in the numerically simulated flow field. In the hydraulic model test, the flow was maintained by the mechanical pumps, and some mechanical noise was thus inevitable. On the other hand, in the numerical simulation, the flow is initiated from the upstream reservoir of the fixed water level, and the presented flow field was obtained after numerous iterations until a steady state is reached. Considering all of the above, since upwelling currents are very weak, these small discrepancies can be acceptable. Other than negligible upwelling currents, the general agreements between the hydraulic model test and numerical simulation are very encouraging.

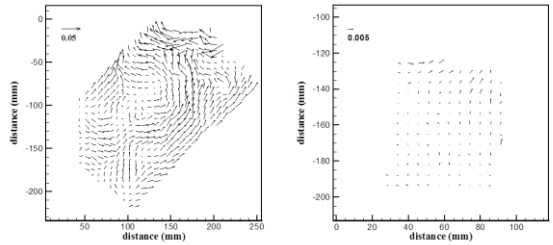



(a) Hydraulic model of the separating system in line with the conventional sedimentation basin, and the location of velocity data acquisition zones for verification.

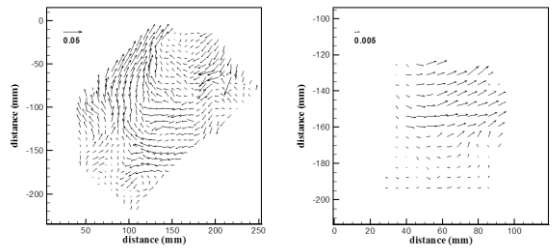



(b) Layout of Computational domain and location of velocity data acquisition zones for verification

Fig. 2 Separating system in line with conventional sedimentation and computational domain

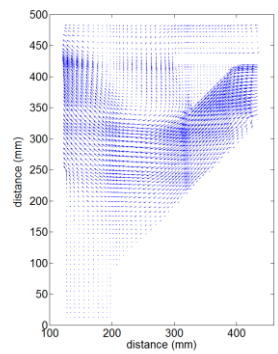



(a)Flow rate=0.8m$^3$/hr

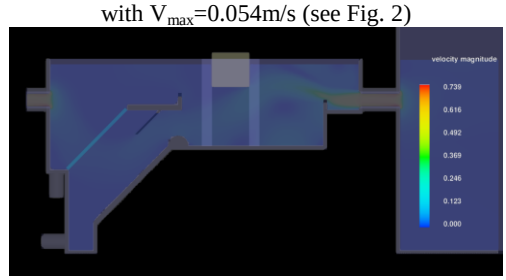



(b) Flow rate=1.0m$^3$/hr

Fig. 3 Vector plot of measured velocities (right panel: zone1, left panel: zone 2)




(a) Vector plot of numerically simulated velocities over zone 1 and 2 with $V_{max}$=0.054m/s (see Fig. 2)




(b) Contour plot of numerically simulated velocities

Fig. 4 Vector and contour plots of numerically simulated velocities

## V. Numerical Simulation And Numerical Result

### *A. Numerical simulation*

First, we numerically simulated the forced vortex flow in the Seoul Vortex Tube by varying the flow rate (h=0.9, 1.2, 1.5m) for 20s. We then carried out the numerical simulation for the Seoul Vortex Tube augmented with an accelerator to observe the difference in the sediment trapping effect due to the accelerator, whereby the total simulation period of 20s was sustained. In order for the Seoul Vortex Tube to trap sediments effectively, the storm water needs to reside long enough for the two counter rotating vortex tubes to be fully developed.

Considering the above, it is easily deduced that the location of the exit channel that dictates the residence time of the storm water in the cylindrical reservoir is a design factor of considerable engineering value. In an effort to find the optimal location of the exit channel of the Seoul Vortex Tube, we also carried out a numerical simulation for the Seoul Vortex Tube with exit channels at 0.05, 0.1, and 0.35m from the left end of the cylindrical reservoir (see Fig. 1), which correspond to RUN_R, RUN_RC, and RUN_C, respectively (see Table I).

TABLE I
LIST OF HYDRAULIC CONDITIONS FOR THE NUMERICAL SIMULATION

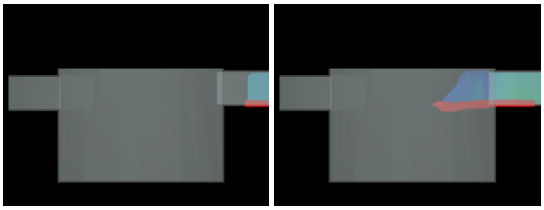
| | Accelerator | Location of Exit Channel | H(m) |
|---|---|---|---|
| RUN_RNA_0.9 | Uninstalled | RL=0.05m (see Fig. 7) | 0.9 |
| RUN_RNA_1.2 | | | 1.2 |
| RUN_RNA_1.5 | | | 1.5 |
| RUN_RA_0.9 | Installed | RL=0.05m | 0.9 |
| RUN_RA_1.2 | | | 1.2 |
| RUN_RA_1.5 | | | 1.5 |
| RUN_RCNA_0.9 | Uninstalled | RL=0.10m | 0.9 |
| RUN_RCNA_1.2 | | | 1.2 |
| RUN_RCNA_1.5 | | | 1.5 |
| RUN_RCA_0.9 | Installed | RL=0.10m | 0.9 |
| RUN_RCA_1.1 | | | 1.2 |
| RUN_RCA_1.5 | | | 1.5 |
| RUN_CNA_0.9 | Uninstalled | RL=0.35m | 0.9 |
| RUN_CNA_1.2 | | | 1.2 |
| RUN_CNA_1.5 | | | 1.5 |
| RUN_CA_0.9 | Installed | RL=0.35m | 0.9 |
| RUN_CA_1.2 | | | 1.2 |
| RUN_CA_1.5 | | | 1.5 |

To investigate the behavior of the sediments carried by the surface runoff within the cylindrical reservoir of the Seoul Vortex Tube, we traced the sand particles initially placed at the bottom of the entrance channel as the numerical simulation proceeded. The density of sand particles is 2500 Kg/m$^3$, and the number of sand particles deployed is 200,000; we attempted to ensure that the behavior of the sediments within the cylindrical reservoir was as realistic as possible. In Table 1, the hydraulic conditions and physical configurations of the Seoul Vortex Tube used in numerical simulations are summarized.

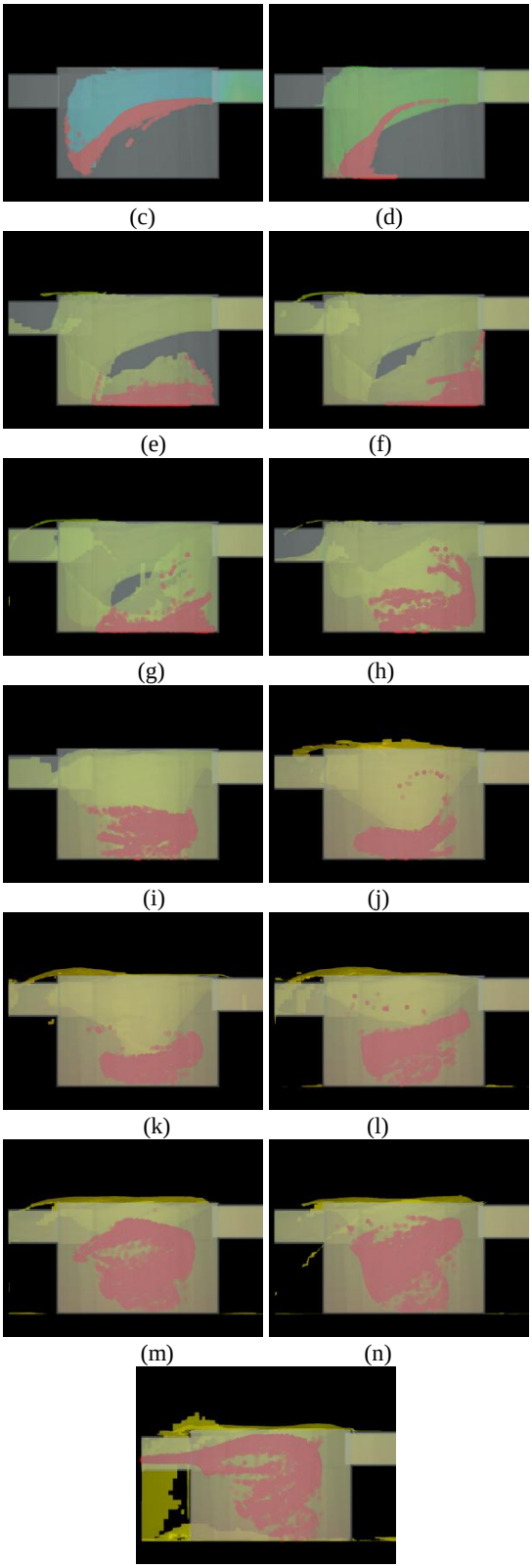
### *B. Numerical results*

In Fig. 5, we plot sequential snapshots of numerically simulated swirling sediment clouds. The sediments that simply moved in the Seoul Vortex Tube due to the initial surface run off swirl along the outer wall of the cylindrical reservoir, and gradually drift toward the central part by the forced vortex flow that was enhanced as the residing water volume within the Seoul Vortex Tube increased (see Figs. 5(i), 5(j), and 5(k)).

However, some of the sediment escaped from the Seoul Vortex Tube after 18 seconds due to the relatively strong influx (see Fig. 5(o)).



(a) (b)



(c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m) (n) (o)

Fig. 5 Sequential snapshots of swirling sediment clouds as they evolve with the forced vortex flow within the Seoul Vortex Tube [RUN_RNA_1.5]

The numerical results show that the accelerator at the entrance channel, the location of the exit channel, and the strength of inflow significantly influence the flow pattern within

the cylindrical reservoir, and consequently influence the sediment trapping efficiency of the Seoul Vortex Tube. Sequential snapshots of numerically simulated sediment clouds are shown in Fig. 8.

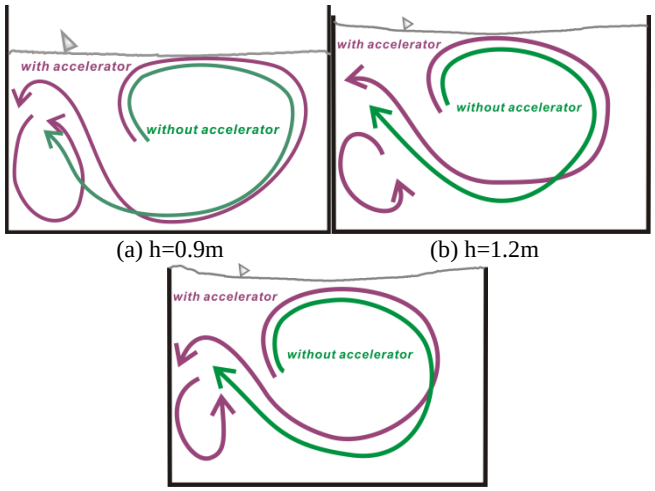
The flow characteristics observed in the numerical simulation are summarized as follows.

- With an accelerator in the entrance channel

In the case where the accelerator is installed, the sediment clouds show a more orderly swirling pattern with respect to the center of the reservoir. On the other hand, once the accelerator is detached, the sediments are more randomly scattered over the entire cylindrical reservoir. Considering these tendencies, we can deduce that the accelerator in the entrance channel would significantly influence the strength and pattern of the two counter rotating vortex tubes within the cylindrical reservoir.

In order to verify these speculations, in Fig. 8, we plotted the velocity distribution on a plane dissecting the cylindrical reservoir along C-C'. In the case where the accelerator is attached, two counter rotating vortex tubes appeared, showing the same formation as that first revealed by Albert Einstein. On the other hand, once the accelerator is detached, only a clockwise swirling vortex cell can be seen. It was also noted that two counter rotating vortex tubes become stronger when the accelerator is attached. Furthermore, as the inflow rate increases, the water depth increases, and the outer skirt of the vortex flow also expands more broadly.

In brief, the intensified inflow forced by the accelerator results in counter rotating vortex cells that are stronger and more even, while more orderly swirling sediment clouds with respect to the center of the reservoir develop, which eventually improves the sediment trapping efficiency of the Seoul Vortex tube.




(a) h=0.9m (b) h=1.2m

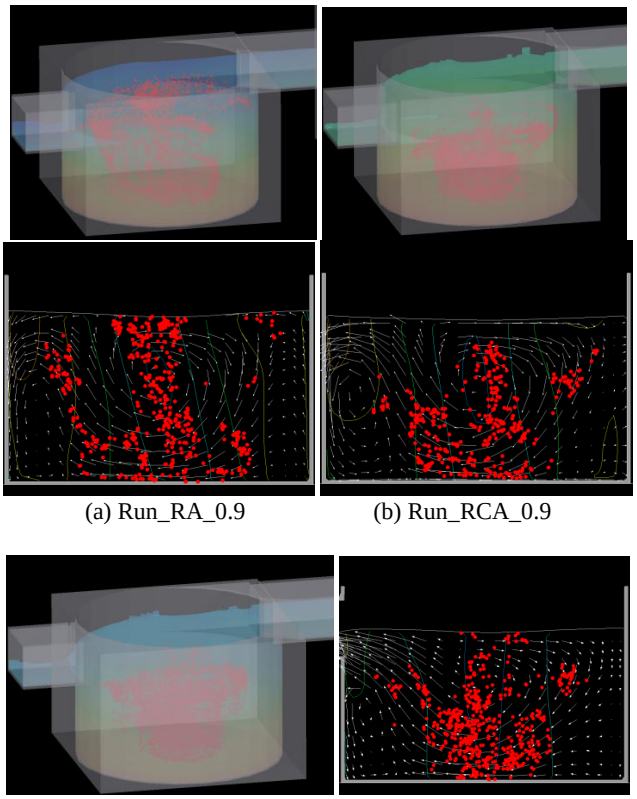
(c) h=1.5m

Fig. 6 Comparison of the secondary currents across C-C' (see Fig. 4.1) within the Seoul Vortex Tube between that with the accelerator and that without the accelerator

- Strength of inflow rate

The numerical results show that the strength of the secondary flow that developed in the Seoul Vortex Tube was proportional to that of inflow rate, which concurs with our empirical results. In the case of H = 0.9m, any overflow was not observed due to the low inflow rate. On the other hand, for H=1.2m, significant overflow was visible, since the inflow rate was relatively large when compared with the carrying capacity of the Seoul Vortex Tube deployed in this study. However, such phenomenon frequently occurs in the drainage system in downtown Seoul, which is forced to drain the storm water well beyond the designed value due to localized heavy rain. Considering this, we elected to include the numerical results of the overflow for the analysis of sediment trapping efficiency of the Seoul Vortex Tube. In the case of H = 1.5m, the overflowing water carried some sediments when the initial storm water entered the cylindrical reservoir of the Seoul Vortex Tube (see Fig. 8).

- Location of exit channel



(a) Run_RA_0.9 (b) Run_RCA_0.9

(c) Run_CA_0.9

Fig. 7 Snapshots of the velocity fields in the Seoul Vortex Tube and the particle clouds

The location of exit channel has a considerable influence on the sediment distribution within the cylindrical reservoir. In the case of Run_CA_0.9, Run_CA_1.2, and Run_CA_1.5, where the exit channel is placed near the center of the downstream boundary of the cylindrical reservoir, more densely packed sediment clouds were swirling clockwise with respect to the center of the cylindrical reservoir. Densely packed sediment clouds imply that relatively strong secondary currents are sustained in the cases of Run_CA_0.9, Run_CA_1.2, and Run_CA_1.5.

In the cases of Run_RA_0.9, 1.2, and 1.5 (where the exit channel is placed furthest away from the entrance channel), as the storm water starts to enter the cylindrical reservoir, the flow rate leaving the cylindrical reservoir is somewhat smaller than

that in the cases of Run_CA_0.9, 1.2, and 1.5, Run_RCA_0.9, 1.2, and 1.5.

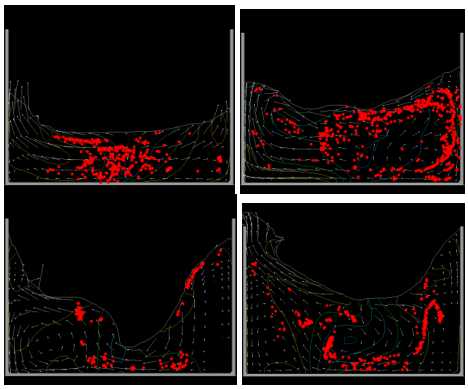
If there is a difference in the inflow and outflow rates, as in the cases of Run_RA_0.9, 1.2, and 1.5, some storm water fills up in the cylindrical reservoir, and the sediments thus become more scattered and the sediment clouds are loosened.

Even though these unexpected phenomena are worth more discussion, for now, we deduce that the sediment clouds loosen due to the ascending flow forced by the water level rise due to the increased level of storm water in the cylindrical reservoir. These upwelling currents eventually disturb the development of the helical flow, which transforms into a two counter rotating vortex tube when projected on the plane crossing the cylindrical reservoir. Here, the two counter rotating vortex tubes obviously cause the sediment clouds to become densely packed toward the center of the cylindrical reservoir. These deductions are based on the fact that the water levels in Run_RA_0.9 are higher than those in Run_RCA_0.9 and Run_CA_0.9.

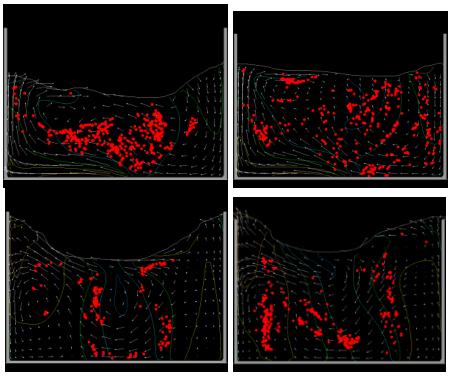
Therefore, in order for the sediment to be trapped efficiently, the water leaving the reservoir needs to be balanced with the incoming storm water. However, after the helical flow in the cylindrical reservoir is fully developed and stabilized after some portion of incoming water has left the cylindrical reservoir, the outflow rates in Run_RA_0.9, 1.2, and 1.5 are larger than those in Run_CA_0.9, 1.2, and 1.5 and Run_RCA_0.9, 1.2, and 1.5 due to the high water level.

- Sediment trapping effect

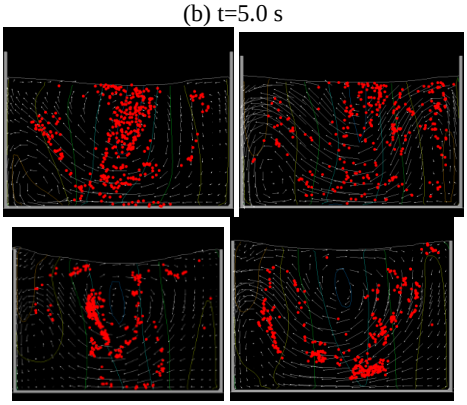
In the case of RUN_CA, where the exit channel was installed at the innermost region, it was shown that the storm water resides only long enough that it does not fill up the cylindrical reservoir, as in RUN_R and RUN_RC. Hence, the ascending flow is weakened over the entire Seoul Vortex Tube such that the swirling shape of sediment cloud trajectories can be more clearly defined.



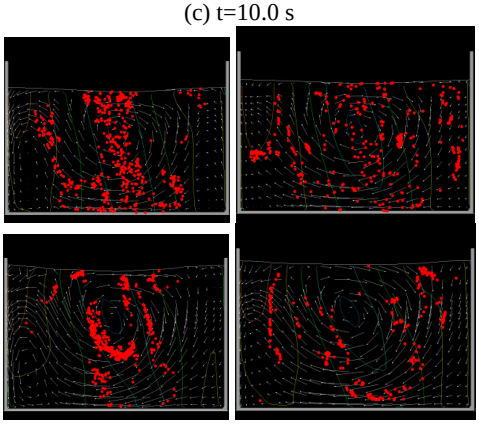
(a) t=3.0 s



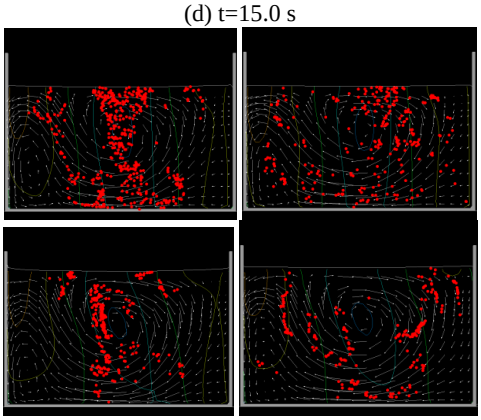
(b) t=5.0 s



(c) t=10.0 s



(d) t=15.0 s



(e) t=20.0 s

Fig. 8 Sequential snapshots of the velocity fields within the Seoul Vortex Tube and particle clouds [1st panel: RUN_RA_0.9, 2nd panel: RUN_RNA_0.9, 3rd panel: RUN_RA_1.2, 4th panel: RUN_RNA_1.2]

## VI. Conclusion

The flooding problem due to extremely localized heavy rainfalls as observed in Seoul in 2012 has previously been addressed by either implementing higher capacity pipe work or installing emergency relief facilities such as an underground storm water storage system.

However, these costly conventional approaches are now generally regarded as unsustainable owing to the resulting land loss, even though they have been preferred due to their short-term convenience.

Besides the aforementioned conventional approaches, it will be very helpful to better utilize the present drainage system by preventing the reduction of carrying capacity due to blockages caused by debris and other pollutants. We could therefore also reduce volume requirements for a new storm water storage system.

Following this rationale, in this study we proposed a debris separating system called Seoul Vortex Tube. This approach was inspired by the classical helical flows found in curved river reaches, which cause the sediments saltated at the toe of the outer bank to drift toward the inner bank. We developed the Seoul Vortex Tube using a cylindrical reservoir, entrance and exit channels, and an accelerator. The underlying mechanism of the classical helical flows forms the basis of the debris trapping effect of the Seoul Vortex Tube. Considering the fact that the Seoul Vortex Tube operates using purely fluidic means, we can easily deduce that the Seoul Vortex Tube is more effective than that of the current separating system affiliated with a classical sedimentation basin.

We induced a forced vortex flow by placing the entrance channel eccentrically to the cylindrical reservoir. Once the forced vortex flow reached an equilibrium state, two counter rotating vortex tubes gradually developed across the flow direction due to the centrifugal force, which causes the sediments to drift toward the center of the cylindrical reservoir.

In order to verify the sediment trapping effect of the Seoul Vortex Tube, we carried out a numerical simulation. After noting that the strength of the cross stream circulation cell depends on the vertical profile of the longitudinal velocities and the advective momentum transport in the transversal direction, we developed a hydrodynamic model using the mass balance and 3-D Navier-Stokes equation [6]. Numerical integration of the hydrodynamic model is implemented using VOF.

Numerical results show that the sediment trapping effect of the Seoul Vortex Tube depends on the strength of the incoming flow and the location of the exit channel, which dictate the residence time of the storm water within the Seoul Vortex Tube. As the inflow intensity increased, the two counter rotating vortices strengthen due to the larger vertical gradient of the longitudinal velocities and the accompanying stronger centrifugal force, which as a result have more sediment trapped near the center of the cylindrical reservoir.

Based on these results, we slightly modified the Seoul Vortex Tube by adding an accelerator at the entrance of the Seoul Vortex Tube, which resulted in considerable improvements in the sediment trapping effects of the Seoul Vortex Tube.

## References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