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COMPUTATIONAL FLUID DYNAMICS DISCRETE PHASE MODELLING IN STORM SEWERS

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Abstract

A Computational Fluid Dynamics (ANSYS Fluent CFD) software was applied for the examination of a critical combined sewer section of Budapest (Hungary) sewer network. The critical part of the main branch is located at a combined sewer overflow (CSO) which is implying environmental risk for the receiving water body. The CFD simulations proved the anticipated disadvantageous hydrodynamic effects of the lateral inflow. A discrete phase model (DPM) was also applied to analyse the sediment transport and settling conditions around a junction structure in the main branch. Various parameters set in the model were recommended. The DPM simulations confirmed the anticipated negative effects of the lateral flow to the sedimentation in the main branch. The effects of the possible change of the particle size distribution were also examined. The smaller were the diameters the less was the sedimentation in the critical section of the main branch. Recommendation for the improvements of the main branch regarding the sedimentation processes were stated including local and wider range solutions.

Key words: CFD, combined sewer, discrete phase, sediment transport

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1. Introduction

Sediment transport in storm sewers is in a quite direct connection with the environment. The subcatchments of the sewers are influencing the quality and quantity of the sediment as described by Beilicci et al. (2017) and Iqbal and Baig (2015). The produced sediment has negative effect on both the capacity of the sewers and the wastewater treatment plant as Fiorentino et al. (2016) and Jin et al. (2016) demonstrated. Advection-dispersion models can calculate the one-dimensional transport of dissolved and suspended substances as has recently been shown by Flamink et al. (2004).

The importance of mathematical modelling for environmental problems was proved by Petrescu et al. (2011). Other researchers modelled the pollution and sediment transport in rivers (Berkun et al., 2015; Dimitriou et al., 2018; Pintilie et al., 2007; Hòa et al., 2017; Pintilie et al., 2007; Zhang et al., 2017). The storm sewer and fluvial transport processes e.g. "bed load" and "suspended load" are quite similar and have significant effect on the receiving waters. However, the size and shape of the channels are different. Sediment models developed for sewers are often originating from fluvial transport researches (van Rijn, 1984).

The hydrodynamic calculations of the water flow in sewer network are usually one-dimensional. Flow volumes and sediment transport are calculated by Casadio et al. (2013) based on the hydrodynamics of the sewage. In case when one-dimensional flow

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conditions are not satisfactory like in combined sewer overflow (CSO) structures, Computational Fluid Dynamics (CFD) 3D models are also available. Several CFD application were born in the field of dam reservoirs (Üneş and Varçin, 2017), hydropower (Popescu et al., 2017), water treatment (Militaru et al., 2013) and urban drainage (Jarman et al., 2008). Several structures are modelled in 3D in the field of sewerage and wastewater treatment like combined sewer overflows (CSOs), storage and attenuation structures, stormwater sediment structures, sewerage conveyance structures, as demonstrated by some scientists (Gabor et al., 2016; Madarász and Patziger, 2018; Patziger, 2016; Stirrup and Marchant, 2002),

The current analysis is presenting the possibilities of a CFD simulation simultaneously for liquid and discrete phase. The selected sewer section is located in one of the biggest main trunk sewers of Budapest, Hungary. The aim of the study was to analyse the current sedimentation and to propose possible operational interventions ranging from more effective cleaning to reconstruction of sewer elements.

Not all the results of the carried analysis are presented in this paper. The DPM results are highlighted because of its novelty feature. The results of the previously carried 1D and 3D simulations are generally mentioned. The previous results are detailed only in cases when they are necessary for the interpretation of the DPM simulations.

2. Materials and methods

The analysed main combined (trunk) sewer is collecting both the storm water and the communal sewage from North of Buda, the hilly side of Budapest (Fig 1.). The size and shape of the critical section (Table 1) is justifying the 3D analysis. Even 1D analysis would be sufficient for the hydrodynamic analysis of most of the pipes, but not for the quite large and irregular shaped junction manhole.

Table 1. Dimensions of the analyzed junction manhole

Depth (m)	4.83
Length (m)	2.40
Starting width (m)	1.80
Ending width (m)	2.00

The analyzed critical sections (Table 2) are just at the inflow point of the biggest sub-branch, i.e. the Ordog-arok sewer. The service provider (FCSM Zrt.) built a reduction of the diameter from 120cm to 90cm subsequently in order to break the energy of the inflow. However, based on the latest operational results the service provider suspects the built concrete step having a backflow effect on the main pipe. The current analysis could also prove that assumption. The size of the catchment area belonging to the section is about 4865 ha, which is including all the pervious and impervious areas. In Fig. 1 the catchment area is colored as orange, the sewers are blue and the city borders are dashed pink lines. The greenish-brownish river along the main combined sewer is the Danube.

Table 2. Dimensions of the analyzed conduits

	Length, m	***Slope, ‰***	***Diameter, cm***
inflowing main combined sewer section	74	0.0000 (horizontal)	180
outflowing main combined sewer section	67.2	0.0024	200
inflowing lateral sub-branch (Ordog-arok):	14.8	0.345	120 (reduced to 90cm)

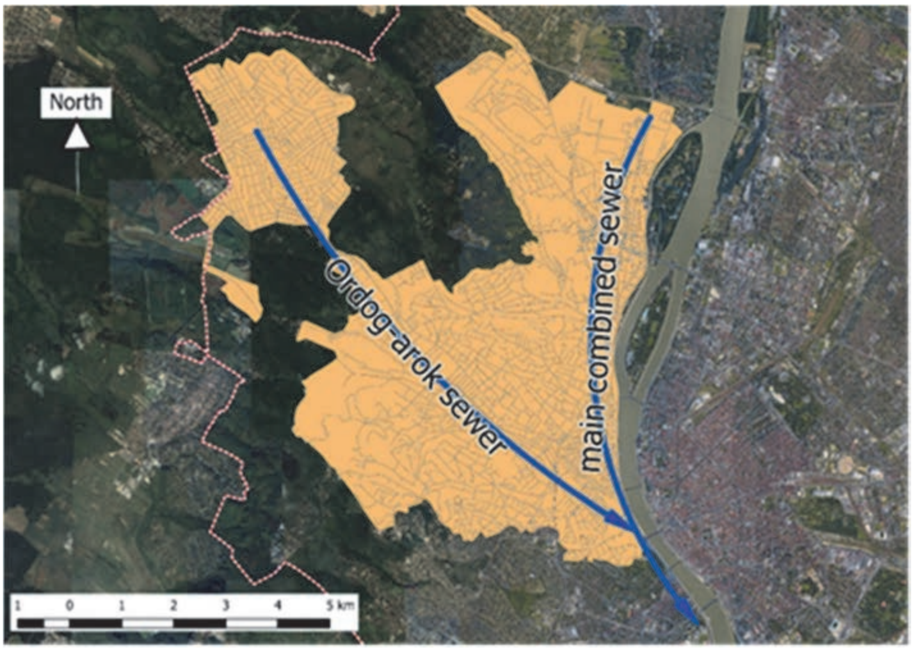

Fig 1. Layout of the CSO system

The size of the main combined sewer is Ø180-Ø200 cm. The size of the Ordog-arok sewer is 474cm (height) x 500cm (width). Inside the sewers, even walking is possible for the sewer operators (Figs. 2-3).

A combined sewer overflow (CSO) structure is splitting the volume of the Ordog-arok sewer. A weir is controlling the split. The storm water part is flowing directly into the Danube in a syphon below the main combined sewer (Fig. 4.). The wastewater part is flowing into the main combined sewer branch at the analysed section in an Ø120 cm lateral branch. At the analysed section, the sediment load is arriving from two directions: from upper part of the main combined sewer and the Ordog-arok sewer. The wastewater service providing company (FCSM Zrt.) suspected the disadvantageous effects of the lateral inflow on the sediment transport: the amount of the sediment is increasing because of the backwater effect of high velocity lateral inflow.

As preliminary steps, 1D and 3D hydrodynamic simulations of the analyzed sections were calculated by EPA Storm Water Management Model (SWMM) and ANSYS Fluent Computational Fluid Dynamics software (ANSYS Inc, 2016).

Fig 2. Laser scanner photo inside of the Ordog-arok sewer

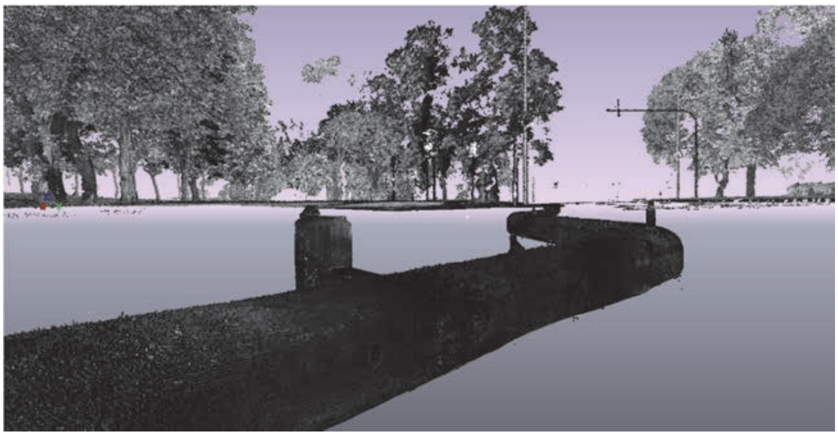

Fig 3. Laser scanner photo outside of the Ordog-arok sewer

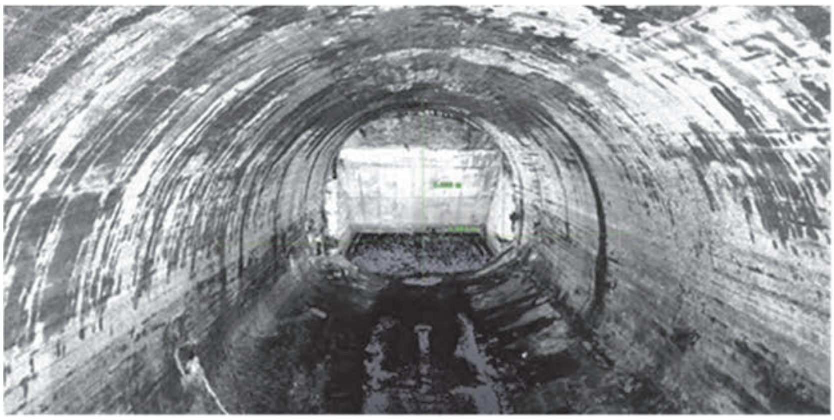

Fig 4. Laser scanner photo of the syphon at the end of the Ordog-arok sewer

The open surface of the channels could be estimated by 1D flow simulations. The Volume of Fluid (VOF) model of Fluent was also tested for the case, but finally no Multiphase Model of Fluent was applied for the hydrodynamic model, because the 1D software calculated the open surface of the channels at sufficient precision. The size of the tetrahedral meshing of the water body applied for the Fluent hydrodynamic simulations was generally in the range of 10-20cm and decreased at transition sites. The hydrodynamic simulation results were proofing the disadvantageous effects of the inflow of the lateral sewer branch:

- The flow in the lateral sewer branch has extreme high velocity (6 m s^{-1}) due to the geometry of the pipe and the weir at the CSO. The slope upstream to the junction structure is 4% and the cross-sectional area was decreased by a concrete still. All the pipes and the junction structure were made from reinforced concrete to stand against the emerging forces.
- The lateral inflow is dominating the flow conditions in the main collector.
- The flow in the main collector up to the junction point has relatively low velocity (1.5 m s^{-1}) due to the small slope (<1 ‰) and the fast flow from the joining lateral pipe.

Based on the hydrodynamic model the Fluent Discrete Phase Model (DPM) was applied for the analyzed sewer section. The DPM is a multiphase model (ANSYS, 2016) in which two different phases are defined: a continuous phase and a particle phase. The continuous phase is modelled in the Eulerian reference frame while the discrete phase is modelled in the Lagrange reference frame.

The DPM tracks the motion of each individual discrete particle (Wu et al., 2017). The trajectory i.e. the track followed by each particle is calculated over a large number of calculation steps as it passes through the flow domain. The calculation of each trajectory is based on the balance of forces acting on the particle (Eq. 1):

$$m_p \frac{d\overrightarrow{u_p}}{dt} = \overrightarrow{F_{drag}} + \overrightarrow{F_{gravitation}} + \overrightarrow{F_{other}} \tag{1}$$

where: m_p -mass of particle; $\overrightarrow{u_p}$ -velocity of particle; $\vec{F}$ -external force.

Eq. (1) can be expressed as Eq. (2):

$$m_p \frac{d\overrightarrow{u_p}}{dt} = m_p \frac{\vec{u} - \overrightarrow{u_p}}{\tau_r} + mp \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F} \tag{2}$$

where: ρ - density of water; ρ_p - density of particle; $m_p \frac{\vec{u} - \overrightarrow{u_p}}{\tau_r}$ - dragging force; τ_r - particle-relaxation time.

Calculation of the particle-relaxation time is done by Eq. (3). Integrated on the flow domain the overall trajectory also can be determined.

$$\tau_r = \frac{\rho_p d_p^2}{18\mu} \frac{24}{C_d Re} \tag{3}$$

where:

μ: molecular viscosity of liquid

d_p: diameter of particle

Re: Reynolds-number

The two phases are coupled via source terms of the governing equations. In the one-way method after the DPM source term update the particle motion is affected by the continuous phase coupling. In case of two-way coupling the particles and the continuous flow are interacting with each other. In our sediment model the one-way coupling was realistic.

DPM also supports evaporation, combustion reactions in more complex cases (Patziger, 2016). In our sediment model, the particles were supposed to be inert. The source of sediment in case of our catchment area is from mainly hilly and green residential areas. It is rather different from the other industrial, commercial parts of the city.

The steady particle tracking calculation was giving sufficient results for our model. Discrete phase was calculated in every continuous flow iteration step. The maximum number of steps (50000) provided to stop the solver being trapped in a recirculation loop and large enough for travelling the whole length of the sewer section. The injection type for the particles in our case was "Surface". The upper ends of the main combined sewer section and the lateral inflow sewer section served for the source of DPM.

The main parameter of the material of the source particles is the density. Based on the previous laboratory measurement results the density of the sediment is 2600 kg/m^3, which is corresponding to the sub catchment types. Sand and gravel are typical sediment types in green, hilly areas. The particle size distribution was also set by minimum, maximum and mean sizes. Ten fractions were giving enough resolution. The analysis was done for three different particle size distribution states: present state, larger diameters and smaller diameters (Table 3). Present state is based on the laboratory results of sparse FCSM samplings having uncertain particle size distribution with large deviation. Larger diameters were assumed to highlight the effect of increased particle size. In case of filtering out the larger diameters, the particle diameters would be smaller.

The minimum diameter was set by the generally accepted definition of the sewer sediment to 0.002 mm. There are not available measured data for the sediment originating from surface runoff in our catchments. The volume of the sediment from the surface runoff can be estimated (Wu et al., 2017).

Table 3. The main parameters of applied particle size distributions in meters

States	***Ø minimum (mm)***	***Ø maximum (mm)***	***Ø mean (mm)***
1. Present state	0.000002	0.02	0.002
2. Larger diameters	0.000002	0.02	0.01
3. Smaller diameters	0.000002	0.005	0.0001

Based on the current particle size distribution about half of the arriving sediment is accumulating in the pipes. The amount of the incoming sediment was set as 0.1 kg/s based on experimental data and the local conditions (Butler et al., 1996). The outlet of the hydrodynamic model was used as DPM “escape” type boundary condition, where the particles leave the system. The pipe walls were defined as DPM “reflect” type boundary conditions, where the particles rebound back into the flow domain. The manhole walls were defined as “trap” type boundary condition, where the particles settle.

The dispersion of particles due to turbulence in the fluid phase is predicted using the stochastic tracking model (random walk). The model includes the effect of instantaneous turbulent velocity fluctuations on the particle trajectories through the use of stochastic methods. The usage of statistical method (particle cloud model) would be another option in Fluent.

3. Results and discussion

The simulation results show the effects of the lateral inflow. The trajectories reveal the high level mixing of arriving particles (Fig. 5). The particle residence time in the main branch is also changing around the junction structure (Fig. 6) because of the lateral inflow. The Figures are primarily showing the trajectories of the particles. The residence time is just giving additional information. The residence time is elapsed time from the inlet of a given particle.

The calculated sediment volumes were proved by the operational data of the FCSM. Based on the operational data, the yearly-excavated volume of the sediment is about 120m-3. The simulation was resulting the volume of the sediment of 100m^3/year based on the statistics of 100 rainy day/year and assuming 1 hour duration of each rain event. Further simulations were executed to analyse the effect of the particle diameter size. The results (Table 4, Fig. 6, Fig. 7) are showing significant effects of diameters. In order to have comparable results, in case of smaller diameters the injection rate was also increased (4.state). As anticipated, increasing the particle size diameter, the rate of settled particles were increasing from 44% to 58%. Decreasing the particle size diameter, the accumulation was also decreasing from 44% to 36%. The decreasing diameter is increasing the particle residence time. The particles are staying longer in the upper part of the main branch. The maximum residence time is also increasing, from 80s to 90s.

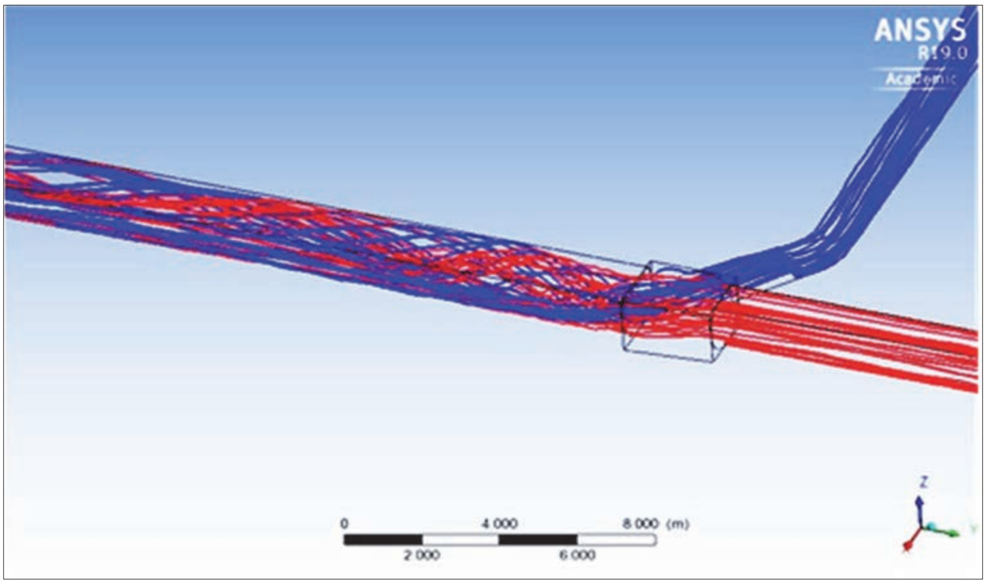

Fig 5. Mixing of particles arriving from two directions

Table 4. The count of particles by the simulation results of DPM

States	***tracked***	***trapped***	***escaped***
1. Present state	639	283	356
2. Larger diameters	2130	1237	893
3. Smaller diameters	213	19	194
4. Smaller diameters with increased injection	639	229	410

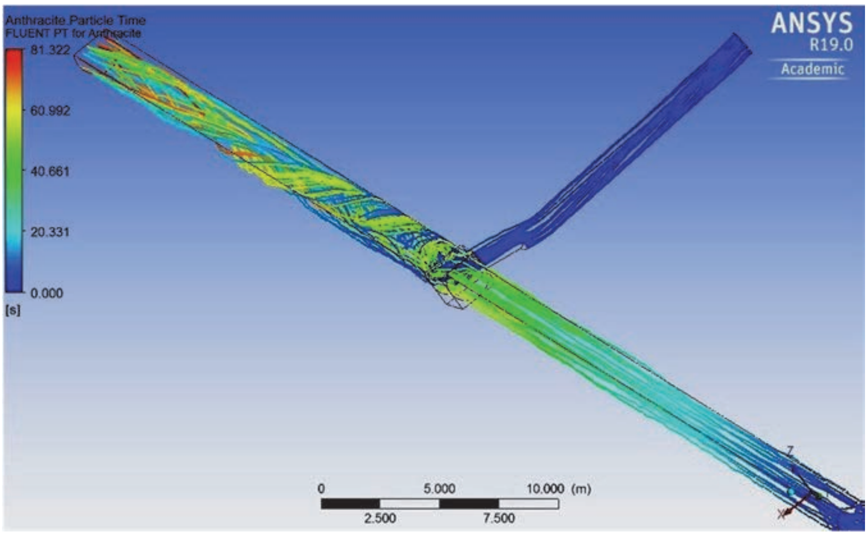

Fig 6. Residence time of particles in case of present state

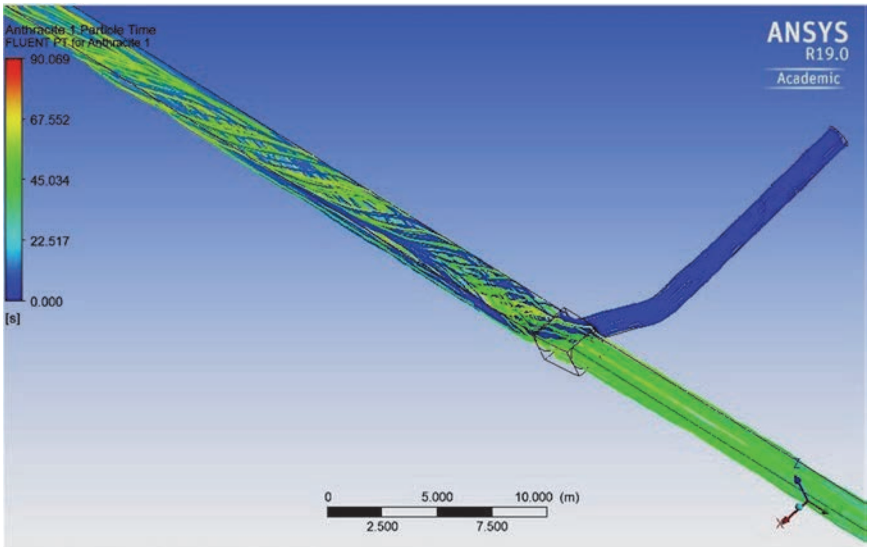

Fig 7. Residence time of particles in case of smaller diameters

4. Conclusions

We tried to share our experiences about application of powerful simulation software in order to simulate non-deterministic phenomena, as sediment transport. The gained results are promising, but further field measurements and model refinements are required for more realistic outcome.

The results of the DPM simulations are mainly confirming the observations and suspicions of the service provider. However, the results refine and provide additional information about the hydrodynamic and sedimentation processes.

Because of the disadvantageous hydrodynamic effects of the lateral inflow, large amount of sediment is setting around the junction structure. In case of storm events, the sediment content is increasing in both incoming branches. Almost half of the sediment is settling. The settled sediment at the bottom of the main branch is decreasing its flow transport capacity.

The regular excavation of sediment is not an economic solution. The modelling results are recommending the decrease of the particle diameter size in order to reduce the amount of the sediment production. Grates, sand traps or decreased the grate size of gully pots can be applied at upper sections of the main branch. Detailed fluid flow simulations can assure the positive effects of the interventions, decreasing the pollution load on the wastewater treatment plant and the receiving waters.

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