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AN OVERVIEW OF SPH SIMULATION AND EXPERIMENTAL INVESTIGATION OF SEDIMENT FLOWS IN SEWER FLUSHING

PRZEGLĄD SYMULACJI SPH ORAZ BADAŃ EKSPERYMENTALNYCH NAD PRZEPŁYWEM OSADÓW W SPŁUKIWANIU ŚCIEKÓW

Abstract

This paper concerns the application of the Smoothed Particle Hydrodynamics (SPH) method for sewer hydraulics with a focus on free-surface flows and sediment flushing. SPH is the most popular mesh-free method and has been widely used in the field of fluid mechanics. Here, the previous studies in the last few years are summarized, which have investigated the application of the relatively new model for the simulation of solid transport, free-surface and multiphase flows.

Keywords: smoothed particle hydrodynamics, free-surface flows, sediment transport, flush cleaning

Streszczenie

Niniejszy artykuł dotyczy zastosowania metody cząstek rozmytych (ang. *Smoothed Particle Hydrodynamics* – SPH) dla hydraulicznych systemów kanalizacyjnych ze szczególnym uwzględnieniem przepływów powierzchni swobodnej oraz spłukiwania osadów. SPH stanowi najbardziej popularną metodę bezsiarkową, powszechnie stosowaną w dziedzinie mechaniki płynów. W niniejszej pracy zestawiono dotychczasowe badania przeprowadzone w ciągu ostatnich kilku lat, które dotyczyły zastosowania stosunkowo nowego modelu do symulacji transportu materiału stałego, przepływów powierzchni swobodnej oraz przepływów wielofazowych.

Słowa kluczowe: metoda cząstek rozmytych, przepływy powierzchni swobodnej, transport osadów, spłukiwanie

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1. Introduction

Solids in sewage originating from precipitation, sanitary, commercial and industrial inputs deposit on the bottom of sewers and build sediments mostly during dry weather periods. Sewer sediment deposition represents a crucial aspect of the maintenance of sewer systems. Therefore, it is very important to avoid the accumulation of large amounts of sediments. Among different cleansing devices, flushing gates have been widely used to remove sediments periodically from sewers. The flushing gates require low maintenance and are cost-effective. In the last decades, many numerical and experimental investigations on the sediment flushing in sewers have been carried out. In some cases (e.g. sewer networks), the practical investigations could be complicated, expensive and time-consuming due to the complex phenomena. Furthermore, for the general design of flushing devices, it is necessary to understand the hydraulic principles of the flush wave. However, it is difficult to transfer the measurement results of one sewer to other sewers as well as to other cleaning devices [45]. Therefore, numerical methods have become an essential alternative to laboratory experiments for simulating several phenomena in the field of sewer networks. For many years, the free-surface flows have been simulated using Eulerian mesh-based methods. However, by dealing with highly deformable flows or complex geometries, creating a mesh can be difficult and expensive. Therefore, in the last years, the Lagrangian mesh-free methods have been widely used to simulate free-surface flows that are rapidly changing. Smoothed particle hydrodynamics (SPH) is a relatively new Lagrangian method developed by Gingolds and Monaghan [22] and Lucy [28] to solve astrophysical problems. The SPH method is the most popular mesh-free method and it is capable of dealing with problems concerning free surfaces, deformable boundary, moving interface, wave propagation and solid simulation. The following paper briefly describes the origins and the characteristics of solids in sewage, sediment transport in sewers, sediment flushing and the SPH method. Finally, the paper summarizes varied applications of the SPH method for simulating free-surface flows and sediment transport.

2. Solids in sewage

The solids in sewage come from different sources, in particular from wastewater and stormwater discharge. They vary from organic to inorganic materials. In sewer systems, it is important to know settle-able sediments, which could form bed deposits, such as faeces, food waste, hygiene items, paper, sand, stone, etc. They have settling velocities between 0.2 and 30 cm/s. However, it is not easy to determine the particle settling velocities accurately because of particle aggregation. There are some other particles of very small size or low density, which remain in suspension under normal flow conditions and do not have a very important influence on the hydraulic capacity of sewerage systems. Many studies have been carried out on characteristics of the sediments in sewers [3, 11, 34, 44, 55]. The non-cohesive materials are mostly characterized by their grain size distribution and the settling velocity [29]. Schlütter [46] categorized the solids according to their pollutants into fine faecal and other organic matter, large faecal and large organic matter (gross solids) and paper and rags (sanitary litter). Ashley et al. [5] subdivided solids in sewers depending on where they are found, in four primary classes: coarse granular bed material widespread, mobile and fine-grained found in slack zones, organic pipe wall slimes and zoogleal biofilms around the mean flow level, and fine-grained mineral and organic material found in the combined sewer overflow (CSO) storage tank. Ashley and Verbanck [4] considered the solids as sanitary, separate (fine) stormwater solids and grit.

3. Sediment transport

The transport of sewage with its solids takes place in sewers. The solids make up only 1% of the total wastewater volume, but they affect the function and operation of the whole wastewater network. They are an essential part of the total pollution load of sewage. Their transportation to the wastewater treatment plant or other water bodies leads to high pollution challenges [19]. It has been required to investigate the sediment transport in sewers to control the pollution transport. The solids move by the flow of the fluid. Therefore, their transport is determined by hydraulic properties, such as viscosity and flow velocity of the fluid, and the characteristics of the solids, such as size and density. In sewers, the rapid change of the hydraulic conditions in time and space affects the sediment transport. Several studies investigated the complex processes of the sediment transport in sewers [4, 16, 19, 24, 25 and 46]. The bed shear stress is an important parameter to define the transport of solids. The mean bed shear stress for stationary and turbulent flow conditions in open channels is evaluated as [17]:

$$\tau_0 = \rho \frac{\lambda}{8} V_m^2 \tag{1}$$

where:

ρ – the water density,
λ – the resistance coefficient of the pipe friction,
V_m – the mean flow velocity,

In general, the solids may travel either in suspension or as bedload, depending on the size of the bed material particles and the flow conditions. The solids in bedload have different movement modes, depending on the value of the bed shear stress: rolling, jumping or sliding. When the value of the bed shear stress just exceeds the critical value for initiation of motion, the particles will be rolling and sliding, or both. When the bed shear stress increases more, the particles will be jumping. The suspended load includes solids that are in suspension because of turbulence and may settle down when flow conditions are insufficient (Fig. 1). Another mode of transport introduced by some researchers is wash load [52]. This mode is in suspension load and includes the proportion of suspended solids that remain in suspension in sufficient flow conditions and never settle down. The total sediment load is the sum of these three loads, which has been investigated by several researchers such as Yang [57] and van Rijn [53]. However, in natural conditions, it is not easy to distinguish between these phases.

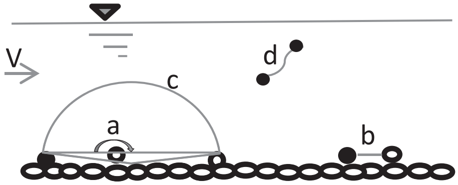

Fig. 1. Different modes of sediment transport: a – rolling, b – sliding, c – jumping, d – in suspension (graphic idea from Bollrich [9])

Another important parameter to describe the transport behavior of solids is the settling velocity, which is influenced by the flow conditions in the channel, such as turbulence, and the solids' characteristics, such as particle size and density. The process of sediment transport in sewage systems is very complex and the available data are insufficient. Furthermore, the laboratory experiments are not able to describe the underlying physics in detail [56]. Therefore, not only experimental investigations are carried out, but also several numerical methods are developed for modelling the sediment transport in sewer systems [19, 46].

4. Sediment flushing

In the last decades, great attention has been drawn to the sediment control in sewers. During periods of dry weather, by low flow velocities and prolonged duration times, the solids deposit on the bottom of sewers and build sediments [50]. Sediment deposition represents a crucial aspect of the maintenance of sewer systems. The accumulation of large amounts of sediments leads to various hydraulic and environmental problems in sewer networks, such as reduction of the design flow capacity and increase of the overflows in combined sewer systems, loss of hydraulic capacity, gas and corrosive acid production, odor problems and concentration of pollutants. There are different techniques for the removal of sediment deposits from sewer systems, based on the use of different mechanical and hydraulic devices [7, 13, 41]. Several studies have investigated the use of flushing devices and the scouring effects of flushing waves [8, 12, 42, 51].

Flushing gates have become very popular, because they are mostly self-controlled systems and a cost-effective solution to remove the sewer sediments. They are in-line flushing devices designed in order to produce flushing waves with high flow velocities and shear stresses that lead to re-suspend and transport the solids along sewers [12, 26]. The function of the flushing device is mostly divided into four general phases. First, the gate is closed. Second, water is stored by a closed gate in the vertical position. Third, the gate is opened, which lead to a fast discharge of the stored water generating the flushing waves. Finally, the flushing process starts. The transported solids can be collected downstream in special tanks or removed manually. The cleansing efficiency of flush waves is the most important parameter, which depends on flush volume, flush discharge rate, sewer slope and length, sewer flow rate, sewer diameter and population density [41]. Experiments have proven that the solids could be re-suspended and transported not only with large flushing waves at high velocity, but also with small waves at low velocity [17].

5. Smoothed Particle Hydrodynamics

During the last decades, numerical models have become very popular, because they are cost-effective and can simulate the same size as the real case. The Lagrangian mesh- free methods have been widely used to simulate free-surface flows that are rapidly changing. Smoothed Particle Hydrodynamics (SPH) is a mesh-free method, which was developed to solve astrophysical problems [22, 28]. Furthermore, it was successfully used to simulate free-surface flows [38] and multi-phase flows [39]. In Lagrangian approaches, the particles are carrying physical properties, such as mass, momentum, density, pressure and velocity. In SPH, the system contains a large number of particles that move with the fluid, which means that the motion of the fluid is represented by the motion of the particles [14]. The mass and the number of particles are constant, so that continuity of mass is solved. The particles interact with each other, controlled by a smoothing function [26], and their properties can change with time [23]. A smoothing kernel $W(h, r)$, which is nonzero only for $r = |x - x_i| \leq 2h$; h = smoothing length and r = position vector; approximates field quantities at arbitrarily distributed discretization points and these points move with their local velocity. The smoothing kernel has compact support to limit the number of interacting particles and the width of this kernel represents the discretization length scale of SPH. Figure 2 shows the kernel-weighted influence of the neighborhood of each particle. The physical quantity of any particle can be obtained by summing the relevant properties of all particles, which lie within the range of the smoothing kernel $W(h, r)$. Spatial derivatives are calculated only from interactions with neighboring particles [1].

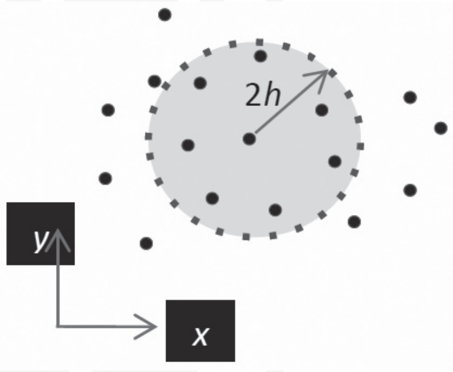

Fig. 2. The kernel-weighted influence of the neighbors of an SPH particle

In order to adapt the SPH method to fluid mechanics applications, the Navier-Stokes equations need to be solved. The Lagrangian form of the Navier-Stokes equations for a weakly compressible viscous fluid is transformed into a system of ordinary differential equations that are written as [31]:

$$\frac{D\rho}{Dt_i} = \sum_{j=1}^{N_i} m_j (u_j - u_i) \nabla_i W_{ij} \tag{2}$$

$$\frac{Du}{Dt_i} = -\sum_{j=1}^{N_i} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij} \right) \nabla_i W_{ij} + \sum_{j=1}^{N_i} \frac{m_j}{\rho_i \rho_j} \frac{4\mu_i \mu_j}{\mu_i + \mu_j} \frac{x_{ij} \nabla_i W_{ij}}{x_{ij}^2 + 0.01h^2} u_{ij} + g \tag{3}$$

where:

N_i – the summation is extended to the N_i points occupied by all neighbors within the compact support of the kernel function centered on the *i*th particle,
$x_{ij} = x_i - x_j$ – relative position vector,
u – particle velocity vector,
$u_{ij} = u_i - u_j$ – relative velocity vector,
g – gravitational acceleration vector,
ρ – density,
μ – dynamic viscosity,
m – mass,
p – pressure of the particle,
Π_{ij} – Monaghan artificial viscosity for the numerical stability of the method that is introduced as:

$$\Pi_{ij} = \begin{cases} -\alpha_M \dfrac{c_{si} + c_{sj}}{\rho_i + \rho_j} \dfrac{h u_{ij} x_{ij}}{x_{ij}^2 + 0.01h^2} & \text{if } u_{ij} x_{ij} < 0 \\ 0 & \phantom{\text{if }} u_{ij} x_{ij} > 0 \end{cases} \tag{4}$$

where:

α_m – constant parameter,
c_s – speed of sound.

Each moving fluid element is followed in time. Therefore, SPH simulations need a large number of calculations that increase with the increasing resolution. To speed up the large SPH simulations, graphics processing units (GPUs) and parallel programming are required [36]. SPH is, in comparison to mesh-based methods, more expensive due to the high computational demand. However, SPH offers important advantages for simulating free-surface and multi-phase flows. Because of the Lagrangian nature of SPH, advection is treated exactly and tracking of the phase interface is very simple. SPH can specially treat complex geometry changes, such as fragmentation without any large preprocessing of a simulation [1]. More details about the methodology of SPH are provided by Monaghan [37, 40] and Liu and Liu [27].

6. SPH application for free-surface and sediment transport simulations

Free-surface flows in hydrodynamic are very important, but they are difficult to simulate due to the boundary conditions on a moving surface. In the last decades, the SPH method has been widely used to model free-surface flows [32, 38] and to simulate free-surface channels [20]. Monaghan [38] concluded that SPH can simulate free-surface flows without any difficulties. Furthermore, many researchers have investigated modelling of multiphase flows using SPH [14, 39] and only a few SPH studies have dealt with the transport of solid bodies driven by a free-surface [2]. The SPH modelling has also been used by many researchers to investigate waves and their breaking process [6, 15, 18, 40, 47, 48, 54]. There are some studies analyzing the simulation of sediment transport using SPH [30, 31, 56]. Some of the most interesting studies for our future work are briefly described in the following.

Amicarelli et al. [2] developed and validated a 3D SPH model for the transport of rigid solids in free-surface flows. This study has implemented fluid-body and solid-solid multiple coupling terms in the SPH equations for both the flow and the transported bodies. The numerical model is validated on a complex 3D experimental test case representing a dam break event. The comparison between validations and experimental, theoretical and other SPH numerical results showed that the SPH method is a reliable way to model the transport of rigid bodies in free-surface flows.

Burger and Rauch [10] introduced the fundamentals of SPH for use in pipe hydrodynamics. The Torricelli's law and Poleni's formel were chosen to test a 2D SPH model, which was implemented for pipe flow hydrodynamics. The results were realistic, but there was still the lack of a turbulence model for pipe hydraulics, which was under consideration. The authors foresee a huge potential of the SPH method in simulating sewer hydraulics, multiphase flow and pollution transport.

Fourtakas et al. [21] used the DualSPHysics code, an SPH solver, to simulate the sediment suspension and the shear layer induced by rapid flows resulting in scouring of the sediments in industrial tanks. The liquid and sediments were treated as compressible pseudo-Newtonian fluids. In this study, two yield criteria the Mohr-Coulomb and Drucker-Prager were used with the SPH formulation. The results of the two models were agreeable, but the DP method is preferred because the MC criterion did not predict the yield strength of the sediment resulting in larger viscosities. It was also concluded that the particle spacing can influence the results of the simulations.

Manenti et al. [30] investigated an application of the improved SPHERA code, an SPH solver, to simulate non-cohesive sediment flushing by bottom discharge of water from a tank. The comparison between the experimental results and the results of 2D and 3D numerical simulations of the sediment profile and water level according to the Shields erosion criterion showed an adequate degree of accuracy of the SPH method. However, the 2D model could reproduce the final eroded profile with higher precision than the 3D model.

Manenti et al. [31] developed an SPH model to simulate the coupled fluid-sediment dynamics induced by the rapid water discharge in an artificial reservoir. The liquid phase and the eroded granular particles are considered as weakly compressible fluids. The Mohr-Coulomb yielding criterion and the Shields criterion were implemented and compared for determining the onset of the bottom sediment motion induced by the hydrodynamic shear stress. The comparison between the experimental and numerical slope profiles showed that the Shields approach is preferable for practical applications because it can represent the sediment dynamics better.

Meister et al. [33] investigated the application of the SPH method for several problems in urban water management. They simulated flume flows, sedimentation and transport processes and also aerated flows in wastewater treatment. Although the results of the study concluded that SPH can be a powerful method for channel flow simulations, some improvements are still needed to use SPH in the field of urban water management particularly due to the high computational demand. The investigation on the sediment flushing using a flushing gate confirmed that the SPH method is especially viable in this case, because the rapid deformation of free-surface flows can be modelled very well with the SPH method.

Mirmohammadi and Ketabdari [35] used the SPH method to simulate water and sandy sediment interaction around a marine pipeline as well as wave generation and propagation. The sediment was assumed as a non-Newtonian fluid and the Bingham model was used to simulate the sediments behavior. The results of the numerical model showed a good level of agreement with the results of inviscid wave propagation and damping empirical model. They concluded that the SPH method is a powerful tool to simulate the transport of sediments, although the sediment transport is a complex and long term phenomenon.

Razavitoosi et al. [43] proposed a two-dimensional SPH model to simulate the sediment transport caused by dam break over a movable bed. The fluid and sediment phases were described by particles as weakly compressible fluids. The fluid phase was modelled as a Newtonian fluid and the sediment phase as a non-Newtonian fluid using three alternative approaches of ‘artificial viscosity’, ‘Bingham and Artificial viscosity’ and ‘Bingham and Cross’. The numerical results were compared with experimental results, showing that the combination of the Bingham model and the artificial viscosity has the most acceptable accuracy.

Sitzenfrei et al. [49] discussed three issues in scientific computing in urban water management involving the SPH method as an alternative to explore fluid flow phenomena. They mentioned that SPH has several advantages due to its Lagrangian nature that make it more applicable than grid-based CFD methods to hydrodynamic simulations in sewers, such as modelling of pollution transport and sewer solids. Despite the challenge of high computational demand for SPH simulations, which could be tackled using technologies like graphics processing units (GPUs), the authors foresee a huge potential of the method to be applied to simulate real world pipe networks in order to tackle the problem of pollution transport in drainage systems.

7. Conclusion

In this paper, an overview of the SPH simulation of free-surface flows and sediment transport has been illustrated. It is important to investigate the sediment transport in sewers in order to be able to predict the transport of pollutants. Several factors influence the efficiency of the flushing devices in sewer systems (e.g. channel geometry and total amount of sediments and their characteristics). Therefore, it is very expensive and time-consuming to assess the efficiency of the cleaning operation with experimental investigations. The numerical methods allow overcoming these difficulties by reasonable simulation of the free-surface flows in channels and sediment transport. The SPH method can simulate very complex geometries, even in 3D. Many studies have been carried out on the SPH simulation of free-surface flows in coastal areas, rivers and artificial reservoirs, but only a few of these studies have investigated the modelling of free-surface channels and sediment flushing in sewers. These studies show satisfactory results. However, there is still a lack of knowdlege on SPH application in sewer management. It could be expected that, in a few years, SPH will be a powerful modelling tool for the simulation of flows and sediment transport in order to solve several problems related to sewer systems.

References

[1] Adami S., Hu X.Y., Adams N.A., *A transport-velocity formulation for smoothed particle hydrodynamics*, Journal of Computational Physics 241, 2013, 292–307.

[2] Amicarelli A., Albano R., Mirauda D., Agate G., Sole A., Guandalini R., *A Smoothed Particle Hydrodynamics model for 3D solid body transport in free surface flows*, Computers & Fluids 116, 2014, 205–228.

[3] Ashley R.M., Crabtree R.W., *Sediment origins, deposition and build-up in combined sewer systems*, Water Science and Technology, 25 (8) , 1992, 1–12.

[4] Ashley R.M., Verbanck M.A., *Mechanics of sewer sediment erosion and transport*, Journal of Hydraulic Research, 34 (6), 1996, 753–770.

[5] Ashley R.M., Bertrand-Krajewski J.L., Hvitved-Jacobsen T., Verbanck M., *Solids in Sewers: Characteristics, Effects and Control of Sewer Solids and Associated Pollutants*, Joint Committee on Urban Drainage, IWA Publishing, 2004.

[6] Aureli F., Dazzi S., Maranzoni A., Mignosa P., Vacondio R., *Experimental and numerical evaluation of the force due to the impact of a dam-break wave on a structure*, Advances in Water Resources, 76, 2015, 29–42.

[7] Bertrand-Krajewski J.L., *Sewer sediment management: some historical aspects of egg-shaped sewer and flushing tanks*, Water Science and Technology, 47 (4) , 2003, 109–122.

[8] Bertrand-Krajewski J.L., Campisano A., Creaco E., Modica C., *Experimental analysis of the Hydrass flushing gate and field validation of flush propagation modelling*, Water Science and Technology, 5 (2), IWA Publishing, 2005, 129–137.

[9] Bollrich G., Technische Hydromechanik, Band 2. Berlin, VEB Verlag für Bauwesen, 1989.

[10] Burger G., Rauch W., *Investigating Smoothed Particle Hydrodynamics in Sewer Hydraulics Modeling*, 12th International Conference on Urban Drainage, Porto Alegre/Brazil, 11–16 September 2011.

[11] Butler D., Tedchanamoorthy S., Payne J.A., *Aspects of surface sediments characteristics on an urban catchment in London*, Water Science and Technology, 25 (8), 1992, 13–19.

[12] Campisano A., Creaco E., Modica C., *Experimental and numerical analysis of the scouring effects of flushing waves on sediment deposits*, Journal of Hydrology, 299, 2004, 324–334.

[13] Chebbo G., Laplace D., Bachoc A., Sanchez Y., Le Guennec B., *Technical solutions envisaged in managing solids in combined sewer networks*, Water Science and Technology, 33 (9) , 1996, 237–244.

[14] Chen Z., Zong Z., Liu M.B., Zou L., Li H.T., Shu C., *An SPH model for multiphase flows with complex interfaces and large density differences*, Journal of Computational Physics, 283, 2015, 169–188.

[15] Dao M.H., Xu H., Chan E.S., Tkalich P., *Numerical modelling of extreme waves by Smoothed Particle Hydrodynamics*, National Hazards and Earth System Sciences 11, 2011, 419–429.

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

[17] Dettmar J., *Beitrag zur Verbesserung der Reinigung von Abwasserkanälen*, Ph.D. Thesis, Fakultät für Bauingenieurwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen, 2005.

[18] Dominguez J.M., Suzuki T., Altomare C., Crespo A.J., Gomez-Gesteira M., *Hybridisation of a wave propagation model (SWASH) and a meshfree particle method (SPH) for real applications*, 3rd IAHR Europe Congress, Book of Proceedings, Porto – Portugal, 2014.

[19] Engelke P., Gießler M., Eckstädt H., *Modelling of Sediment Transport in Sewers*, 16th International Conference Transport and Sedimentation of Solid Particles, Rostock, Germany, 18–20 September 2013.

[20] Federico I., Marrone S., Colagrossi A., Aristodemo F., Antuono M., *Simulating 2D open-channel flows through an SPH model*, European Journal of Mechanics B/Fluids 34, 2012, 35–46.

[21] Fourtakas G., Rogers B.D., Laurence D.R., *Modelling sediment resuspension in industrial tanks using SPH*, La Houille Blanche, 2, 2013, 39–45.

[22] Gingold R.A., Monaghan J.J., *Smoothed particle hydrodynamics: Theory and application to non-spherical stars*, Monthly Notices of the Royal Astronomical Society, 181, 1977, 375–389.

[23] Gomez-Gesteira M., Rogers B.D., Dalrymple R.A., Crespo A.J.C., *State-of-the-art of classical SPH for free-surface Flows,* Journal of Hydraulic Research 48, Extra Issue, International Association of Hydraulic Engineering and Research, 2010, 6–27.

[24] Ghani A.Ab., *Sediment transport in sewers*, Ph.D. Thesis, University of Newcastle upon Tyne, Department of Civil Engineering, 1993.

[25] Graf W.H., *Hydraulics of sediment transport*, McGraw-Hill Book Company, New York 1971.

[26] Liu M.B., Liu G.R., Lam K.Y., *Constructing smoothing functions in smoothed particle hydrodynamics with applications*, Journal of Computational and Applied Mathematics, 155, 2003, 263–284.

[27] Liu G.R., Liu M.B., *Smoothed Particle Hydrodynamics: an Overview and Recent Developments*, Archives of Computational Methods in Engineering, 17, 2010, 25–76.

[28] Lucy L., *A numerical approach to the testing of fusion process*, Journal of Astronomical, 82, 1977, 1013–1024.

[29] Lucas-Aiguier E., Chebbo G., Bertrand-Krajewski J.L., Gagne B., Hedges P., *Analysis of the methods for determining the settling characteristics of sewage and stormwater solid*, Water Science and Technology, 37 (1), 1998, 53–60.

[30] Manenti S., Sibilla S., Gallati M., Agate G., Guandalini R., *3D SPH Simulation of non-Cohesive Sediment Flushing*, 6th International SPHERIC workshop, Hamburg, Germany, 2011.

[31] Manenti S., Sibilla S., Gallati M., Agate G., Guandalini R., *SPH Simulation of Sediment Flushing Induced by a Rapid Water Flow*, Journal of Hydraulic Engineering, 138 (3), 2012, 272–284.

[32] Maruzewski P., Oger G., Le Touzé D., Biddisccombe J., *High performance computing 3D SPH model: Sphere impacting the free-surface of water*, 3rd ERCOFTAC SPHERIC workshop on SPH applications, Lausanne, Switzerland, 2008.

[33] Meister M., Fleischhacker N., Rauch W., *Anwendung von Smoothed Particle Hydrodynamics in der Siedlungswasserwirtschaft*, Conference Aqua Urbanica, Innsbruck, Germany, 2015.

[34] Michaelbach S., *Origin, resuspension and settling characteristics of solids transported in combined Sewage*, Water Science and Technology, 31 (7), 1995, 69–76.

[35] Mirmohammadi A., Ketabdari M.J., *Numerical simulation of wave scouring beneath marine pipeline using smoothed particle hydrodynamics*, International Journal of Sediment Research, 26, 2011, 331–342.

[36] Mokos A., *Multi phase Modelling of Violent Hydrodynamics Using Smoothed Particle Hydrodynamics (SPH) on Graphics Processing Units (GPUs)*, Ph.D. Thesis, University of Manchester, 2013.

[37] Monaghan J.J., *Smoothed Particle Hydrodynamics*, *Annual Review of Astronomy and Astrophysics*, 30, 1992, 543–574.

[38] Monaghan J.J., *Simulating free surface flows with SPH*, Journal of Computational Physics, 110, 1994, 399–406.

[39] Monaghan J.J., Kocharyan A., *SPH simulation of multi-phase flow*, Computer Physics Communications, 87, 1995, 225–235.

[40] Monaghan J.J., *Smoothed particle hydrodynamics*, Reports on Progress in Physics, 68, 2005, 1703–59.

[41] Pisano W.C., Barsanti J., Joyce J., Sorensen H., *Sewer and tank sediment flushing: case studies*, US EPA National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio 45268, Report No. EPA/600/R-98/157, 1998.

[42] Pisano W.C., Queiroz C.S., *Automated sewer and drainage flushing systems in Cambridge, Massachusetts*, Journal of Hydraulic Engineering, 129 (4), 2003, 260–266.

[43] Razavitoosi S.L., Ayyoubzadeh S.A., Valizadeh A., *Two-phase SPH modelling of waves caused by dam break over a movable bed*, International Journal of Sediment Research, 29 (3), 2014, 344–356.

[44] Ristenpart E., *Sediment properties and their changes in a sewer*, Water Science and Technology, 31 (7), 1995, 77–84.

[45] Schaffner J., Oberlack M., Kirchheim N., *The application of numerical modeling (3-D) for the calculation of flush waves in sewer channels*, 6th International Conference on Urban Drainage Modelling, Dresden, Germany, 2004.

[46] Schlütter F., *Numerical Modelling of Sediment Transport in Combined Sewer Systems*, Ph.D. Thesis, Aalborg University, Department of Civil Engineering, 1999.

[47] Shao S.D., *Simulation of breaking wave by SPH method coupled with k-epsilon model*, Journal of Hydraulic Research, 44 (3), 2006, 338–349.

[48] Shao S.D., Lo E.Y.M., *Incompressible SPH method for simulating Newtonian and non-Newtonian flows with a free surface*, Advances in Water Resources, 26 (7), 2003, 787–800.

[49] Sitzenfrei R., Kleidorfer M., Meister M., Burger G., Ulrich C., Mair M., Rauch W., *Scientific Computing in Urban Water Management*, Computational Engineering, Springer International Publishing, Switzerland, 2014, 173–193.

[50] Thamsen P.U., Gerlach S., Höchel K., *Remarks on wastewater transport challenges for today and the future*, 16th International Conference Transport and Sedimentation of Solid Particles, Rostock, Germany, 18–20 September 2013.

[51] Todeschini S., Ciaponi C., Papiri S., *Experimental and numerical analysis of erosion and sediment transport of flushing waves*, 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 2008.

[52] van Rijn L.C., *Sediment transport, part I: bed load transport*, Journal of Hydraulic Engineering, 110 (10), American Society of Civil Engineers, Reston, VA, USA, 1984, 1431–1456.

[53] van Rijn L.C., *Sediment transport, part II: suspended load transport*, Journal of Hydraulic Engineering, 110 (11), American Society of Civil Engineers, Reston, VA, USA, 1984, 1613–1641.

[54] Vaughan G.L., *Simulating Breaking Waves Using Smoothed Particle Hydrodynamics*, Ph.D. Thesis, University of Waikato, Hamilton, New Zealand, 2005.

[55] Verbanck M., *Sewer Sediment and its relation with the quality characteristics of combined sewer overflows*, Proceedings of the 2^{nd} Wageningen Conference, 1989, 11.

[56] Vetsch D., *Numerical Simulation of Sediment Transport with Meshfree Methods*, Ph.D. Thesis, Mitteilungen 219, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW) der Eidgenössischen Technischen Hochschule Zürich, 2012.

[57] Yang C.T., *Unit Stream Power and Sediment Transport*, Journal of the Hydraulics Division, 98 (10), 1972, 1805–1826.