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DETERMINATION OF PARTICLE TRANSPORT CHARACTERISTICS FROM SEWER SYSTEMS

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Avoiding sediment formation in wastewater pressure pipes is often in contrast to the wish of energy efficient pump operation. Characterization of particle behaviour depending transport mechanisms in sewer networks can help to define minimum hydraulic requirements to achieve reduced energy demand for pumping without risking blockages. For this, wastewater specific lab experiments to assess sedimentation and erosion characteristics have been developed. Once constructed, analysis on several wastewater samples can be performed within short periods of time. Different pumping stations with different inflow conditions with respect to location, pre-treatment technology (rake, cutting system, no treatment) and dry as well as wet weather conditions have been investigated regarding settling and erosion behaviour. The received data from the experimental procedures have been processed into sedimentation (settling rates) and erosion (erosion function) data to characterise the sewer conditions inside the sewer system. Thus for each investigated pumping station, specific settling rates and erosion functions have been developed.

KEY WORDS Sedimentation, erosion, re-suspension, settling rate, pressure pipe system, experimental study

1. INTRODUCTION

The operation of water and wastewater facilities nearly always rely on pumping processes. Thus, regarding energy saving intentions, one main potential lies in the process step of wastewater transport though pumps. Power consumption of sewage pumps can be reduced by the use electronic speed control. Thereby the optimal pumping operation aims at a reduction of flow velocity by a related reduction of friction losses. However, the advantage of reduced friction losses come at a price of potential increase in sedimentation. The identification of optimal speed controlled pumping operation and a safe particle transport is related to particle behaviour such as sedimentation and erosion of transported solids. In order to investigate solids transport for these conditions, two experimental procedures have been designed. Selected results are presented within this work.

2. METHODS AND STUDY AREA

To determine sedimentation and erosion characteristics, two experimental setups were designed, based on several constructions found in literature. Samples were then collected from three different pumping stations in northern Germany and investigated using the constructed devices. Subsequently, various data processing methods to define sewage characteristics regarding settling behaviour depending on settling duration and erosion or resuspension behaviour depending on shear stress.

2.1. EXPERIMENTAL DEVICES

Sedimentation

Based on Gromaire et al. (2008), an experimental set up was constructed to identify a set of settling classes related to the mass portion within a short time and by using a simple and robust design (Fig.1a). For this, seven sedimentation columns (volume $V_c = 2.4\ L$, height $H_c = 380\ mm$) were used, each with separate inlet (filling) and outlet (sampling). Sewage samples were stored in a *30 L* stirred tank. Columns filled by gravitation, while a *10 mm* glass tube connected to a central vacuum pump took out samples. Using this setup, a large amount of data (solids concentration, chemical parameters) can be produced within a few days.

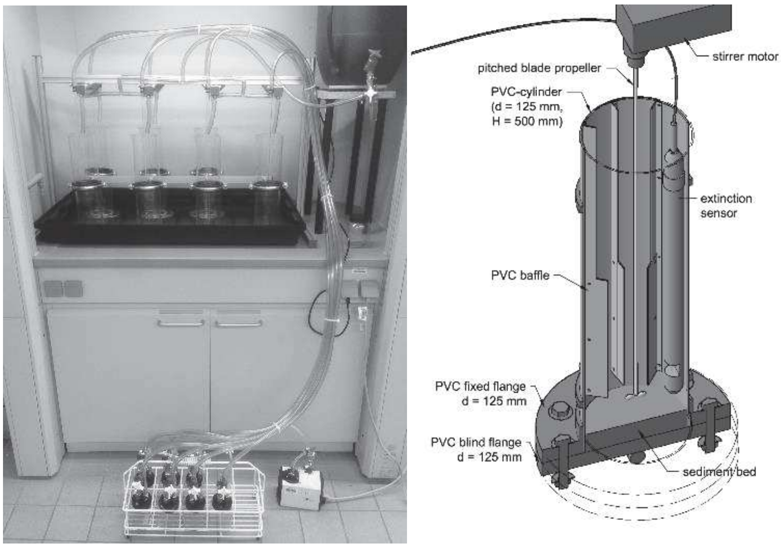

Fig.1: a: sedimentation device, b: CAD-Modell of erosion cylinder

The experimental setup varies between *15 s* and *24 h*, see Table 1. Each starts with filling of each column with a particular wastewater sample. After each sedimentation sequence a sample ($V_s = 0.345\ L$) is extracted by the vacuum pumping system from the bottom of the respective column and analysis on *TSS* – total suspended solids (mgL^{-1}) are conducted. Finally, the mass of each column is determined.

Table 1

Settings for sedimentation tests

column *n*		1	2	3	4	5	6	7
settling duration *t*	s	15	45	180	420	1,800	14,400	86,400

Erosion

The presented experimental design based on Lange (2013) and Hoeft (2015), while both refer their constructions to Liem et al. (1997). The applied device for measuring erosion events (see Fig.1b), consists of the following components:

- polyvinyl chloride (PVC) cylinder (diam. *125 mm*), as reaction chamber
- PVC fixed flange (diam. *125 mm*), as mounting fixture for the PVC-cylinder
- PVC blind flange (diam. *125 mm*), as bottom component
- 6 PVC baffles, for axial direction of flow conditions
- speed controlled stirrer motor (Heidolph RZR 2102 control), pitched blade propeller, for applying shear stress
- extinction sensor (Semitec DEP), for continuous extinction measurement

After filling the erosion cylinder with the sewage sample ($V = 6.5\ L$), settling process follows and ends after: *20 min, 1 h, 4 h, 8 h, 14 h, 17 h, 24 h* or *72 h*. Once settling is completed, a motor control mode for stirring is defined: start rpm $(rpm_{start}) = 20\ min^{-1}$, stirrer speed increase per level $(rpm_{inc}) = 10\ min^{-1}$, level duration $(level_t) = 60\ s$, end rpm $(rpm_{end}) = 400\ min^{-1}$. Subsequently, stirrer motor and extinction sensor starts working and ends automatically.

2.2. STUDY AREA

Analysed samples taken from three PS – pumping stations in northern Germany:

i) PS-Rostock (Schmarl):
   a. inflow: mainly untreated domestic sewage (≈ 40,000 inhabitants)
   b. separate sewer network (surface runoff from roads also connected)
   c. mechanical treatment: rake with a wide space bar opening
   d. connection: *DN 600* cast iron pipeline, *4,500 m* length

ii) PS-Prerow:
   a. inflow: mechanical pre-treated domestic sewage (high touristic fluctuation, ≈ 4,000 inhabitants in winter, ≈ 20,000 in summer season)
   b. supplied by various small pressure pumps, all equipped with a cutting system
   c. separating system (influence from rainfall events verified and proven by correlation of rainfall and discharge)
   d. connection: *DN 400* PE-HD pipeline, length *2,519 m*

iii) PS Schoenberg:
   a. inflow: untreated domestic sewage
   b. separating system (storm water system for rain events), ≈ 5,000 inhabitants
   c. no treatment technology installed
   d. connection: *DN 250* PE-HD pipeline, length *7,842 m*

2.2. DATA PROCESSING

Sedimentation

To describe sewer sedimentation characteristics, an exponential function was used to fit experimental data to a settling rate, see equation (1).

$$C_s(t) = c_o \cdot e^{-b \cdot t \cdot \frac{H_c}{DN}} + c_{rest} \quad (1)$$

The settling behaviour is realised with a settling rate, which shows the decrease of particle mass inside the water column. Settling at time $t = 0$ *[s]* starts with the initial mass or concentration c_0 *[-]* + c_{rest} *[-]* = *1*. Particle loss inside the fluid described by term $e^{-b\,t}$, decisively influenced by parameter b *[s^{-1}]*. While raising b, particles will precipitate faster and in turn by lowering b, the settling process is extended. Now after each time step during a settling event, a specified proportion of particles is deposited. Quotient form dividing the height of the settling column (H_c *[mm]*) to *DN* (diamètre nominal *[mm]*) serves as an adaption to the settling height. After sedimentation is completed, the residual particle mass inside the fluid is described by c_{rest} *[-]*.

Erosion

Several approaches for defining critical shear stress points exists, all trying to define the instant were the point of interest (e.g. critical shear stress point for commencing erosion) is located. Points of interest were: τ_{crit} (definition of commencing erosion) and τ_{100} (definition of erosion were settling begins). Used approaches and functions are listed in Table 2.

Selected approaches to define shear stress points (τ_{crit} and τ_{100}) Table 2

Amos and Gibson (1994)	Amos et al. (2004)	University of Rostock
$f(x)_1 = a\,x^b$ $f(x)_2 = c\,x^d$	$f(x)_1 = ax + b$ $f(x)_2 = c\ln(x) - d$	$f(x) = \left(\frac{c}{1 + a\,e^{-b\,x}}\right) + d$
	Defining shear stress points	
$f(x)_1 - f(x)_2$	$f(x)_1 - f(x)_2$	$\lim_{x\to\infty} f(x)$

Listed functions were fitted to measured data set of each experimental procedure (extinction (y) depending on stirrer speed (x)). For Amos and Gibson (1994) and Amos et al. (2004) 2 functions were fitted to each data set, then the point of intersection p_x was calculated. Afterwards, calculated x-coordinate from p_x (stirrer speed) transferred to shear stress using a calibration function. Logistic function used as an alternative method for defining shear stress points, where limits value of the fitted function leads to points of interest. The presented results were produced using the Amos et al. (2004)-method, which is due to an easy automation (MatLab) and plausible results with small standard deviations.

3. RESULTS AND DISCUSSION

3.1. SETTLING BEHAVIOR

Results from settling tests are shown from Fig.2 to Fig.6. Differences in treatment technologies (rake, cutting system) were not obtained within one flow condition, while untreated sewage significant differed compared to treated samples. Comparing wet weather and dry weather inflow conditions, all curves show significant differences. For a better and faster comparison of the settling process, a term called "half-life period" (*HLP*) introduced (period were particle mass inside fluid halved):

$$HLP\ [s] = -\frac{ln\left(\frac{|c_0 - c_{rest}|}{2 \cdot c_0}\right)}{b \cdot \frac{H_c}{DN}} \quad (2)$$

HLP was calculated by means of equation (2) for the considered examples are shown in Table 3. Particle concentration decreases quickly within wet conditions, while under prevailing dry conditions concentration decreases *8* to *10* times slower. PS-Rostock (treatment: rake) shows a large spread of *HLP*. For dry weather inflow, *50 %* of particles reaching the bottom within *245.23 min* ($C_{s\ dry\text{-}rake}$ *(14,714) = 0.5)*. By this, concentration will be reduced by *50 %* every *4.08 h*. At the same time, settling process under wet weather inflow conditions is almost over, only 12 % of the particles from the original mass c_0 are left inside the fluid *(*$C_{s\ wet\text{-}rake}$*(14,714) = 0.12)*, which corresponds to *HLP = 18.9 min (*$C_{s\ wet\text{-}rake}$ *(1,135) = 0.5)*. At *18.9 min*, *94.7 %* of particles are still inside the fluid *(*$C_{s\ dry\text{-}rake}$ *(1,135) = 0.947)* taking into account dry weather inflow. Similar results were obtained for PS-Prerow (pre-treatment: cutting system). The *HLP* for untreated sewage sample (PS-Schoenberg) under dry weather conditions located halfway between treated wet- and dry weather inflow conditions.

HLP – half-life period for all five settling rates Table 3

no	*b [s⁻¹]*	*HLP [s]*	condition
1	$5 \cdot 10^{-5}$	14,714	dry weather, treatment: rake
2	$7.5 \cdot 10^{-5}$	9,661	dry weather, pre-treatment: cutting system
3	$1.4 \cdot 10^{-4}$	5,756	dry weather, untreated sewage
4	$5.2 \cdot 10^{-4}$	1,135	wet weather, pre-treatment: cutting system
5	$7.4 \cdot 10^{-4}$	1,533	wet weather, treatment: rake

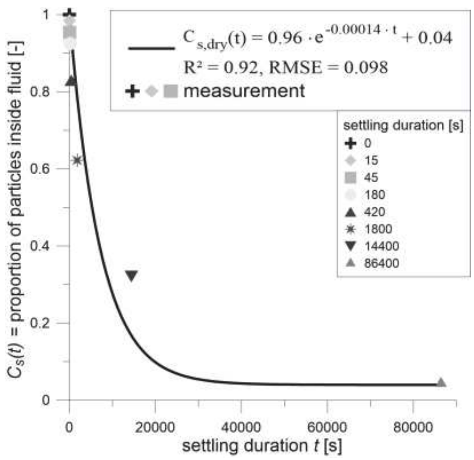

Fig.2: $C_s(t)$ for dry weather inflow (PS-Schoenberg), no treatment

Both, calculating *HLP* and pictured graphs showing significant differences in sewage settling behaviour, depending on inflow condition and treatment or no treatment. The differences result from particle concentration and distribution, while several reasons can be mentioned: diurnal particle concentration and inflow fluctuation, fluctuation of backward pumping stations, infiltration, rain and storm events and seasonal fluctuation.

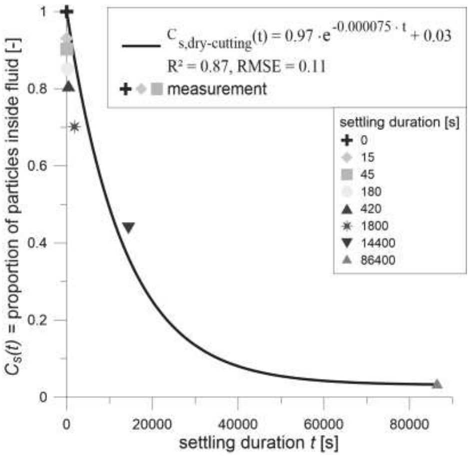

Fig.3: $C_s(t)$: dry weather inflow (PS-Prerow), treatment: cutting system

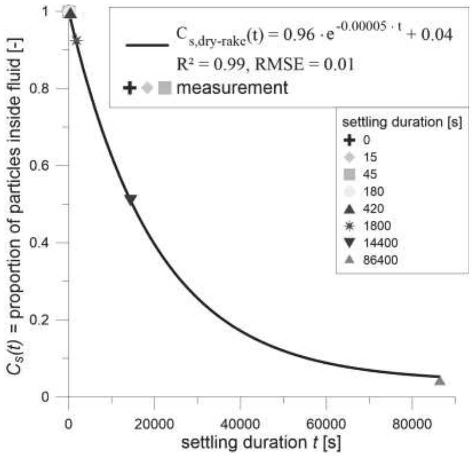

Fig.4: $C_s(t)$: dry weather inflow (PS-Rostock), treatment: rake

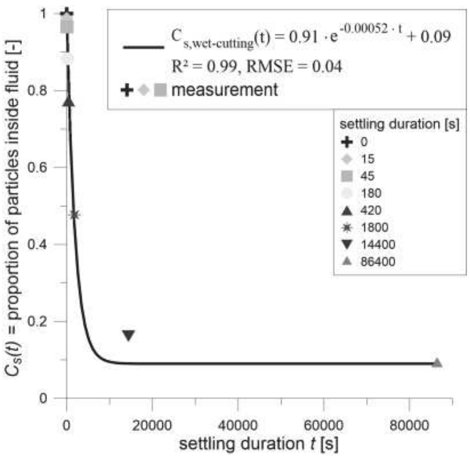

Fig.4: $C_s(t)$: wet weather inflow (PS-Prerow), treatment: cutting system

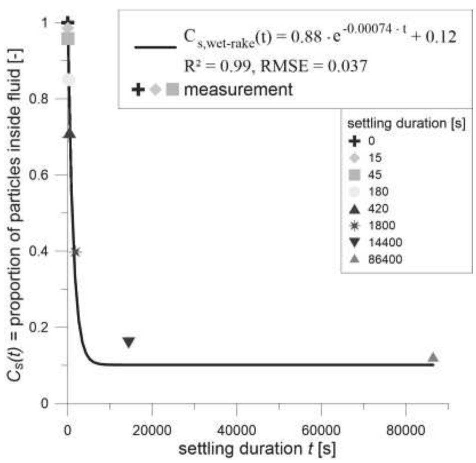

Fig.6: $C_s(t)$: wet weather inflow (PS-Rostock), treatment: rake

3.2. EROSION BEHAVIOR

Erosion tests were performed for dry weather inflow conditions for PS Rostock (treatment: rake) and PS-Schoenberg (no treatment). Results from erosion tests are shown in Fig.7 and Fig.8 for untreated sewage. Significant differences, comparing both PS samples were not obtained, which is contrary to the expectations (see settling tests results). However, increase of required shear stress, for commencing erosion as well as erosion where settling begins, was significantly detected within all experimental procedures. Power function used for fitting. Thus, required shear stress after specific settling period for dry weather sewage samples can be calculated within the generated erosion functions. While a strong growth of shear stress for short settling periods was detected, required shear stress for longer settling events growing slower, which is due to: fast settling of heavy particles, light particles settling much slower, small particles irrelevant for erosion under short settling periods, processes of consolidation (gravitation, cohesion, biogenic consolidation) not yet relevant.

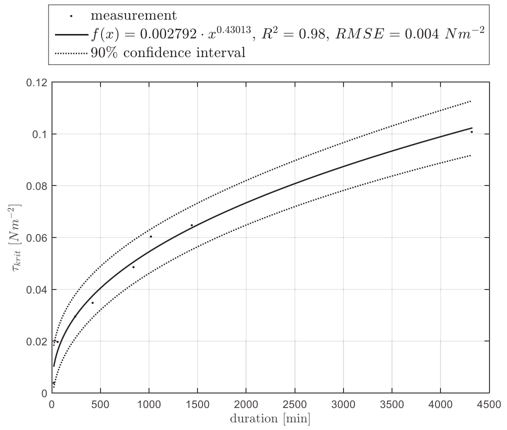

Fig.7: Erosion function for τ_{krit}, dry weather inflow (PS-Schoenberg)

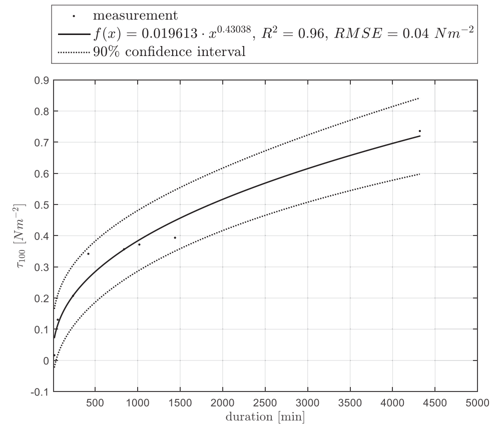

Fig.8: Erosion function for τ_{100}, dry weather inflow (PS-Schoenberg)

Compared to various results found in the literature (see Table 4 and Table 5), results for dry weather inflow of domestic sewage samples located at the lower end. For this, several reasons can be mentioned: time for settling periods before stirring (usual settling periods up to several years (field measurement), type of sample (cohesive material, large particles, high sand load in combined systems), method for generating shear stress data (open channel designs, cylindrical shape, pipeline).

τ_{crit} values for different samples and settling durations Table 4

τ_{krit} *[Nm⁻²]*	source	method/ material
7 – 2,500	Wotherspoon and Ashley (1992)	Lab test (cohesive sediment samples)
1.3/20	Kamphuis (1990)	Lab test (with/without sand)
5 – 7	Kleijwegt et al. (1990)	Lab test (cohesive material)
1.8 – 2	Ashley et al. (1992)	Field measurement
2.2 – 5.6	Ristenpart (1995)	Field measurement (combined flow)
0.44 – 1.02		Field measurement (dry weather flow)
0.015 – 0.16	**University of Rostock**	**Lab test (dry weather flow)**

τ_{100} values for different samples and settling durations Table 5

$\tau_{100}\ [Nm^{-2}]$	source	method/ material
1 – 8	Macke (1982)	recommendation (lab test, sand)
4	Ackers (1991)	Channel flow
1 – 2	Brombach et al. (1993)	recommendation (field measurement)
0.04 – 0.67	Ristenpart (1995)	Field measurement (dry weather flow)
0.031 – 0.71	**University of Rostock**	**Lab test (dry weather flow)**

4. SUMMARY AND CONCLUSIONS

The presented experimental procedures were built up based on literature data (originally designed for combined systems) and modified for pressurized (separating) systems. Both providing a robust and efficient design to achieve high-quality data from sewage samples. The presented results can be used for a PS to be optimized with regard to operation mode (i.e. after rainfall events), pipe flushing or energy efficient operation (low flow velocities). While sedimentation in pressure pipes occurs only for short periods, settled mass, especially for dry weather inflow, is low. Furthermore, even long settling periods can be tackled by low shear stresses. Consequently, the risk of blockages can be minimized, e.g. with regard to energy saving pumping operation.

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