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SOME MODELS OF SEDIMENTS TRANSPORT IN GRAVITATIONAL SANITATION SYSTEMS

WYBRANE MODELE TRANSPORTU OSADÓW W SYSTEMACH KANALIZACJI GRAWITACYJNEJ

Abstract: The sediments in gravitational sanitation systems appear when the velocity of flow decreases below the value of hydraulic self-purification. These sediments have the significant influence on the processes occurring in the sanitation systems, causing inter alia the periodical fluctuation of loads entering the wastewater treatment plants. The sediments deposited in the channel are also causing the changes of the shape of pipe cross-section thus influencing the changes of physical and hydrodynamic parameters of the whole system. The sediments are also influencing the development of the sulphuric corrosion of pipes and intensity of biological biodegradation of wastewater in sanitation conduits. The research concerning the wastewater sediments and the connected processes are pretty costly so they are only being conducted in countries in which the biding law requires the mathematical modeling of mass transport to the wastewater plants and storm spillways. The results of this research give the necessary data to calibration of hydraulic models. The general description of structure and properties of sediments should be known at the stage of the consideration of minimal inclinations of conduits. It is also very important during the modeling of pollutants load transport in sanitation system and the process of wastewater biodegradation, because for different type and properties of sediments different model of transport should be used. The classification of sediments based on literature research and the results of classification research in sanitary systems in Chelm, Poland, as well as models often used for describing of sediment transport in gravitational conduits were presented.

Keywords: gravitational sewer system, sludge in sewer system, sludge classification, sludge transport in sewer system

The sediments in gravitational sanitation systems appear when the velocity of flow decreases below the value of hydraulic self-purification. The sediments have the significant influence on the processes occurring in the sanitation systems, causing inter alia the periodical fluctuation of loads entering the wastewater treatment plants. The deposited sediments during the phase of low canal filling and low flow velocity reduce the pollutants load, thus during the phase of high filling and high flow velocity the

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deposited pollutants are being washed away, rapidly increasing the concentrations and loads of transported pollutants. This phenomenon directly influences the pollutants load entering the wastewater treatment plant or storm spillway and sewage discharge receiver. The sediments deposited in the channel are also causing the changes of the shape of pipe cross-section, thus influencing the changes of physical and hydrodynamic parameters of the whole system [1–4]. The sediments are also influencing the development of the sulphuric corrosion of pipes and intensity of biological bio-degradation of wastewater in sanitation conduits [5–9].

The actually applied techniques of sampling and measurements allow to obtain the results only partially reflecting the properties of sediments in their natural environment [9, 10].

The researches focused on the susceptibility of the analyzed sediments on pollutants release suggest that infringement of the sampled sediments basic structure causes the problems of the lack of proper mapping of sediments properties.

The reologic properties are influenced by the sediments accumulation just beneath the wastewater surface. This is, probably, one of the major reasons causing the increased resistance of the sediments to the shear stress noted in the laboratory conditions. The research of sanitation sediments properties are usually conducted in order to obtain the knowledge about the level of pollutants release and description of reologic properties, particularly the shear stress determining the sediments erosion.

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Classification of sediments forms in sewer systems

The following classification of sediments is used in EU [9–13]:

A – non-organic and non-cohesive sediments,

B – sediments of A type non-organic structure but agglomerated by oil derivatives and characterized by cohesive properties,

C – organic sediments, moving over the surface of A and B sediments with lower velocity than flowing sewages,

D – biofilm developed on pipe walls,

E – sediments in storage tanks.

Sometimes, two another groups of sediments are distinguished [9]:

F – storm conduits sediments,

G – pressure pipes sediments (after pressure sanitation attachment).

The A and B sediments are mostly noted in wastewater systems, thus, the highest load of COD is being accumulated in it, although the concentration of pollutants in these sediments is lower than in case of C type [9].

The highest content of organic pollutants was noted in C group sediments, in which the COD content reaches level of up to several hundred (even 300–500 $gO_2\ dm^{-3}$).

These sediments move over the surface of A and B group during the phase of sewage low level flow in a wastewater pipe. The presence of C and D sediments in sanitation systems results in the occurrence of biodegradation processes, because these sediments are consisting of heterotrophic organisms being the process factor of mentioned transformations.

The D group sediments are consisting of heterotrophic living organisms so the organic content in this sediments group is high. The D group layer thickness is usually low (generally not exceeding 2 mm) but the anaerobic conditions are possible. Which, in turn, contributes to hydrogen sulfide creation, influencing the sulphuric corrosion of pipes surface, attacking in sequence the vault and side walls of the canal.

The E group sediments are characterized by a high degree of fragmentation so the grains surface area in the unit volume of sewage is significant. This allows the extensive adsorption of practically insoluble organic pollutants and heavy metals.

The F group sediments indicated in wastewater and storm systems are characterized by the variable, time dependant (seasonal) composition. Particularly during the late autumn there are a lot of leaves falling down from the trees in it. Pressure pipes sediments (G group) commonly occur at the pipe slope and contain huge amounts of organic compounds, especially fats.

The general description of structure and properties of sediments should be known at the stage of the consideration of minimal inclinations of conduits. It is also very important during the modeling of pollutants load transport in sanitation system and the process of wastewater biodegradation, because for different type and properties of sediments different model of transport should be used [9].

The sediments transported in the sanitation are often the subject of physical and biochemical analysis and the proper way of sampling is necessary to obtain the credible results, for instance by the sediment trap installed at the bottom of pipes. The exemplary measurements results are presented in Table 1.

Table 1

Near-bed sediments characteristics inside egg-shaped conduits
(1 – 1030 × 686 mm; 2 and 3 – 1780 × 1625 mm) [5, 9]

No.	Particles diameter d_{50} [mm]	Wet state density [$kg \cdot m^{-3}$]	Volatile components content [%]	Mean COD value [$gO_2 \cdot m^{-3}$]	Mean BOD_5 value [$gO_2 \cdot m^{-3}$]	Mean daily flow rate [$m^3 \cdot d^{-1}$]
1	0.5–11.0	1143–1998	1.4–28.6	87 522	28 594	1900
2	0.5–4.0	1000–1066	31.8–68.1	214 000	82 758	6700
3	0.09–2.5	1000–1108	55.6–91.2	124 246	96 119	7500

The Polish researches [9] showed that phenomena connected to sediments transport and pollutants release are greatly dependent on the relations among the particular sediments properties – the most important are: density, moisture and porosity.

Sediments transport in gravity sewer system

The proper exploitation of sanitation system requires the assurance of hydraulic conduits self-purification conditions. Such conditions appear with adequate incidence when the canal inclinations were chosen properly. But, the economic conditions limit the pipes designing which would eliminate any sediments deposition, affirming their transport throughout the all day. So, the binding rules of sanitation systems design assert the periodical transport of the best part of sediments, transmitting the maximal yearly sewage flow rates and effective channels ventilation [9, 14]. Thus, in the real conditions of sanitation systems functioning the sediments are periodically accumulated in the pipes and then are washed away during the high rates phases of wastewater flow.

The field and literature studies show that particles concentration is non-uniform in the whole stream of flowing sewages and its value rapidly increases close to the pipe bottom [5, 9]. Taking into account the existence of one more increase of constant phase concentration connected to the sediments deposited on the pipe bottom, the suspension transport in the layer placed between two mentioned layers of constant phase densification is determined as the near bed transport [9, 15]. It is connected to the following phenomenon appearance: turning, displacement and saltation.

Information presented in widely used engineering literature [14, 16] suggest that to obtain the proper working conditions of the sanitation system, at the designing phase, the assurance of the pipes inclinations enabling the lowest velocity of channel self-purification are necessary. This notion is understood as velocity which stops the creation of sediment bed at the canal bottom. It is also advisable that velocity of self-purification should occur even during the flow of the lowest flow rate and filling.

The mentioned velocities are understood in two ways: as non silting velocity as well as the terminal velocity [17].

The convection velocity is a mean velocity in the active cross-section at which all particles are being transported in the channel, partially in the suspended form and partially dragged near the bottom. In this case, the processes of sediments deposition and creation of sediments bed do not occur. This terminology is accepted in literature focused on the processes occurring in sanitation systems and originated in the research description of debris transport in rivers and the other watercourses [9, 15, 17].

The terminal velocity is a mean velocity in the stream cross-section which triggers the process of erosion of sediments deposited during the lowest filling of the canal. The laboratory researches showed that the uniform sediments are completely removed after the excess of described flow velocity by more than 10 % [18–20]. The literature sources do not present the universal value of required terminal velocity because its value depends to the sewage composition, type and shape of the sediment particles as well as the hydraulic radius value – the shape, geometric characteristics and filling of the sanitation canal [9, 14, 20, 21].

It is assumed, when the mean velocities are in use, that the flow velocity is equal in all points of given cross section. But in reality, the flow velocity is different in every point – the lowest near the canal bottom, which is presented in Fig. 1.

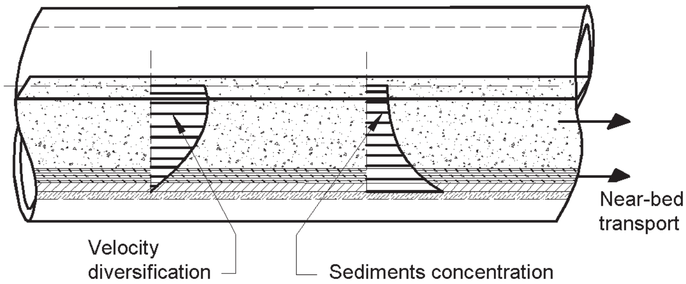

Fig. 1. Sediments transport in sanitation conduit – constant sewage level [12]

The close preservation of wastewater flow velocity at the level of 1 m · s^{-1}, which seems to be the simplest method of designing, would result, in some cases, in too high inclination of pipes leading to too high and economically unjustified pipe depression. Though, the sewage flow velocity in sanitation and storm canals should not be lower than 0.8 m · s^{-1} during the phase of the maximum canal filling. In specific cases, when there is no possibility to assert the self-purification velocity of flow, the capability of pipes flushing should be available.

The third essential in sanitation exploitation practice value of the flow velocity is connected to the beginning of conduit side walls erosion. To prevent the mechanical damages of pipes inner surface the flow velocity should be lower than 3.0 m · s^{-1} for concrete and ceramics pipes as well as 5.0 m · s^{-1} for cast iron pipes. The maximum admissible velocity of sewage flow inside the storm conduits equals 7.0 m · s^{-1} [14].

The recent approach to the problem of sanitation conduits self-purification is based on the shear stress method [22–24].

The both mentioned methods – based on the self-purification velocity and critical shear stress, allow to gain the same purpose, which is to prevent the transported sediments deposition inside the gravitational sanitation conduits. This matter is very important because the cohesive properties of transported sediments [24–26]. The shear stress of about 1.8 N · m^{-2} is required to remove the layer of freshly deposited sediments while the stress value of 800–1000 N · m^{-2} is necessary to remove the sediments after a long-lasting pipe exploitation. To illustrate the problem scale we would like to add that during the rainy weather the values of shear stress of 20 N · m^{-2} were noted inside the pipes constructed with relatively high inclinations (apart from sanitation systems in mountain regions). The inclination of sanitary conduit should ensure daily cyclical removal of deposited sediments occurring during the phase of the maximum flow rate. In case of the storm systems the removal of sediments should occur during the rainfall event of a required intensity. If this condition is not fulfilled after some years of the sanitary system exploitation only the special methods of conduit rehabilitation may restore the hydraulic capacity of the pipe.

The technical activities aimed to deposited sediments removal are often very costly so the proper choice of the minimal conduits inclination leading to the self-purification velocity (the suitable values of shear stress) occurrence becomes an important matter at the stage of sanitation system design. Besides, the sediments deposited at the canals bottom become a serious threat for the receiver of storm spillway wastewater and cause the heterogeneity of wastewater treatment plant strain by the pollutants load.

Modeling of sediments transport in gravitational sanitation

The hydraulic transport of solid particles inside the sanitation systems may occur by floating by the sewage stream and dragging along the canal bottom. The movement of single A group sediment particle is induced by the forces of hydrodynamic pressure force. The component of gravitation force parallel the conduit bottom may be insufficient because the commonly used low conduits bottom angle of inclination.

This situation may be graphically presented as shown in Fig. 2 [14].

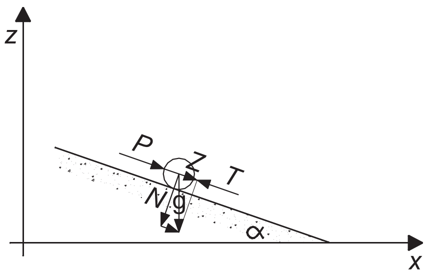

Fig. 2. Forces influencing the spheroid particle of group A at the bottom of gravitational conduit [14]

The particle presented in Fig. 2 is influenced by the following forces: P – hydrodynamic pressure force [kg · m · s^{-2}], Z – gravitational force component [kg · m · s^{-2}], T – friction force dependent to the friction factor and normal component of gravitational force $T = f\,N$ [kg · m · s^{-2}]. The inertial force and the congruency of the particle to bottom are neglected. The required mean sewage flow velocity, authoritative for the inorganic and incohesive sediment particle of diameter d [m], dragged along the bottom of a sanitation pipe of diameter D [m] may be calculated basing in Fig. 2 [14]:

$$U = \frac{u_d}{\varepsilon} \tag{1}$$

where: U – mean cross-section velocity [m · s^{-1}],
ε – velocity distribution factor [-].

The ε factor is described as:

$$\varepsilon = m - \frac{2}{3}(m-1)\ln\frac{1.25D}{d} \tag{2}$$

where: m – relation of maximum cross-section velocity to the mean velocity value [-].

The other commonly cited equation has a following form [9]:

$$\frac{v_c}{\sqrt{gd\,(s_\rho - 1)}} = a\left(\frac{d}{R_h}\right)^b \tag{3}$$

where: v_c – limit velocity [m · s^{-1}],
a, b – dimensionless factors: a = 0.61 for the smooth circular cross section, a = 0.54 for the smooth rectangular cross-section, a = 0.50 for the smooth rectangular cross-section, b = –0.38 for the smooth circular cross-section,
d – particle diameter [m],
g – acceleration of free fall [m · s^{-2}],
R_h – hydraulic radius [m],
s_ρ – comparative density of dry mass suspended in relation to water [-].

The presented equation (3) shows that the limit velocity depends to hydraulic radius, but is independent to the suspension concentration. This shows why there is no universal value of sewage flow velocity.

The following formula describing the convection velocity in the circular pipe may be used during the sediments transport modelling [20]:

$$\frac{v_c}{\sqrt{gd\,(s_\rho - 1)}} = 3.08 d_{gr}^{-0.09}\, C_v^{0.21} \left(\frac{R_h}{d_{50}}\right)^{0.53} \lambda_s^{-0.21} \tag{4}$$

where: s_ρ – relative density of solid phase $\rho_s\rho^{-1}$,
ρ_s – density of constant phase dry mass [kg · m^{-3}],
d_{50} – particles diameter, accounting for, with the smaller ones, 50 % of mass [m],
d_{gr} – dimensionless diameter of d_{50} particles $((s_\rho - 1)\, gv^{-2})^{1/3} d_{50}$,
v – kinematics viscosity factor [m^2 · s^{-1}],
C_v – volumetric concentration of sediments [ppm].

The friction factor of water suspension flow resistance λ_s calculations may be calculated basing on the friction factor for clear water λ:

$$\lambda_s = 1.13\lambda^{0.98}\, C_v^{0.02}\, D_{gr}^{0.01} \tag{5}$$

where: λ – clear water friction factor [-].

The acknowledgement of sediments deposited inside the sanitation pipes is necessary during the determination of old canals capacity. The sediments settled inside the sanitation conduits influence the hydraulic resistance of flow by three different manners: decreasing the inner cross-section area, changing the roughness coefficient of pipe walls and decrease the flow energy caused by the work load during elution of deposited sediments.

The changes of roughness coefficient value, influencing the flow resistance, are difficult to predict because the sediments bed surface usually forms spatially different shapes, dependent to dimensionless Froud number. For Fr < 0.2 the most probable is the smooth shape of sediments surface, for Fr = 0.2–0.35 the noticeable ripples and Fr = 0.35–0.6 dunes were observed. Thereafter, the sediments surface re-smoothing occurs for Fr = 0.6–1.0, and anti-dunes appear for Fr > 1.0 [9].

Summary and conclusions

The presented information concerning transport and quality of sediments along with pipes inclination in sanitation systems are the key factors during designing and modeling of the sewage systems in the variable environmental conditions.

The most frequently occurring type of sediments during our research in Chelm, Poland was the B group. The biofilm developed beneath the water level was classified as the D group. The biofilm development was not observed above the sewage surface. The G group sediments were observed in gravitational sanitation pipes in Chelm, at location of pressure sanitation attachment.

Our paper presents different models of solids transport in sanitation pipes, based on various approach to the problem and of variable complexity. The number of required input data resulting in intricacy and research or design costs increases for the more complex approaches. The simplest attitude to sediments transports is based on the self-purification velocity of constant value. The most advanced of the presented variants of sediments transports modeling concerns the convection velocity dependant to hydraulic conditions of flow and parameters of the dispersed phase.

The proper model of solid substances transport at gravitational sanitation should be chosen according to the type and properties of sediments.

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WYBRANE MODELE TRANSPORTU OSADÓW W SYSTEMACH KANALIZACJI GRAWITACYJNEJ

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Abstrakt: Osady w kanalizacji grawitacyjnej występują w przypadku, gdy prędkość przepływu ścieków spada poniżej prędkości hydraulicznego samooczyszczania przewodów. Osady mają duży wpływ na procesy przebiegające w systemie kanalizacyjnym, powodując m.in. znaczne okresowe wahania ładunku w dopływie do oczyszczalni. Gromadzące się na dnie przewodów osady powodują również zmianę kształtu i pola powierzchni przekroju czynnego przewodu, a tym samym wpływają na zmianę parametrów fizycznych i hydrodynamicznych całego systemu. Osady wpływają też w dużej mierze na rozwój korozji siarczanowej kanałów oraz na intensywność procesów biodegradacji ścieków w przewodach kanalizacyjnych. Badania dotyczące osadów ściekowych oraz związanych z nimi procesów są dość kosztowne, więc prowadzi się je na szerszą skalę jedynie w tych krajach, gdzie regulacje prawne wymagają matematycznego modelowania transportu masy zanieczyszczeń do oczyszczalni ścieków oraz przelewów burzowych. Wyniki takich badań dostarczają danych niezbędnych do kalibracji odpowiednich modeli matematycznych. Ogólna charakterystyka struktury i właściwości osadów powinna być znana na etapie rozważania metody doboru minimalnych spadków dna kanałów grawitacyjnych, ma także duże znaczenie podczas modelowania transportu ładunków zanieczyszczeń w sieci kanalizacyjnej oraz powiązanych z tym zagadnieniem procesów biodegradacji ścieków. Właściwości osadów muszą być uwzględnione przy doborze modelu opisującego ich transport. Przedstawiono klasyfikację osadów na podstawie literatury krajowej i zagranicznej, modele stosowane do opisu transportu osadów w kanalizacji grawitacyjnej oraz zaprezentowano wyniki badań klasyfikacyjnych osadów zlokalizowanych w sieci kanalizacyjnej Chełma.

Słowa kluczowe: kanalizacja grawitacyjna, osady w kanalizacji, klasyfikacja osadów, transport osadów w kanalizacji