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INFLUENCE OF CONDUIT GEOMETRICAL CHARACTERISTICS ON SEWAGE FLOW PARAMETERS

WPŁYW CHARAKTERYSTYK GEOMETRYCZNYCH KANAŁU NA PARAMETRY PRZEPŁYWU ŚCIEKÓW

Abstract: The shape of sanitary conduits consistently defines the cross-section of the wastewater stream, which influences the basic parameters of flow hydrodynamics. The most important of these parameters are wetted perimeter and hydraulic radius, the values commonly used in sanitation systems designing and their work condition modeling. The determination of these parameters is quite simple in case of new conduits in a good technical condition, without the sediments. During the determination of old channels discharge capacity and their work modeling the providing for the sediments deposition is necessary. Deposits covering the bottom of sanitation conduits influence the hydraulic resistance of flow in three different ways: decreasing the cross-section area of the stream, increasing the roughness of the side walls and bottom of the pipe and decreasing the kinetic energy of the stream. The simulation of sanitary network working conditions concerning sediments may have a very important practical meaning. The storm spillways deliveries of the pollutant load included in sediments are, in some cases equal to yearly mean value of pollution contained in treated wastewater delivered to the rivers were observed. Additionally, the variable load of sediments causes non-uniform strain of wastewater treatment plants. The conducted in situ research showed that the height of deposited sediments sometimes was higher than the height of an active area of the stream. The analysis of changes in channel characteristics caused by sedimentation process and their influence on sewage flow parameters were presented. The gained results of calculations showed that sediments bed deposited in the 0.4, 0.5, 0.6 and 0.8 m diameter pipe caused maximum decrease of its wetted perimeter equal to 23.6 %, 22.9 %, 22.3 %, 21.6 % and 39.6 %, 38.7 %, 38.3 %, 37.9 % reduction of actual hydraulic radius value, respectively. The further research concerning other diameters and different shapes of sewer conduits should be conducted.

Keywords: gravitational sewer system, parameters of flow hydrodynamics, calibration of sewer system hydraulic model

The geometrical shape of sanitary conduits cross-section and its wall material roughness directly influence the basic hydrodynamics parameters of the sewage flow. The flow rate and flow velocity distribution in the cross-section of the stream are

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directly connected to wetted perimeter and hydraulic radius of the conduit as well as the coefficient of roughness. These parameters are commonly used in sanitation systems designing and their work condition modeling [1, 2]. Despite the fact that the conduits of sanitation systems may be produced with use of different materials and formed in different shapes, the wetted perimeter and hydraulic radius calculations are quite easy for the brand new, freshly assembled pipes. The flow resistance in this case originates only from the pipe wall roughness. During the long-lasting use of sanitation system the process of sediments deposition appears. Sediments are often defined as any type of settleable particulate material which may be found in sewage and is able to form bed deposits in sewers and their appurtenances [2]. The sediments deposited along the sanitation pipe and creating the bed of different forms [3] clearly influence the parameters of sewage flow. When sediment bed appears in the sanitation conduit, the sewage flow may be influenced by the new types of resistance, besides the pipe material itself – resistance from the sediment grains and resistance from the sediment bed recently formed. The other sources of energy loss may also appear during the sanitation exploitation ie aging effect, construction failures of pipes and biological film development on the pipe wall. The sediments thus influence the hydraulic condition of sewage flow in three different ways: decrease of effective cross section of a flowing stream, increment of the roughness of the side walls and bottom (surface of the sediment bed) of the pipe and decrease the kinetic energy of the stream used to separate sediments particles from the bed [3, 4]. The in situ research conducted by us showed that the height of deposited sediments sometimes was higher than the height of active area of the stream. The sediments in gravitational sewer systems affect not only the hydraulic conditions of flow but also the pollutant management in the network. The storm spillways in combined sanitation systems deliver the pollutant load included in sediments equal to yearly mean value of pollution contained in treated wastewater delivered to the receivers. Additionally, the variable load of sediments causes the non-uniform strain of wastewater treatment plants. The surface of sediment bed may form the following types of arrangement: ripples, dunes and plane bed. Both, ripples and dunes are prone to transformations and further depositions thus the plane bed in case of high sediment load remains stable. The shape of sediment bed surface is directly dependent to the value of dimensionless Froude number comparing inertial and gravitational forces in moving fluid.

Recently the computer modeling of sanitation systems becomes a very useful tool in designing and exploitation of sanitation and combined sewer systems as the example of environmental systems [5]. The computer modeling allows variable, optional design of considered layout of sanitation and its short- and long-term efficiency in different conditions. The choice of the most suitable solution in aspect of hydraulic conditions is also possible due to the numerical calculations. The model of existing sewer network makes the analysis of adding new parts of systems and new users possible. In this case the system operational conditions may be considered taking into account the additional wastewater discharge from the newly designed parts of network. But the quality and accuracy of the computer modeling in reflecting the real conditions, despite its proper mathematical description, are directly connected to the introduced input data [6]. When the geometrical parameters and pipe material roughness for the new, unused material are input the results of flow parameters calculation may differ from the real values. The calibration of computer model becomes necessary [1, 3, 7]. The real shape of the sewage stream cross-section, its wetted perimeter and hydraulic radius as well as resultant roughness coefficient describing additionally resistance after sediments deposition and type of sediments have to be reflected.

This paper presents the results of changes in channel characteristics caused by sedimentation process and their influence on sewage flow parameters. The main objects of analysis were stream geometry, its wetted perimeter and hydraulic radius as well as resultant roughness coefficient of the circular sanitary conduit with different sediments deposition.

Basic equations

The basic description of unsteady flow in open channels may be given by a simplified form of Saint Venant's formula [8]:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\beta Q^2}{A}\right)+gA\frac{\partial h}{\partial x}+g\frac{n^2}{R_h^{4/3}}\frac{|Q|Q}{A}=0, \qquad \frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0$$

where: R_h – hydraulic radius [m],
A – stream cross sectional area [m^2],
Q – flow rate [$m^3 \cdot s^{-1}$],
β – dimensionless velocity coefficient [-],
n – roughness coefficient [$s^1 \cdot m^{-1/3}$].

The empirical equation for the friction slope in unsteady flow can be written in the following manner [1]:

$$S_f=\frac{1}{C_{CH}^2}\frac{1}{R_h^{2a}}\frac{Q|Q|}{A^2}$$

where: S_f – friction slope [$m \cdot m^{-1}$],
C_{CH} – empirical resistance coefficient,
a – empirical exponent [-].

The hydraulic radius is described as follow:

$$R_h=\frac{A}{P_w}$$

where: P_w – wetted perimeter [m].

The empirical roughness coefficient may be presented as Darcy-Weisbach equation:

$$C_{CH} = \left(\frac{8g}{\lambda} \right)^{\frac{1}{2}}$$

where: λ – friction factor [-].

The dimensionless friction factor may be calculated after the Prandtl-Colebrook formula:

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{2.51}{\mathrm{Re}\sqrt{\lambda}} + \frac{k/D}{3.71} \right) = -2\log\left(\frac{2.51}{\mathrm{Re}\sqrt{\lambda}} + \frac{1}{3.71} + \frac{k}{4R_h} \right)$$

where: D – pipe diameter [m],
k – wall sand roughness [m],
Re – dimensionless Reynolds number [-].

The α angle [rad] is the central parameter in the flow geometry mathematical description. Its definition was shown at Fig. 1 and it may be calculated as:

$$\alpha = \cos^{-1}[(D/2 - d_{max})/(D/2)]$$

where: d_{max} – maximum water depth [m].

The α angle can be also determined as follows [1]:

$$h/D = 1/2(1 - \cos\alpha)$$

where: h – actual water depth [m].

In the designing practice the flow description is often reduced to the steady flow equation (mass conservation):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0, \quad Q = C_{CH}\, R_h^{1/2}\, s^{1/2}\, A$$

In this description of steady flow the inclination of water surface s is parallel to the friction slope S_f.

The empirical roughness coefficient in this case is represented by Manning equation:

$$U = \frac{1}{n} R_h^{2/3}\, s^{1/2}$$

where: U – mean flow velocity in steady conditions [$m \cdot s^{-1}$].

The presented mathematical description of water flow in open channels clearly shows that despite the flow state, hydraulic parameters such as hydraulic radius, wetted perimeter and material roughness coefficient are the most important factors in the analysis.

Material and methods

The presented study was based on hydraulic parameters like wetted perimeter and hydraulic radius changes caused by sediments deposition in the cross section of a sanitation pipe. The analysis of *n* coefficient changes was also conducted. The calculations were conducted for the 0.4, 0.5, 0.6 and 0.8 m diameter circular pipe with different height of sediments bed. The mentioned diameters were chosen in connection to the parallel field research on gravitational sanitation system in Chelm, Poland.

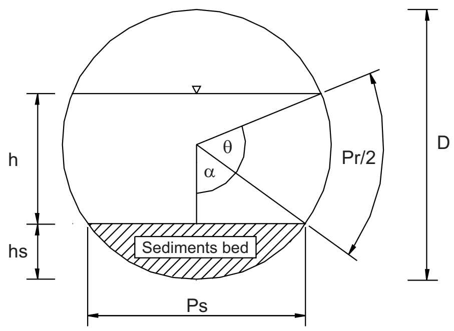

Fig. 1. Studied circular pipe

The resultant roughness coefficient *n* for the studied pipe was calculated as follows [9]:

$$n = \left(\frac{P_r n_r^2 + P_s n_s^2}{P_w} \right)$$

where: P_r – wetted perimeter of pipe wall [m],
n_r – pipe wall material roughness coefficient [$s^1 \cdot m^{-1/3}$],
P_s – wetted perimeter of sediment bed [m],
n_s – sediments bed surface coefficient of roughness [$s^1 \cdot m^{-1/3}$].

The resultant roughness coefficient was calculated for 0.4, 0.5, 0.6 and 0.8 m pipes and variable sediments bed height – h_s from 5 to 40 cm. In the presented calculations n_s was assumed as equal 0.025 $s^1 \cdot m^{-1/3}$, n_r as like for the new PE pipe – 0.0125 $s^1 \cdot m^{-1/3}$ [9–13]. The length of wetted perimeter for pipe material and sediments bed surface was obtained by standard geometrical calculations.

Results

The results of water flow hydraulic parameters calculations are presented at Fig. 2 and Fig. 3. Figure 2 shows the wetted perimeter of 0.4, 0.5, 0.6 and 0.8 m circular pipe as a function of water depth and in dependence to the height of sediments bed. The decrease of wetted perimeter at the same water depth caused by the increase of sediments bed level is clearly visible. For instance, the wetted perimeter for the new

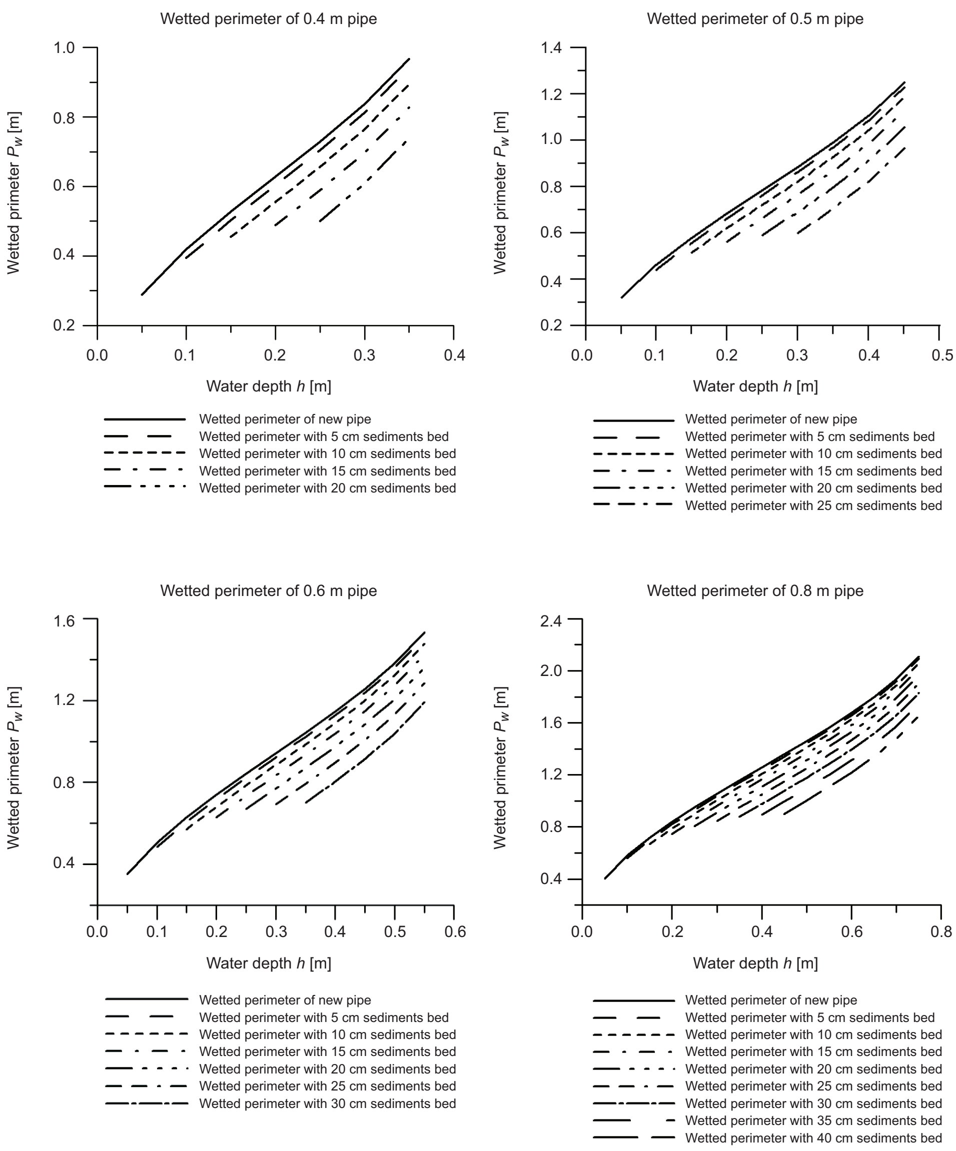

Fig. 2. Wetted perimeter of circular pipe as a function of water depth

pipe 0.5 m, with water depth h = 0.45 m, without sediment deposition was calculated as 1.125 m when the obtained wetted perimeter with sediments bed height equal to 25 cm was 0.9636 m. The difference of nearly 22.8 % has significance in water flow rate calculations. In case of the other studied pipes the wetted perimeter length decrease of 23.6 %, 22.3 % and 21.6 % was noted for 0.4, 0.6 and 0.8 m diameters consequently.

Figure 3 presents the results of hydraulic radius of 0.4 m, 0.5 m, 0.6 m, as well as 0.8 m circular pipes calculations as a function of water depth for different level of sediments deposition. The influence of sediments bed height on actual value of hydraulic radius is visible – the higher sediments bed, the lower value of hydraulic radius. The minimum value of R_h was obtained for sediments bed height h_s = 0.2 m – it was equal to 0.1042 m, when the hydraulic radius for the new pipe, at the same h was

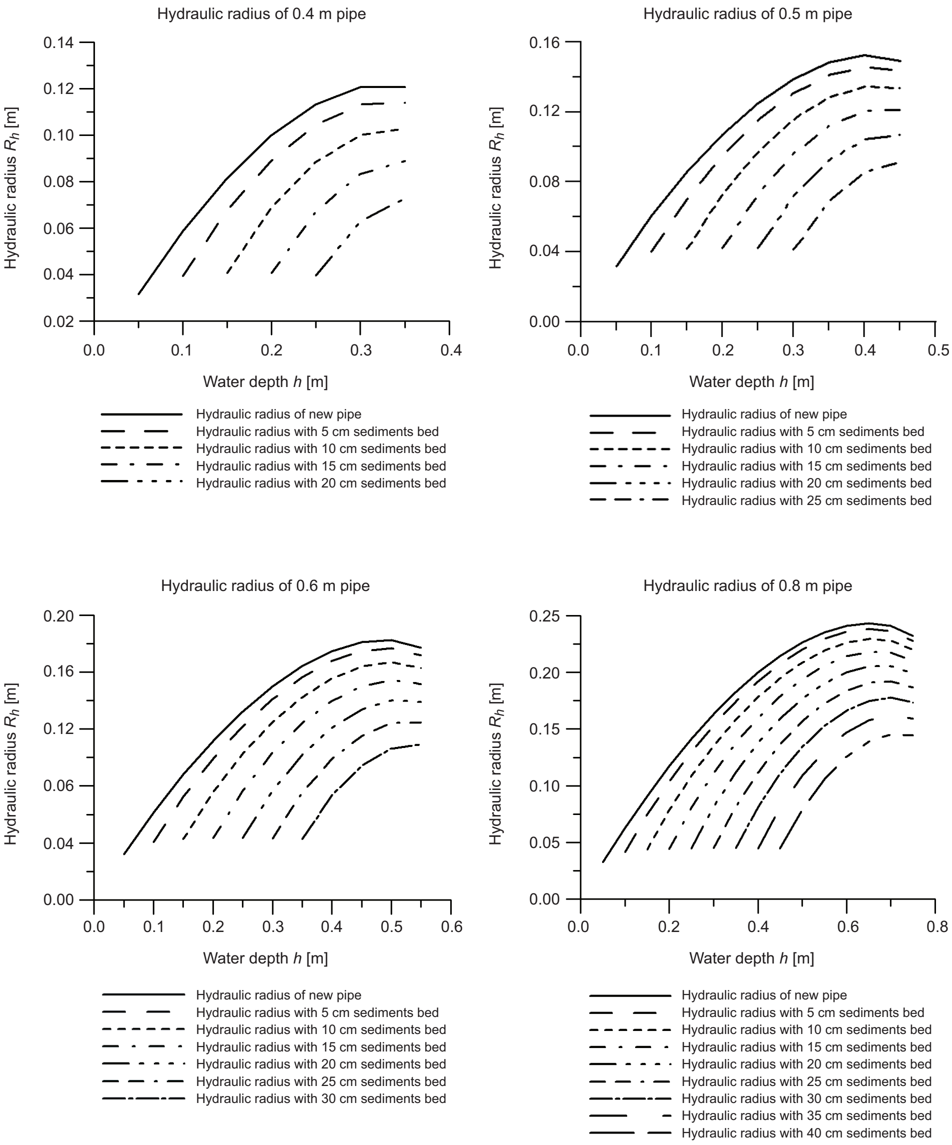

Fig. 3. Hydraulic radius studied pipes as a function of water depth

calculated as 0.1524 m. The maximum observed decrease of hydraulic radius length reached the level of 39.6–37.9 % for all studied cases. This means the notable influence on the flow rate in considered pipes.

The results of resultant roughness coefficient calculations for different water levels and various sediments bed heights are presented in Fig. 4. The obtained results show that deposited sediments clearly cause the additional resistance of water/sewage flow in the studied circular pipes. The higher sediments bed the higher flow resistance,

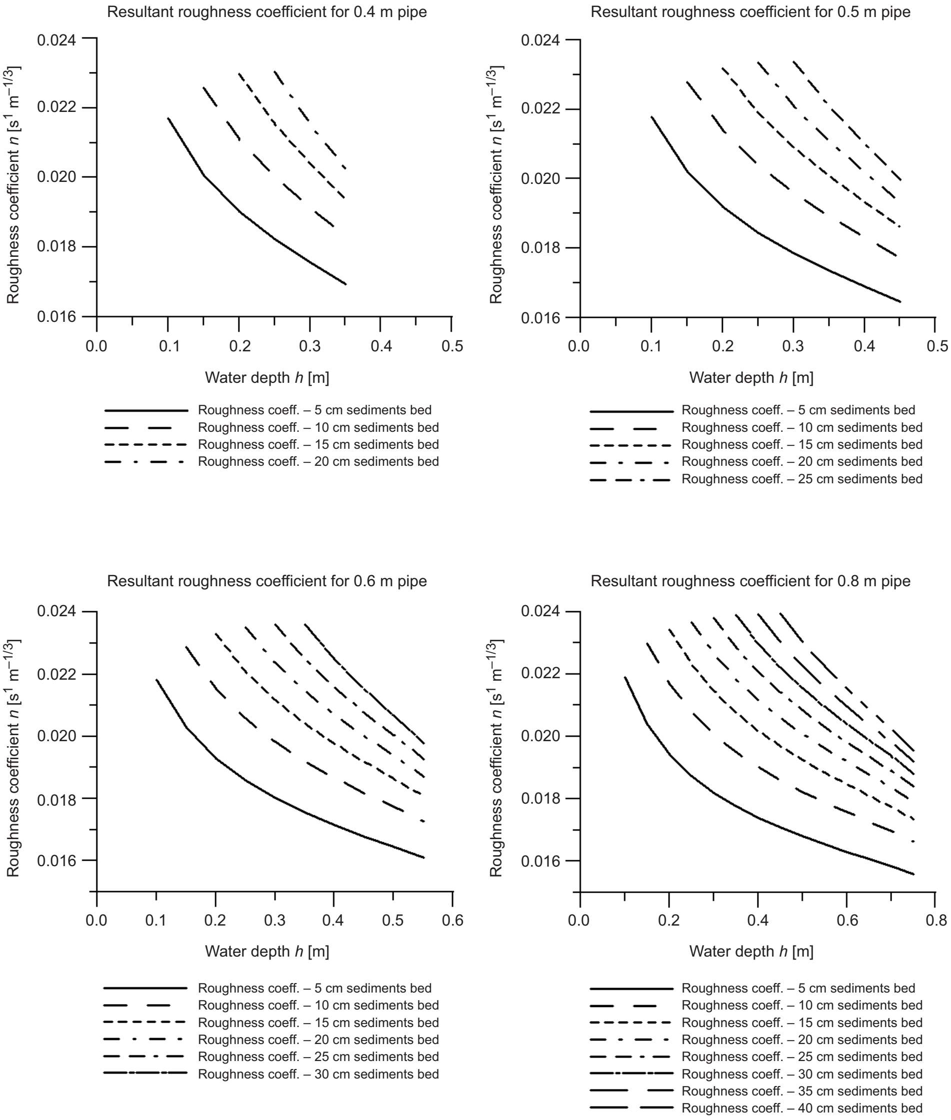

Fig. 4. Resultant roughness coefficient for studied pipes as a function of water depth

especially at low water depth. The maximum calculated resultant roughness coefficient for polymer pipe with sediments bed reached the level of n = 0.0203–0.0239 $s^1 \cdot m^{-1/3}$ for $h_s = 0.5\ D$ and sewage depth h = 5 cm. It means the maximum 62.4–91.2 % increase of n value for the mentioned cases.

The exploitation practice shows that so high sediments deposition is possible only inside wrongly designed sanitation conduits but our calculations show that serious increase of additionally resistance was obtained for all studied sediments bed heights.

The presented research results showed that calibration of numerical model including changes in wetted diameter, hydraulic radius and additionally flow resistance caused by deposited sediments is necessary. Otherwise, the design errors and exploitation problems are possible.

Conclusions

1. Sediments deposited along the sewage pipes clearly influence the hydraulic conditions of flow.
2. Sediments bed deposited in the 0.4, 0.5, 0.6 and 0.8 m diameter pipe caused maximum decrease of its wetted perimeter equal to 23.6 %, 22.9 %, 22.3 %, 21.6 % and 39.6 %, 38.7 %, 38.3 %, 37.9 % reduction of actual hydraulic radius value respectively.
3. The maximum calculated increase of resultant roughness coefficient for polymer pipe with sediments bed reached the level 91.2 % for the studied pipes.
4. The obtained results of calculation showed that calibration of sanitation systems models considering sediments and their influence on hydraulic conditions of fluid movement is necessary.
5. The results of our studies may be directly used in sanitation systems designing, computer modeling and models calibration.
6. The further research concerning other diameters and different shapes of sewer conduits should be conducted.

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WPŁYW CHARAKTERYSTYK GEOMETRYCZNYCH KANAŁU NA PARAMETRY PRZEPŁYWU ŚCIEKÓW

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Abstrakt: Kształt kolektora kanalizacyjnego w sposób jednoznaczny definiuje przekrój poprzeczny strumienia ścieków, który z kolei wpływa na podstawowe parametry związane z hydrodynamiką przepływu. Najważniejsze z tych parametrów to obwód zwilżony i promień hydrauliczny, czyli wielkości standardowo wykorzystywane w pracach projektowych systemu kanalizacyjnego oraz przy symulacjach komputerowych pracy tych systemów. Wyznaczenie tych parametrów jest stosunkowo proste w przypadku wspomnianych nowych kolektorów w dobrym stanie technicznym, bez złogów osadów. Przy określaniu przepustowości starych kanałów oraz modelowaniu ich pracy niezbędne staje się uwzględnianie osadów odkładających się na dnie kanałów oraz narastających na ściankach. Osady zalegające na dnie przewodów kanalizacyjnych mają wpływ na opory hydrauliczne przepływu na trzy różne sposoby, a mianowicie: zmniejszają przekrój wewnętrzny kanału, zmieniają szorstkość ścian i dna oraz podczas rozmywania nagromadzonych złogów zmniejszają energię strumienia przepływających ścieków. Symulacja pracy sieci kanalizacyjnej z uwzględnieniem odkładających się osadów wydaje się mieć duże znaczenie praktyczne, z uwagi na fakt odprowadzania z sieci ogólnospławnych przez przelewy burzowe do wód odbiornika ładunku zanieczyszczeń zawartego w osadach, którego wartość średnia w skali rocznej odpowiada ładunkowi odprowadzanemu z oczyszczalni wraz z oczyszczonymi ściekami. W przypadku sieci rozdzielczej okresowo wymywane osady wpływają także na nierównomierne obciążenie ładunkiem oczyszczalni ścieków. Podczas prowadzonych pomiarów terenowych zaobserwowano, iż wysokość złogów osadów przekraczała niekiedy wysokość czynnego przekroju strumienia ścieków. Zaprezentowano w pracy analizę wpływu zmian charakterystyk kanału wywołanych przez proces sedymentacji osadów na parametry przepływu ścieków. Osady zsedymentowane na dnie przewodów o średnicy 0,4, 0,5, 0,6 oraz 0,8 m powodować mogą zmniejszenie obwodu zwilżonego maksymalnie o 23,6 %; 22,9 %; 22,3 %; 21,6 % oraz promienia hydraulicznego o 39,6 %; 38,7 %; 38,3 % i 37,9 %. Należy przeprowadzić kolejne badania rozwojowe dotyczące innych średnic, kształtów oraz materiałów przewodów kanalizacyjnych.

Słowa kluczowe: kanalizacja grawitacyjna, parametry hydrodynamiczne przewodów kanalizacyjnych, kalibracja modelu hydraulicznego sieci kanalizacyjnej