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MATERIALS, EXPLOATATION MANNERS AND ROUGHNESS COEFFICIENT IN GRAVITATIONAL SANITATION CONDUITS

RODZAJE MATERIAŁU I SPOSOBY EKSPLOATACJI A WSPÓŁCZYNNIKI SZORSTKOŚCI W PRZEWODACH KANALIZACJI GRAWITACYJNEJ

Abstract: The interceptor of urban wastewater should be treated as a collector and transporter of sewage. The roughness coefficient *n* is one of the basic parameters influencing the hydraulic conditions of open channels (gravitational flow). The value of *n* coefficient depends on channel material, carefulness of conjunctions execution and the amount of settled sediments. During the conducted experiments real roughness coefficients of four chosen sanitation conduits in Chelm, Poland were obtained. The choice was made because the different: age of pipes, materials, diameters, inclinations and mean sewage flow velocities. The calculations of *n* coefficient were based on the Manning formula. The gained results proved the hypothesis of real roughness coefficient increase during the long-lasting exploitation of sanitation channels. The analysis of gained results for selected sanitation pipes in Chelm showed the maximal 43.1 % gain of *n* coefficient compared with values presented in projecting guidelines. The presented research may be useful during creation and calibration of Chelm sanitation network numerical model. Application of real values of roughness coefficient during model calibration allows to obtain results of calculations more precisely describing the simulated phenomenon.

Keywords: roughness coefficient, Manning formula, calibration of sewer system hydraulic model

During the analysis of sanitation system operation one may note many factors and parameters causing perturbations and deteriorating wastewater and sediments transport. One of the most important factors influencing hydraulic conditions of sewage flow is roughness coefficient *n* [1]. However, the geometric characteristics of the conduit, usually presented in technical documentation, as well as the real value of sewage flow velocity and height of deposited sediments are necessary to obtain the *n* factor. The knowledge of factors describing the pipe inner side roughness and coarseness is very

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important because of several reasons. The pipes' inner side roughness is a very important hydraulical factor predicativing their capacity and exploitation parameters.

In case of pipes positioned with low inclinations, their roughness is usually causing the increased sediments deposition. In order to prevent this effect, the sewage flow velocity should amount to 0.8 m s^{-1}. This value ensures the self-purification of pipes, so the designing of conduits according to prescribed minimal inclinations, obtained from the contrary of pipe diameter is often used [2, 3]. The criteria of pipes material choice should be analyzed separately for the each studied case, taking into account, besides the economical reasons, also the local conditions, ground and groundwater parameters, type of sanitation systems and chemical composition of wastewater.

The reliability and security of sanitation system, even designed and constructed according to the best, actual engineering knowledge can not be assured. In this case, the ultimate requisites to obtain this purpose are the proper exploitation of the sewage system by the wastewater delivers and the proper maintenance conducted by the exploitation companies.

The avoidance or limitation of sanitation systems failures and their consequences is possible due to the elimination of their formation reasons. Therefore, the regular diagnostics of sanitation system condition and planned pipes regeneration, precluding the occurrence of particularly hazardous threats is necessary. The planning of exploitation activities in operated conduits may be considerably facilitated by the calibration of hydraulic computer network models based on the real values of roughness coefficients.

The aim of this paper is to determine the real values of roughness coefficients n describing sanitation pipes after the long lasting time of exploitation. Four channels of different exploitation time were considered. Our studies were based on the following measurements: sewage flow velocity in steady conditions, height of deposited sediments bed, sewage level and geometrical parameters of the studied pipes.

Materials and methods

This research was based on measurement of sewage flow velocity in the chosen sanitation Pipes in Chelm, Poland along with the geometrical characteristic of pipes, active wastewater stream height and amount of deposited sediments [4, 5]. The sanitation system in Chelm is consisting of circular pipes of diameters from 200 mm to 1400 mm. The 200 mm PVC and ceramics pipes prevail in the studied network. The sewages are transported mainly gravitationally. Table 1 presents the materials used in sanitation system of Chelm city as well as their total length. The percentage share of particular material length in the length of the whole network is also presented at Table 1 [4].

Pipes of diameters up to 250 mm have the highest share among ceramics conduits – 57 %, pipes of diameters 250–600 mm represent 43 %. The ceramics pipes of diameter higher than 600 mm are not present in the sanitation system of Chelm city. Among the PVC sanitation conduits the dominant part are pipes of diameter up to 250 mm (75 %). The group of concrete pipes covers nearly all available diameters, whereof diameters up to 250 mm are 9 % of the whole length of concrete pipes and diameters from 250 to 600 mm represent the share of 29 %. The most frequently noted concrete pipes have the diameter larger than 600 mm – 62 % share.

Table 1

Conduits of different materials in studied sewer system – Chelm, Poland (situation in 2006)

Material	Length [m]	[%]
Ceramics	70 000	40
Concrete	52 500	30
PVC	42 000	24
Cast iron	7 000	4
Cement	3 500	2
Σ	175 000	100

The measurements of *n* roughness coefficient real values for the four selected sanitation pipes were conducted. The real value of *n* coefficient represents the actual flow conditions in the pipe – considering the wetted perimeter of pipe material and sediment bed. The choice of selected pipes was influenced by the time of their exploitation, material, diameters as well as pipes inclination. Thus, the following pipes were selected to studies: 800 mm at Pilarski St., constructed in 1970s, 600 mm at 3rd May St., constructed in 1980s, and 400 mm at Karlowicz St., exploited since 2007 [4].

The conducted linear measurements covered the height of sewage flow level and the height of deposited sediments bed. The sewage temperature was also measured. The Pitot-Darcy probe was used to obtain the wastewater velocity flow. The flow velocity was calculated according to equation (1) [6].

$$v = 4.47\sqrt{h} \tag{1}$$

where: v – sewage flow velocity [m s^{-1}],
4.47 – correcting coefficient [-],
h – height difference in Pitot-Darcy probe [m].

In order to confirm the obtained results, the sewage velocity flow was additionally measured by the floating object method. The flow direction and pipe longitudinal axis were parallel in sanitation conduit in which the floating object method was used.

The segmental wastewater flow velocity was calculated by follows [6]:

$$v = \frac{L}{t} \tag{2}$$

where: L – length of floating object movement [m],
t – floating object movement time [s].

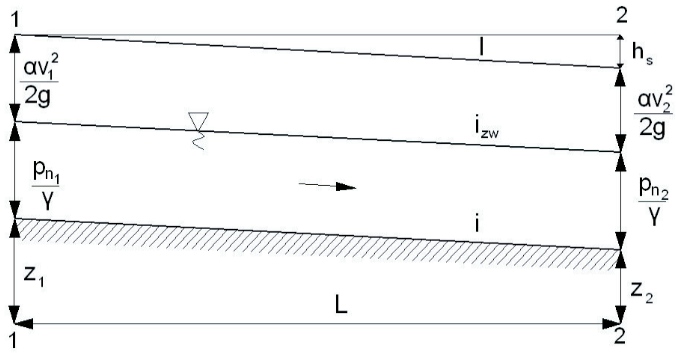

Fig. 1. Graphical scheme to Bernoulli equation (4) [7]

The constant flow is a steady flow, therefore kinetic energy and liquid flow velocity are constant. All this mean that the channel bottom inclination *i* is equal to the inclination of the piesometric pressure line i_{zw} and the inclination of the energy line – hydraulic inclination *I* [7].

$$i = i_{zw} = I \tag{3}$$

Bernoulli equation for 1-1 and 2-2 cross sections presented at Figure 1 may be written as follows:

$$z_1 + \frac{p_1}{\gamma} + \frac{\alpha v_1^2}{2g} = z_2 + \frac{p_2}{\gamma} + \frac{\alpha v_2^2}{2g} + \lambda \frac{L}{4R_h} \frac{v^2}{2g} \tag{4}$$

where: R_h – hydraulic radius [m],
z – elevation [m],
p – pressure at the point [N m^{-2}],
α – Coriolis coefficient [-],
γ – specific weight [N m^{-3}],
λ – the dimensionless coefficient of Darcy friction factor [-] [8].

Taking above into account, we may use the following formula describing the sewage flow velocity:

$$v = \sqrt{\frac{8g}{\lambda}} \sqrt{R_h I} \tag{5}$$

The first part of equation (5) may be described as *C*, known as Chezy factor [7, 9, 10]:

$$C = \sqrt{\frac{8g}{\lambda}} \tag{6}$$

The relative coarseness value depends on the value of the absolute coarseness k connected to the mean height, shape and distribution of inner pipe surface inequality [7].

The formula describing the mean value of flow velocity may be written as follows:

$$v = C\sqrt{R_h I} \tag{7}$$

Beside the presented formula (6), many other empirical formulas may be used to obtain the C factor. The comparison of Chezy formula and the formula of steady flow velocity in open channels presented by Manning is frequently used:

$$v = \frac{1}{n} R_h^{2/3} I^{1/2} \tag{8}$$

Thus, the description of C factor in dependence of roughness coefficient n [s m$^{-1/3}$] and hydraulic radius R_h is possible [8]:

$$C = \frac{1}{n} R_h^{1/6} \tag{9}$$

In order to calculate the roughness coefficient, Manning formula (8) may be transformed to:

$$n = \frac{1}{v} R_h^{2/3} i^{1/2} \tag{10}$$

where: v – mean value of flow velocity measured by the floating object method and Pitot-Darcy probe [m s^{-1}].

The hydraulic radius was calculated with use of the following formula (11):

$$R_h = \frac{A_c}{P_w} \tag{11}$$

where: A_c – conduit cross sectional flow area [m^2],
P_w – wetted perimeter [m].

Results

The results of sewage flow velocity measurements by the Pitot-Darcy probe are presented in Table 2. The other data, necessary to floating object method, as pipe inclination and conduit segment length were obtained from the representatives of Chelm city sanitation network exploitation company [4].

Table 2

Measured velocity of sewage flow by Pitot-Darcy probe in chosen sanitation conduit in Chelm, Poland

No.	Sewage level *h* [m]	Flow velocity *v* [m s^{-1}]	Mean flow velocity v_m [m s^{-1}]
Pilarski St., ∅ 800; *i* = 2.0 ‰, concrete			
1	0.0140	0.529	0.532
2	0.0145	0.538	
3	0.0140	0.529	
3rd May St., ∅ 600; *i* = 2.5 ‰, concrete			
1	0.0050	0.316	0.311
2	0.0045	0.300	
3	0.0050	0.316	
3rd May St., ∅ 600; *i* = 2.5 ‰, concrete			
1	0.0060	0.346	0.341
2	0.0055	0.332	
3	0.0060	0.346	
Karlowicz St., ∅ 400; *i* = 5.0 ‰, PVC			
1	0.0025	0.224	0.238
2	0.0030	0.245	
3	0.0030	0.245	

The results of wastewater flow velocity obtained by the floating object method are presented in Table 3.

Table 3

Measured velocity of sewage flow by floating object method in chosen sanitation conduit in Chelm, Poland

No.	Flow duration			Pipe length [m]	Sewage level [m]	Sediments height [m]	Sewage temperature [°C]	Velocity [m s^{-1}]	Mean velocity [m s^{-1}]
	min	sec	cs						
Pilarski St., ∅ 800; *i* = 2.0 ‰, concrete									
1	0	26	15	15.1	0.26	0.08	16	0.575	0.528
2	0	29	1					0.520	
3	0	30	3					0.502	
4	0	28	43					0.526	
5	0	29	12					0.517	
3rd May St., ∅ 600; *i* = 2.5 ‰, concrete									
1	7	12	30	142.22	0.19	0.09	16	0.329	0.317
2	7	32	20					0.314	
3	7	20	3					0.323	
4	7	24	50					0.320	
5	7	52	41					0.301	

Table 3 contd.

No.	Flow duration			Pipe length [m]	Sewage level [m]	Sediments height [m]	Sewage temperature [°C]	Velocity [m s^{-1}]	Mean velocity [m s^{-1}]
	min	sec	cs						
3rd May St., ∅ 600; *i* = 2.5 ‰, concrete									
1	3	41	15	75	0.195	0.09	16	0.339	0.336
2	3	50	3					0.326	
3	3	38	42					0.343	
4	3	33	17					0.352	
5	3	55	5					0.319	
Karlowicz St., ∅ 400; *i* = 5.0 ‰, PVC									
1	3	28	4	46.22	0.04	0.015	16.5	0.222	0.226
2	3	18	15					0.233	
3	3	25	3					0.225	
4	3	21	40					0.229	
5	3	30	7					0.220	

The measurements which results are presented in Table 2 and 3 were conducted for every studied pipe at the same time – abut 10 and 12 a.m., when the sewage level in pipes was relatively constant. In this case, the assumption of constant sewage flow is close to reality – the sewage stream of constant flow rate Q, constant crosssection area A_c, fixed height of sewage level h on the whole length of conduit are required to obtain the parallel position of water table and pipe bottom.

The obtained during research real coefficient of roughness for studied sanitation pipes placed in Chelm city is presented in Table 4:

Table 4

Measurements results for selected sanitation pipes in Chelm, Poland

Street	Material	Diameter ∅ [m]	Inclination *i* [‰]	Hydraulic radius R_h [m]	Mean velocity *v* [m s^{-1}]	Roughness coefficient *n* [s m$^{-1/3}$]
Pilarski	Concrete	0.800	2.0	0.064	0.530	0.0141
3rd May	Concrete	0.600	2.5	0.040	0.314	0.0186
3rd May	Concrete	0.600	2.5	0.036	0.339	0.0160
Karlowicz	PVC	0.400	5.0	0.010	0.232	0.0142

Discussion

Figure 2 presents the results of flow velocity measurements by floating object method as well as by the Pitot-Darcy probe. The comparison of obtained velocity values to the self-purification velocity was also presented.

The results of conducted research showed that the self-purification velocity of flow was not secured in the examined conduits. In the studied case the process of sediments

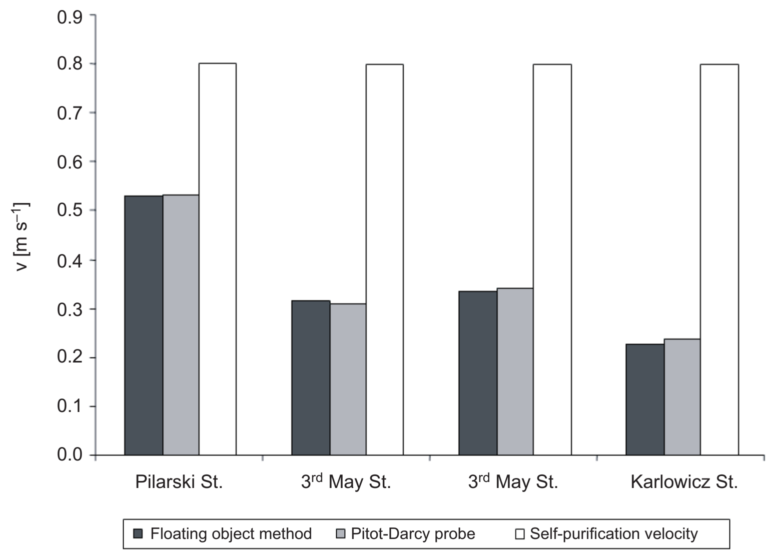

Fig. 2. Graphical illustration of sewage velocity measurements results compared to self-purification velocity

deposition will occur, resulting in creation of sediments bed, decrease of active area of flow, increase of flow resistances and reduction of channel hydraulic capacity. The field research covering flow velocity and sediments bed height showed that in case of insufficient flow velocity, sediments deposition was noted in all studied pipes. The thickness of sediments beds starting from 1.5 cm in channel used since 2007 to 8–9 cm in pipes used for 20–30 years were observed. This status certainly adversely influence the hydraulic conditions of studied parts of the sanitation system by, for instance, increase of the real roughness coefficient of the conduit.

The other conduit parameters such as inclination and diameter are chosen to secure the self-purification velocity of wastewater flow.

The value of n equal to 0.013 s $m^{-1/3}$ is usually used for concrete pipes in hydraulical calculations during the sanitation designing. Table 5 present the record of the most frequently cited values of n for several materials.

Our research proved the hypothesis of roughness coefficient increase during the long term exploitation of sanitation system. In some cases even the 43.1 % gain of n coefficient compared with values presented in designing guidelines was noted.

The increase of roughness coefficient n results from the decrease of flow velocity calculated after Manning formula (8). Thus, the noted value of flow velocity is lower that assumed during designing calculations. If its value is lower than the velocity of pipe self-purification the process of sediments deposition will occur. The velocity of flow is dependent to pipe roughness but reduction of velocity causes the increase of real surface roughness through the decline of deposited sediments. Hence, the real roughness coefficient n studied in this paper becomes one of the major factors influencing the hydraulic conditions of flow in the gravitational sanitation systems.

Table 5

Coefficient *n* by Manning, *M* coefficient by Manning-Strickler [11–13]

No	Type of surface, material	$n = 1/M$ [s m$^{-1/3}$]	M [m$^{1/3}$ s^{-1}]
1	Smooth glaze surfaces	0.009	111
2	Planed wood	0.010	100
3	Smooth concrete	0.0118	85
4	Normal concrete	0.0133	75
5	Rough concrete	0.0147	68
6	Plastic	0.0125	80
7	Smooth stone	0.0125	80
8	Ceramics	0.0143	70
9	Iron	0.0143	70
10	Bricks	0.0167	60
11	Broken stone wall, channel in bad condition	0.020	50
12	Channel in extremely bad condition, silted	0.030	33

The choice of the most suitable solution in aspect of hydraulic conditions is also possible due to numerical calculations. The computer modeling allows variable, optional design of considered layout of sanitation and its short- and long-term efficiency in different conditions. 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 [13, 14]. 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. The real shape of the sewage stream cross-section, its wetted perimeter and hydraulic radius as well as resultant roughness coefficient *n* describing additionally resistance after sediments deposition and type of sediments have to be reflected.

Summary and conclusions

The roughness coefficient value depends on pipe material as well as type and quality of pipe segments bonds and sediments deposited along the conduit.

Considering the roughness of sanitation pipe walls we have to distinguish the initial and final roughness – after the specified time of exploitation.

At the analysis of measurement results and comparison to the values used in the designing practice we may state that the values of the actual real roughness coefficient *n* obtained during measurements are higher than values used in the process of sanitation system designing. The roughness coefficient value 0.014–0.018 s m$^{-1/3}$ for the concrete pipes were observed, as 0.013 s m$^{-1/3}$ is the basic value in designing.

The increase of *n* coefficient is connected to the low values of sewage flow, which does not provide the correct flushing of the sanitation pipes. In result, the sediments deposition occurs and the deposited sediments are adversely influencing hydraulical conditions of flow.

The on-line measurements are recommended in order to obtain more precise data concerning sewage flow and roughness coefficient in sanitation system in Chelm, Poland.

The presented research may be useful during creation and calibration of Chelm sanitation network numerical model. Application of real values of real roughness coefficient during model calibration allows to obtain results of calculations more precisely describing the simulated phenomenon.

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RODZAJE MATERIAŁU I SPOSOBY EKSPLOATACJI A WSPÓŁCZYNNIKI SZORSTKOŚCI W PRZEWODACH KANALIZACJI GRAWITACYJNEJ

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Abstrakt: Współczynnik szorstkości *n* jest jednym z podstawowych parametrów wpływających na warunki hydrauliczne przepływów ze swobodnym zwierciadłem. Wartość współczynnika szorstkości zależy od materiału, z którego zbudowany jest kanał, od rodzaju, staranności wykonania połączeń oraz od zgromadzonych na dnie i obrastających ściany kanału osadów. Przeprowadzono badania współczynnika szorstkości *n* dla 4 wybranych przewodów kanalizacji sanitarnej w Chełmie. Wyboru dokonano ze względu na różny czas ich eksploatacji, rodzaj materiału, średnice i spadki kanału oraz prędkości przepływu ścieków. Obliczenia współczynnika szorstkości *n* przeprowadzono, wykorzystując przekształcony wzór Manninga. Uzyskane wyniki potwierdziły hipotezę, zakładającą wzrost wartości współczynnika *n* w czasie eksploatacji sieci. Analizując otrzymane wyniki i porównując je z założeniami projektowymi, stwierdzono, iż wyznaczony współczynnik szorstkości dla wybranych przewodów sieci kanalizacyjnej w Chełmie jest większy nawet o 43,1 % od wartości podanych w wytycznych do projektowania. Przeprowadzone badania mogą być pomocne przy budowie i kalibracji modelu hydraulicznego sieci kanalizacyjnej miasta Chełm. Zastosowanie rzeczywistych wartości współczynnika szorstkości w procesie kalibracji modelu numerycznego umożliwi uzyskanie wyników obliczeń symulacyjnych w lepszym stopniu odzwierciedlających procesy zachodzące w opisywanych obiektach.

Słowa kluczowe: współczynnik szorstkości, wzór Manninga, kalibracja modelu hydraulicznego sieci kanalizacyjnej