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EXFILTRATION FROM SANITATION PIPES AND TRANSPORT OF CHOSEN POLLUTANTS – A MODEL STUDY

PROCES EKSFILTRACJI Z PRZEWODÓW KANALIZACYJNYCH A ROZPRZESTRZENIANIE SIĘ WYBRANYCH ZANIECZYSZCZEŃ – BADANIA MODELOWE

Abstract: Sanitation systems exploitation may result in the possibility of sewage exfiltration. The exfiltering sewage, very often containing the high concentration of organic and inorganic pollutants may cause the clear danger for the groundwater and soil environment. The qualitative and quantitative monitoring of wastewater leaving the damaged sewage pipe is quite difficult and often, in practice – impossible. Recently, the numerical modeling of pollutants transport in groundwater and soil has gained the increased popularity. This paper presents the results of numerical calculations of chosen pollutants (cadmium and chromium) exfiltering from the damaged gravitational sewer system pipe located in the profile of Nadstawna St., Lublin, Poland. The numerical calculations were conducted by FEFLOW 5.2, WASY, Germany software. Soils' transport parameters as well as initial and boundary conditions were obtained by results of laboratory, field and literature studies. The results of our researches enables the analysis of sanitation pipe failure effect on soil environment and groundwater. However, the empirical verification of the modeling results in order to verify the validity of initial and boundary conditions is required.

Keywords: exfiltration, pollutants transport, numerical modeling

Heavy metals naturally appearing in the environment do not cause hazard for plants and animals. However, some of anthropogenic activities, particularly the metallurgical, textile, tanner and chemical industry burden the sewer system with enlarged concentration of the chromium and cadmium in the transported sewage [1].

The chromium appears commonly in two oxidation states as Cr(III) and Cr(VI). The chromium(III) occurs naturally in the environment and is indispensable for living beings. The trivalent chromium is relatively insoluble. Whereas Cr(VI) is comparatively soluble, so can be easily transported to groundwater and soil environment. Up to 90 %

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chromium pollutants are Cr(VI) [2]. Because of its strong mutagenic and carcinogenic attributes it is an essential threat for the natural environment. It causes, among others, many illnesses such as: damage of the liver and kidney, problems with the respiratory system and the ulceration of the skin.

Cadmium appears naturally in the environment as the effect of the erosion of rocks and soils as well as eruptions of volcanoes and fires of forests. Cadmium in sewage is equally dangerous as chromium. It has a carcinogenic and teratogenic activity and accumulates in the human organism mainly in kidney. Cadmium in sewage is connected directly to the intensive anthropogenic activity, mainly in metallurgical and chemical industry. Transport, concentration and the toxicity of Cr(VI) and cadmium in the environment depends on many physical, chemical and biological processes occurring in groundwater and soil [3, 4].

In order to define the range of the influence of chromium and cadmium pollutants outflowing the damaged gravitational sewer system numerical models are built. They allow the comprehensive simulation for different computational variants. The aim of this paper was to present the spread of chosen pollutants (cadmium, chromium) leaving the damaged sewage pipe located in the profile of Nadstawna St., Lublin, Poland.

Materials and method

To our numerical calculations the program FEFLOW 5.2, WASY GmbH Germany was chosen [5–7] and MPWiK Sp. z. o.o. Lublin delivered such information and data sources as:

1. The map with marked points of the conscription of samples of the ground (with wells) to laboratory-research in the scale 1:500.
2. The numeric map of sewage system and water-supply system in the scale 1:500, dated on 2007-10-17.
3. The results of inspection of sewage pipes in Nadstawna St., Lublin, Poland (The report from inspection No. /607/T/06 dated on 2006-11-15).
4. Materials from surveys of the construction of the existing road surface and the ground basis. The reconstruction of the water supply and sanitary sewage system with parachannels in Targowa St., Nadstawna St., Nowy Plac Targowy St. in Lublin, made by the Road-Laboratory "LABDROG" Grygowej 23 St., Lublin in 2004-09-03 and 2005-04-06.
5. Composition of raw sewage obtained on 2007.

On the basis of materials made accessible by MPWiK Sp. z o.o. Lublin (1–3) as the source of the pollutants (chromium and cadmium) to research the ceramics pipe of the sanitary gravitation sewage system was chosen. It had the 250 mm diameter and was located in Nadstawna Street in Lublin. These (4) materials allowed also to accept to research the soil profile which is presented in Fig. 1.

Research of the soil profile in Nadstawna St., Lublin conducted by the Road-Laboratory "LABDROG" allowed to specify eight layers in the accepted profile. The composition of individual layers was presented in the Table 1. Simultaneous research showed that groundwater did not appear to the depth 5.20 m under the level of road. In

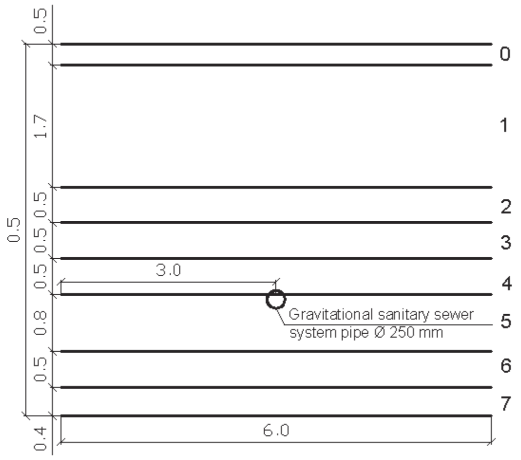

Fig. 1. Scheme of modeled profile accepted to studies

the model the fact, that the profile was covered by impermeable tight asphalt-surface was also taken into account. The profile of 6.0 m width, with sewage pipe was situated centrally on the depth 3.7 m (the level of pipe's bottom) was accepted to research. For individual distinguished layers in the profile the net of triangular finite elements was developed.

Table 1

Composition of individual layers of the profile

No. layer	Type and colour of the soil
0	mass mineral – asphalt, the rag, the layer draining off base coal
1	not building embankment – clayey sand impure stones and grey-beige bricks
2	not building embankment – clay, grey bricks
3	not building embankment – humic clay with admixtures of stones
4	not building embankment – dusty humic clay and grey bricks
5	not building embankment – dusty humic clay, dust, grey bricks
6	not building embankment – dusty humic clay, dust, grey bricks
7	dusty humic clay, dust, grey bricks

The physical-water parameters for individual layers of the profile were accepted on the basis of literature studies [8–10] and put together in the Table 2.

As basic pollutants leaving the damaged sewage pipe chromium and cadmium was chosen. The concentration of these elements in raw sewage was accepted on the basis of research carried out in 2007 by the Central Laboratory of MPWiK Lublin (5). For chromium the 0.1 mg $\cdot$ dm^{-3} concentration was accepted, whereas for cadmium 0.337 mg $\cdot$ dm^{-3}. It was also suitable to establish the boundary conditions. Parameters of adsorption and dispersion, presented in the Table 3, were accepted basing on numerous literature studies [11–15]. Physical-water parameters of the ground and parameters of the adsorption and the dispersion were assigned to the partuicular layers of the profile.

Table 2

Physical parameters of soils in individual layers of the studied profile

No. layer	Parameters of water retention curve		Saturated hydraulic conductivity K_{sat} [m · s^{-1}]	Porosity ε [-]	Maximum saturation S_s [-]	Residual saturation S_r [-]
	A [cm^{-1}]	n [-]				
0	4.100	1.100	$1.00 \cdot 10^{-9}$	0.100	1.0	0.000
1	0.075	1.890	$1.23 \cdot 10^{-5}$	0.410	1.0	0.159
2	0.036	1.560	$2.89 \cdot 10^{-6}$	0.430	1.0	0.181
3	0.0065	1.325	$1.78 \cdot 10^{-7}$	0.430	1.0	0.000
4–7	0.019	1.310	$7.17 \cdot 10^{-7}$	0.410	1.0	0.232

To numerical calculations was necessary to accept initial and boundary conditions. For the water flow the initial condition of the profile's saturation 70 % was accepted. Whereas the initial concentration of pollutants in the ground 0.0 mg · dm^{-3} was assumed. Boundary conditions were founded on the surface of the street in the top of the profile which assured the tightness of the street pavement. This caused that flow of water and pollutants to the studied profile does not exist. For the water flow in nodes of the finite elements net the second kind condition 0.0 m · d^{-1} as well as a value of 0.0 m · d^{-1} for species mass transport inflow were set. In the bottom of the profile the gradient boundary condition was accepted, enabling free outflow of water and pollutants inside the profile.

Table 3

Parameters of adsorption and dispersion for the individual layers of the profile

	No. layer	Coefficient				
		Henry's coefficient	molecular diffusion [$m^2 \cdot s^{-1}$]	longinear dispersion [m]	transverse dispersion [m]	first-order reaction decay constant [s^{-1}]
Cadium	1	79.57	$1.0 \cdot 10^{-9}$	4.00	0.5	$1.727 \cdot 10^{-8}$
	2	29.70	$1.0 \cdot 10^{-9}$	36.00	0.5	$1.727 \cdot 10^{-8}$
	3	27.94	$1.0 \cdot 10^{-9}$	2.50	0.5	$1.727 \cdot 10^{-8}$
	4–7	28.16	$1.0 \cdot 10^{-9}$	1.50	0.5	$1.727 \cdot 10^{-8}$
Chromium	1	2.43	$1.0 \cdot 10^{-9}$	4.00	0.5	$2.886 \cdot 10^{-7}$
	2	0.20	$1.0 \cdot 10^{-9}$	36.00	0.5	$2.886 \cdot 10^{-7}$
	3	0.191	$1.0 \cdot 10^{-9}$	2.50	0.5	$2.886 \cdot 10^{-7}$
	4–7	0.192	$1.0 \cdot 10^{-9}$	1.50	0.5	$2.886 \cdot 10^{-7}$

The water transport in the soil profile is described by the Darcy Law (1) [5]:

$$q = -[K \cdot \nabla(\Psi + z)] \cdot n, \ [\mathrm{m} \cdot \mathrm{d}^{-1}] \tag{1}$$

where: K – hydraulic conductivity coefficient, [m · d^{-1}],
∇ – Hamilton's operator, [-],

Ψ – soil water potential [m],
z – height of position [m],
n – normal vector for Hamilton's operator, [-].

In order to conduct the simulation of water and pollutants outflow from the damaged gravitational sewer system pipe in place of its location the boundary conditions were set.

For the water flow the first kind condition of Head = 0.2 m was treated as the pressure of sewage in pipe, whereas for the flow of pollutants the first kind condition was understood as the concentration of the pollutant. The water flow in the ground is described in the program by Darcy's and Richard's equations [16], and the hydraulic conductivity in unsaturated state by modified version of the Van Genuchten's equation [5]:

$$K = K_{sat} \cdot S^{l}\left[1-\left(1-S^{\frac{1}{m}}\right)^{m}\right]^{2}, \ [\mathrm{m} \cdot \mathrm{s}^{-1}] \tag{2}$$

where: K_{sat} – saturated hydraulic conductivity coefficient, $[\mathrm{m} \cdot \mathrm{s}^{-1}]$,
S – effective saturation, [-],
l – exponent related with the logic diagram of pores, [-], $l = 0.5$,
$m = l - A/n$, $A = 1$ according to Mualem [17],
n – coefficient being the measure of the schedule of the pores size, [-].

The saturation in the model is described by the equation [5]:

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \ [-] \tag{3}$$

where: θ – volumetric content of water in the ground $[\mathrm{m}^3 \cdot \mathrm{m}^{-3}]$,
θ_r – residual volumetric water content $[\mathrm{m}^3 \cdot \mathrm{m}^{-3}]$,
θ_s – saturated volumetric water content $[\mathrm{m}^3 \cdot \mathrm{m}^{-3}]$.

In order to read the concentrations of pollutants accepted to research in chosen places of the profile six reference points were established (Fig. 2). Points No. 1, 3 and 5 were

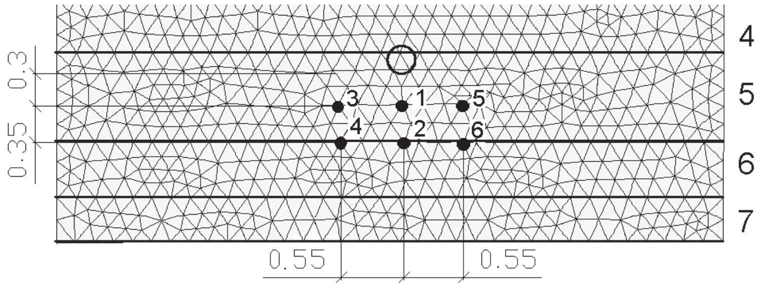

Fig. 2. Scheme of the profile with reference points

situated 0.3 m under the studied pipe and points No. 2, 4 and 6 were situated 0.55 m under this pipe.

The physical-water parameters of the soils, parameters of adsorption and dispersion introduced to the model and accepted initial and boundary conditions made possible the numerical calculations. The reference points enabled reading the pollutants concentrations in dependence on the time of the simulation.

Results

Our calculations were conducted for three different variants: variant I a period of the failure 1 day, variant II a period of the failure 2 days and variant III a period of the failure 3 days. Simulation calculations were conducted for 14 days for each variant. For each variants time-varying boundary conditions for water flow (head of 0.2 m) and for mass transport (cadmium – 0.337 mg · dm^{-3}, chromium – 0.1 mg · dm^{-3}) were set depending on the duration of the failure.

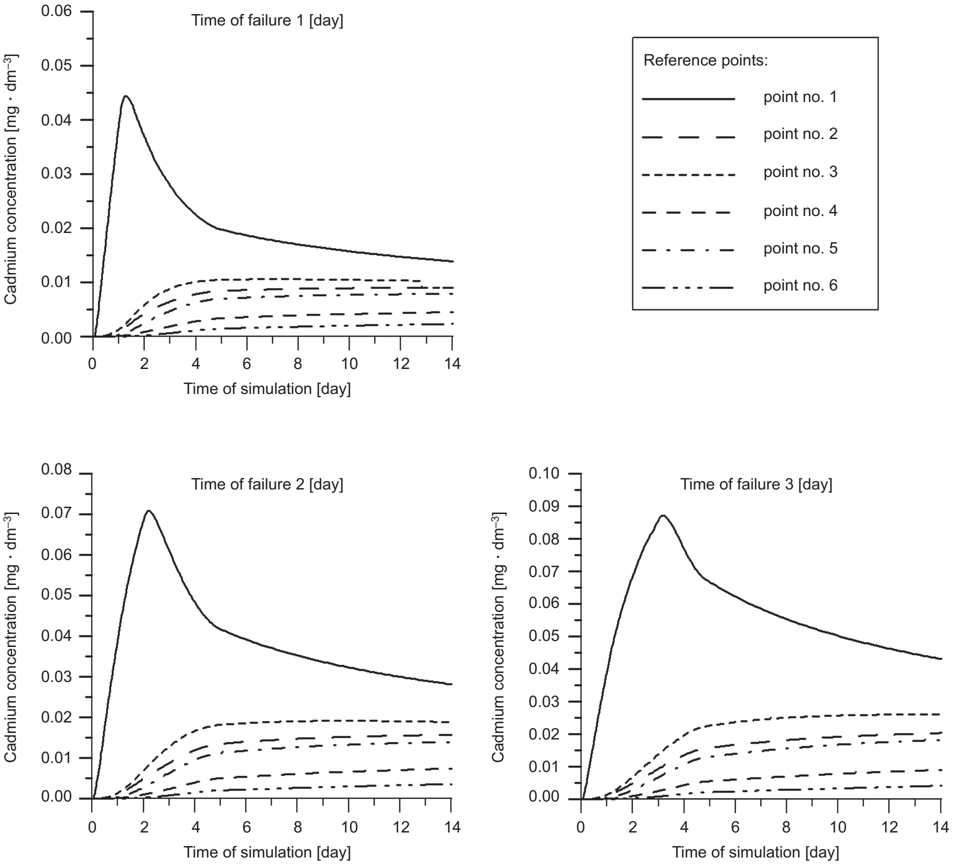

Fig. 3. Changes of the concentrations of cadmium in time

Individual computational variants allowed to reach different concentrations of chosen pollutants in the accepted reference points.

Changes of cadmium concentrations in time for accepted reference points are presented in Fig. 3. For each computational variants in point No. 1 concentration of cadmium rapidly grows, and after overrun the duration of the failure, with slight delay, gradually decreased, which was not observed in the rest of points. In remaining points the cadmium concentration after the achievement of the certain value is not prone to greater changes. Moreover, the longer duration of the failure the highest values of cadmium concentrations were obtained in the reference point No. 1. For the failure lasting 1 day concentration was 0.044 mg · dm^{-3} after the time of 1.28 day from the beginning of the simulation, for the failure lasting 2 days – 0.071 mg · dm^{-3} after the time 2.21 days, and for the failure lasting 3 days – 0.087 mg · dm^{-3} after the time of 3.19 days from the beginning of the simulation. The lowest values of the concentration of cadmium were obtained for reference points No. 6 and for the duration of the failure 1 day it was $3.86 \cdot 10^{-5}$ mg · dm^{-3} after the time of 1.28 day from the beginning of the simulation.

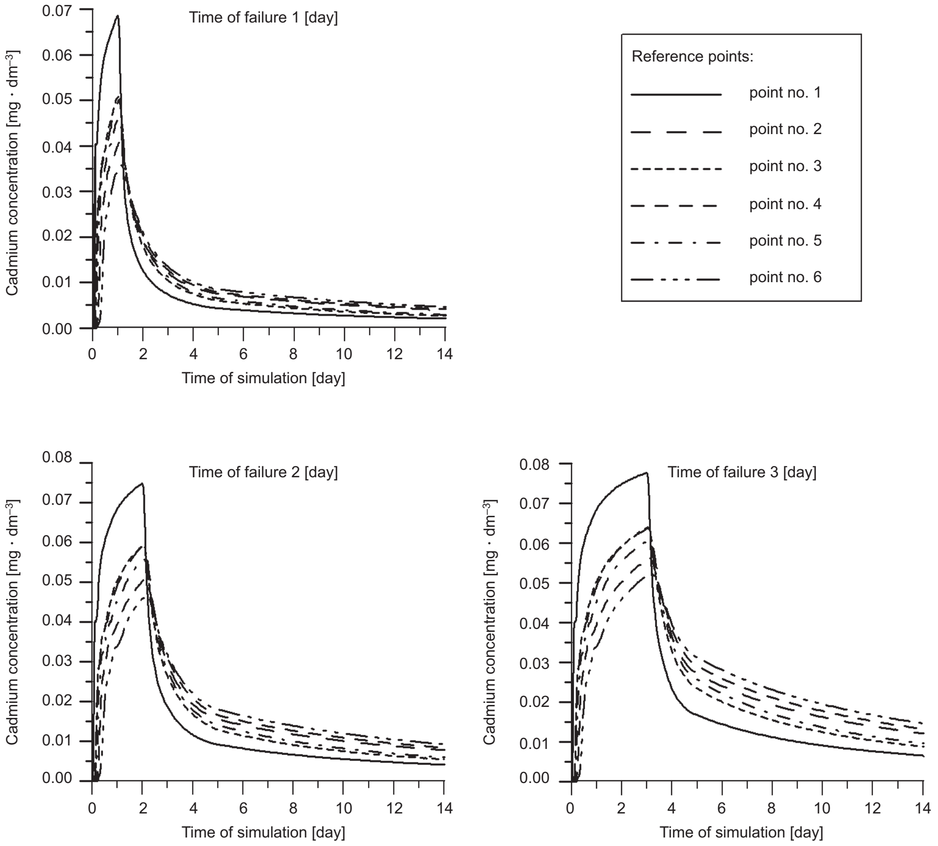

Fig. 4. Changes of the concentrations of the chromium in time

Changes of the chromium concentrations depending on the duration of the failure for the reference points are presented in Fig. 4. In each reference point, the chromium concentration in the beginning of the simulation rapidly grows, and after reaching the duration of the failure, with delay, it clearly decreases. More rapid increase causes equally significant decrease of chromium concentration. The more rapid initial increase of simulated chromium concentration, the higher later decrease of this concentration. The greatest values of concentrations aside from the computational variant were observed in the reference point No. 1 which was situated centrally under the studied pipe. For the failure lasting 1 day the highest chromium concentration was 0.69 mg · dm^{-3}, noted exactly after the time of 1 day from the beginning of the simulation. In variant No. 2 the greatest value of chromium concentration was 0.075 mg · dm^{-3} after the time 2 days, and for the variant 3 – 0.078 mg · dm^{-3} after the time 2.99 days. The least concentrations of the chromium were observed in reference point No. 6 and for the variant No. 1 after the time 1 day from the beginning of the simulation was 0.034 mg · dm^{-3}.

Conclusions

The obtained results of conducted numerical calculations allowed to draw the following conclusions:

1. Numerical calculations enable the analysis of the influence of pollutants (cadmium and chromium) leaving from the damaged gravitational sewer system pipe on the ground – water environment.
2. Numerical calculations showed that together with the growth of the duration of the failure the concentration of pollutants in the reference points increased. The longer duration of the failure, the greater concentration of pollutants in the reference points were observed. For each pollutant the highest value of the concentration was obtained at the failure lasting 3 days, for cadmium it was 0.087 mg · dm^{-3} , and for chromium 0.078 mg · dm^{-3}.
3. Obtained results of numerical calculations showed that chromium concentrations were greater in comparison with cadmium concentrations despite the fact that the chromium concentration leaving from the damaged gravitational sewer system pipe was above three times smaller than cadmium.
4. For chromium pollutant the rapid increase and the decrease of the concentration in the reference points are observed which means that it easily shifts in the ground centre and in small extent undergoes to the process of the sorption.
5. On the basis of obtained results it can be ascertained that the cadmium pollution accumulates in ground medium more than the chromium.
6. The empirical verification of the modeling results in order to verify the validity of initial and boundary conditions is highly required.

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Abstrakt: Eksploatacja sieci kanalizacji sanitarnej związana jest z możliwością wystąpienia eksfiltracji ścieków z przewodu kanalizacyjnego do otaczającego środowiska gruntowego. Eksfiltrujące ścieki zawierające często duże stężenia zanieczyszczeń organicznych i nieorganicznych mogą stanowić zagrożenie zarówno dla jakości wód gruntowych, jak i środowiska naturalnego gleby. Monitoring jakościowo-ilościowy wód wydostających się z uszkodzonego przewodu kanalizacyjnego jest bardzo trudny, a często w warunkach terenowych niemożliwy. W związku z tym coraz większą popularność zdobywa numeryczne modelowanie rozprzestrzeniania się zanieczyszczeń w środowisku gruntowo-wodnym. Niniejsza praca przedstawia wyniki obliczeń numerycznych rozprzestrzeniania się wybranych zanieczyszczeń (kadm, chrom) wydostających się z uszkodzonego przewodu kanalizacji sanitarnej grawitacyjnej, zlokalizowanego w profilu ul. Nadstawnej w Lublinie. Obliczenia numeryczne zostały wykonane za pomocą oprogramowania FEFLOW 5.2, WASY, Niemcy. Parametry transportowe gruntów, warunki początkowe oraz warunki brzegowe zostały wyznaczone na podstawie wyników badań literaturowych, laboratoryjnych i terenowych. Dane z obliczeń umożliwiają analizę wpływu awarii przewodów kanalizacyjnych na środowisko glebowe i wody gruntowe. Obliczenia symulacyjne należy poddać weryfikacji empirycznej w celu potwierdzenia prawidłowości przyjętych warunków początkowych i brzegowych.

Słowa kluczowe: eksfiltracja, rozprzestrzenianie się zanieczyszczeń, modelowanie numeryczne