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Numerical Investigations of Water Outflow After the Water Pipe Breakage

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1. Introduction

Breakages and failures accompany water network maintenance all over the world (Puust et al. 2010, Kutyłowska & Hotloś 2014, Kwietniewski & Rak 2010). Water supply pipes failures generate economic costs due to water losses (Żaba & Langer 2012) and the necessity of repairing pipes (Hotloś 2009). Therefore, the minimization of the water lost through leakage from water systems has become an accord priority for corporations managing water distribution systems in recent years. Different methods of detecting leakages from damaged water pipes have been developed lately.

Generally, there are two basic approaches to minimize water leakages: active inspections (Farley & Trow 2003, Romano & Kapelan 2013) and passive observations (Piechurski 2013). However, many of these methods are unavailable for corporations with a limited budget. The observation of the water outflow on the soil surface on the water supply pathway is still among the simplest and the cheapest methods. Except financial costs, water pipes failures can also generate social consequences threatening people's health or even lives. The most onerous of them are: surface subsidence, foundations washes out, water entering into buildings – all caused by washing out fine particles from soil matrix – called suffusion effects (Iwanek et al. 2016).

The character of a water flow in soil is a complex issue and depends on many different external and internal factors (e.g. soil parameters, pressure head in pipe) (Iwanek et al. 2015). The water outflow on a soil surface after the breakage of a buried water pipe can occur just after a pipe breakage or a long time later. It is also possible that water will never flow out on the soil surface. It is mainly caused by soil parameters variation. The complexity and variability of water transport in soil make the experimental observations of this phenomenon difficult, and conclusions based on these observations may not have a general character. That is why each experimental investigation should also be accompanied by numerical simulations (Iwanek et al. 2015). Usually it is said that numerical calculations should be empirically verified (Krukowski et al. 2010) – in case in question the verification process is duplex and combined.

In the range of the presented article, the numerical simulation analysis of a water pipe failure was conducted using FEFLOW v. 5.3 software, for different variants of leak size and leak location against the pipe axis. The obtained results were empirically verified on the basis of measurements of time between an occurrence of a water leakage from a damaged pipe and the moment of a water outflow on the soil surface during laboratory test.

2. Material and methods

Numerical investigations of a water pipe failure were conducted using FEFLOW v. 5.3 software (WASY Institute for Water Resources Planning System Research Ltd., Germany), widely applied to simulate water and pollutants transport in porous media, both in saturated and unsaturated conditions (e.g. Diersch & Kolditz 2002, Krukowski et al. 2010, Trefry & Muffels 2007, Widomski et al. 2013). Simulation variants corresponded with parallel conducted laboratory tests of a failure of a buried water pipe (diameter: DN40, pressure head: 4 m H_2O).

The cross section of soil profile with water pipe: the 2-dimentional rectangular numerical model (dimensions: 1.5 m × 0.5 m) (Fig. 1) reflected the cross-section of a cuboid laboratory setup filled by sand (dimensions: 1.5 m × 1.5 m × 0.5 m). The detailed description of laboratory setup, soils parameters and experiment methodology are given in the article of (Iwanek et al. 2016).

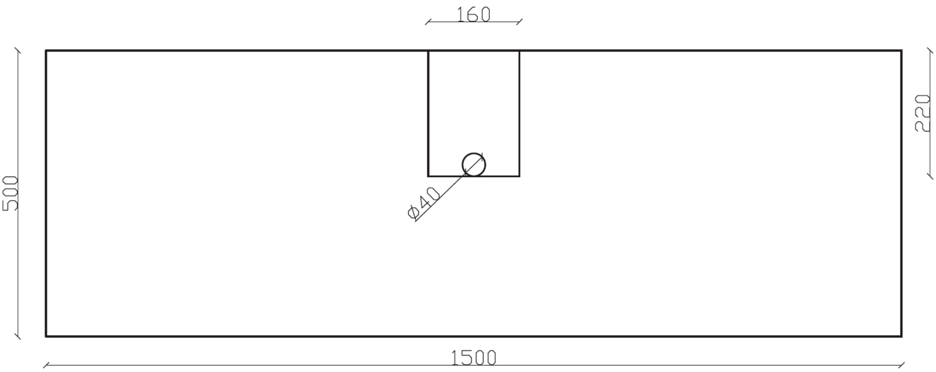


Fig.1. Cross section of soil profile with water pipe in excavation
Rys. 1. Przekrój poprzeczny profilu gruntu z przewodem wodociągowym w wykopie

In order to characterize soils unsaturated properties, the van Genuchten (1980) relationship (given by formula 1) was selected, considering its common using (e.g. Dettmann et al. 2014, Iwanek et al. 2010, Oh et al. 2015, White et al. 2015, Widomski et al 2015). Hydraulic parameters (such as θ – actual water content, K_s – saturated hydraulic conductivity coefficient, P – porosity, α and n – fitting parameters of water retention curve according to van Genuchten formula) of soils tested in laboratory investigations used as input data to the model are given in Tab. 1. Mean value of volumetric moisture content measured just before the each repetition of an experiment was assumed as an initial condition.

$$K = K_s S^l \left[1 - \left(1 - S^{\frac{1}{m}}\right)^m\right]^2 \quad (1)$$

where:
K – hydraulic conductivity, m/s
K_s – saturated hydraulic conductivity coefficient, m/s
S – degree of saturation given by formula (2),
l – fitting parameter (Mualem 1976, Diersch 2005, Widomski et al. 2013a),
m – fitting parameter given by formula (3).

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha h)^n]^m} \quad (2)$$

$$m = 1 - \frac{1}{n} \tag{3}$$

where:
θ – volumetric water content, m^3/m^3
θ_r – residual volumetric water content, m^3/m^3
θ_s – saturated volumetric water content, m^3/m^3
α, n – fitting parameters, 1/m, -
h – pressure head, m

Table 1. Hydraulic parameters of soils used in investigations
Tabela 1. Parametry hydrauliczne gruntu wykorzystanego do badań

Soil	θ	K_s	P	α	n
	% (vol.)	$\cdot 10^{-4}$ m/s	% (vol.)	1/m	–
around the excavation	6.09	1.4	26.56	0.4545	1.4638
in the excavation	6.09	33.0	28.29	6.7620	1.2311

Two types of boundary conditions were used in the model: the first-type (Dirichlet) – a boundary condition on the leaking part of the pipe (4 m H_2O), and the second-type (Neumann) as a top boundary condition covering evaporation, as a bottom boundary condition and as a boundary condition on the tight part of the pipe (flow through the wall equals 0 m/d). A scheme of the soil profile model with finite element mesh and boundary conditions is given in Fig. 2.

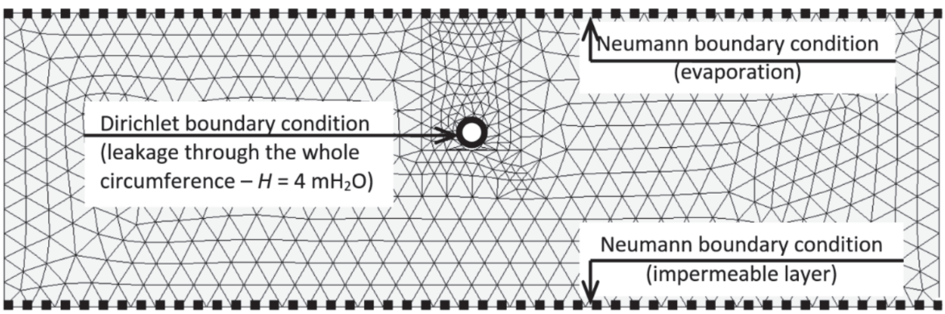


Fig. 2. Analyzed soil profile with finite element mesh and boundary conditions
Rys. 2. Profil analizowanego gruntu wraz z siatką elementów skończonych i warunkami brzegowymi

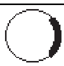
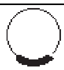
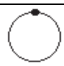
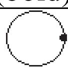
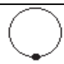
Numerical simulations of a buried water pipe breakage were conducted for 10 combinations of leak size (whole, half, or quarter of a pipe circumference, or a point outflow) and leak location in a pipe cross section (top, side or bottom). Characteristics of variants are shown in Table 2. Variant I reflected the laboratory conditions of the experiment and was used to verify simulations effects on the basis of measurement of time of water outflow on the soil surface after a failure of a buried water pipe in laboratory investigations. For this purpose a relative error δ was calculated according to the formula (4):

$$\delta = \frac{|t_m - t_s|}{t_m} \cdot 100\% \tag{4}$$

where:

t_m, t_s – time between an occurrence of a water leakage from a damaged pipe and the moment of a water outflow on the soil surface in laboratory tests and in numerical simulation, respectively.

Table 2. Characteristics of numerical simulation variants
Tabela 2. Charakterystyka wariantów symulacji numerycznej

Number of variant and location and size of leak (bold)									
									
I	II	III	IV	V	VI	VII	VIII	IX	X

3. Results and discussion

Time between an occurrence of a water leakage from a damaged pipe and the moment of a water outflow on the soil surface during numerical simulations is given in Fig. 3. As it was expected, smaller size of leak resulted in higher value of the time. The influence of leak location on the time was not observed during simulations. However, it should be emphasized that differences between time values in particular variants are very small – only 0.06 s between external values.

Saturation of soil profile for selected variants is presented in Fig. 4 and Fig. 5 as an example. For variants I-II, IV-V, VII-VIII and X, outflow on the soil surface occurred exactly over a pipe axis. For variants III, VI and IX, a slight shift of the outflow to the side of leakage from a pipe (no more than 2 cm) was observed (Fig. 4). Comparing two cases (variants VIII and X) of opposing leakage point (Fig. 5), it is visible that in variant X the most saturated soil occurs around the whole pipe, while in variant VIII soil around the bottom of a pipe is less saturated (on average the saturation was smaller by approx. 0.13).

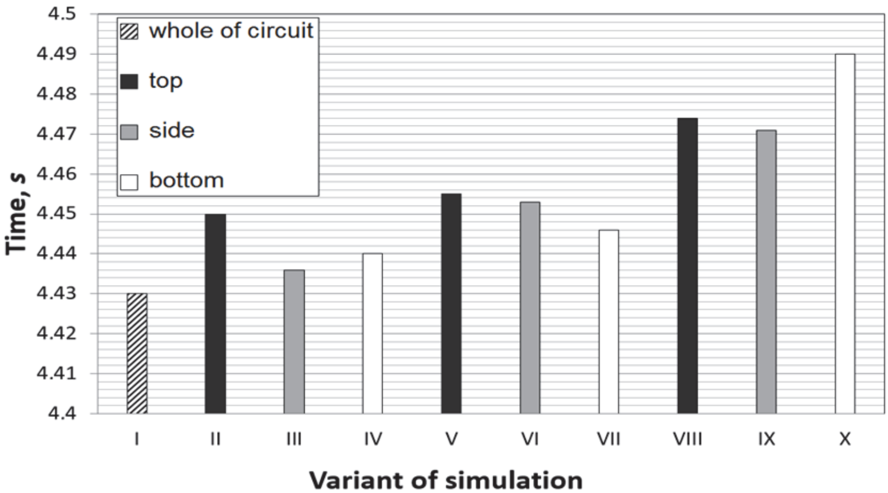


Fig. 3. Results of numerical simulations of time of water outflow on the soil surface after a pipe failure
Rys. 3. Wyniki symulacji numerycznej czasu wypływu wody na powierzchnię gruntu po awarii przewodu wodociągowego

Results of empirical verification of numerical simulations on the basis of measurement of time of water outflow on the soil surface after a pipe failure in laboratory conditions, considering dimensional analysis (Iwanek & Malesińska 2015) are presented in Fig. 6. The most convergent results of simulated and measured time occurred for the first repetition of the experiment (δ = 2.31%). The highest difference was observed for the fifth repetition and it was one of two cases with a relative difference exceeding 20%. For other repetitions a relative difference was lower than 15%. The discrepancy can be caused by simplifications necessary in numerical investigations, as well as some deviations from heterogeneity of soil in the laboratory setup connected with difficulties in compaction process.

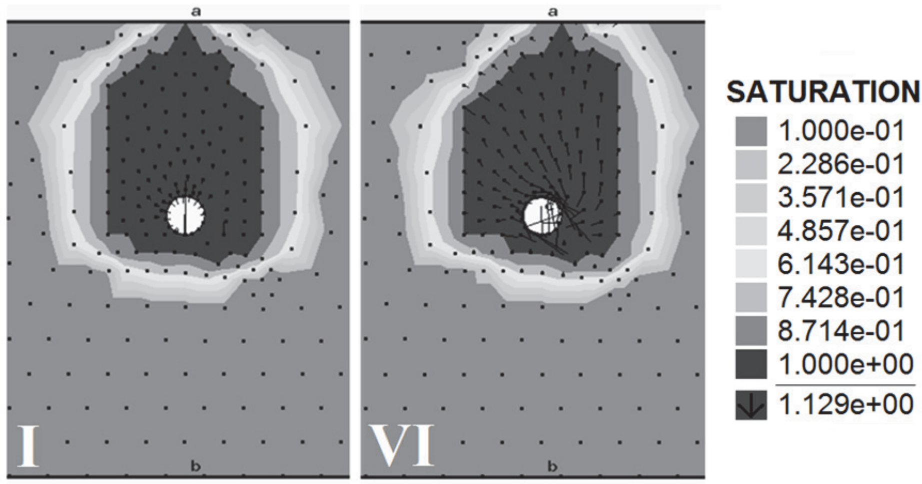


Fig. 4. Saturation of soil profile in the moment of water outflow on the surface – variants I & VI
Rys. 4. Nasycenie profilu glebowego w momencie wypływu wody na powierzchnię – warianty I oraz VI

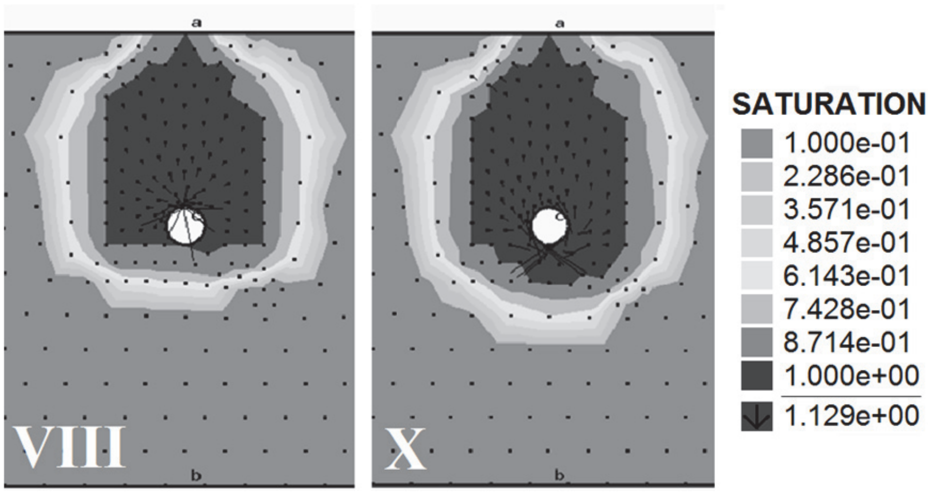


Fig. 5. Saturation of soil profile in the moment of water outflow on the surface – variants VIII & X
Rys. 5. Nasycenie profilu glebowego w momencie wypływu wody na powierzchnię – warianty VIII oraz X

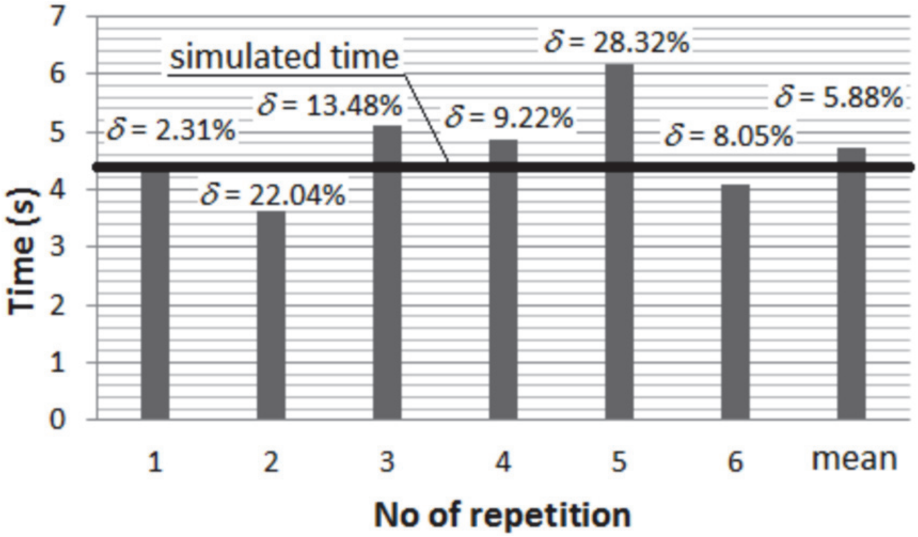


Fig. 6. Comparison of time of water outflow on the soil surface after a pipe failure – simulated and measured
Rys. 6. Porównanie czasu wypływu wody na powierzchnię gruntu po awarii przewodu wodociągowego – wartości modelowe oraz zmierzone

4. Conclusion

Numerical simulations of water leakage from a damaged buried pipe provide an alternative of experimental investigations. The analysis conducted using the FEFLOW v. 5.3 software for ten different variants indicated that neither leak size nor leak location in a pipe cross section influence time of water outflow on the soil surface significantly. There is no visible trend and dependence between the leak size and location on the water time outflow. However, higher values of the time were observed for smaller size of leak, but differences between the cases occurred of only a few thousandths of a second.

The empirical verification of numerical simulations results indicated almost exact coincidence of the measured and calculated values of time for the first repetition of the experiment only. It should be emphasized that neither the numerical model nor the laboratory setup reflect the actual conditions accurately, because of simplifications necessary to conduct a numerical or a physical simulation. Thus, further verification of the numerical investigation results is still needed, based on the effects of in-situ tests in actual conditions. However, the obtained results certainly justify further work on water network failures. Next phases of the water network failures will include more advanced laboratory investigations (including other parameters influencing the process) and also investigations of a water pipe failure in natural conditions.

Acknowledgement

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Analiza numeryczna wypływu wody po awarii przewodu wodociągowego

Streszczenie

W skali światowej, uszkodzenia i awarie nieodłącznie towarzyszą procesowi eksploatacji sieci wodociągowej. W ostatnich latach, minimalizacja strat wody, spowodowanych przeciekami z przewodów, stała się priorytetowym celem przedsiębiorstw zarządzającym systemami dystrybucyjnymi. Stąd też, metody i sposoby wykrywania przecieków przewodów wodociągowych uległy znacznemu rozwojowi. Jednakże, wiele z obecnie proponowanych metod jest niedostępnych dla przedsiębiorstw wodociągowych o ograniczonym budżecie. Obserwacja wypływu wody na powierzchnię terenu wzdłuż trasy wodociągu jest wciąż jedną z najprostszych i najtańszych wykorzystywanych metod. Wypływ wody na powierzchnię może nastąpić bezpośrednio po awarii lub w dużym odstępie czasu. Zdarza się również, że wypływ wody na powierzchnię nie wystąpi nigdy. Poza kosztami finansowymi, awarie przewodów wodociągowych powodują również konsekwencje społeczne, które mogą zagrażać zdrowiu, a nawet życiu, ludzi.

Charakterystyka przepływu wody w gruncie jest zagadnieniem złożonym i zależy od wielu, zarówno zewnętrznych jak i wewnętrznych, czynników. Złożoność i różnorodność transportu wody w gruncie czyni obserwacje doświadczalne tego zjawiska trudnymi, zaś wnioski wyciągane na podstawie obserwacji mogą nie mieć charakteru uniwersalnego i ogólnego. Zakres prezentowanego artykułu obejmował analizę numeryczną wypływu wody po awarii przewodu wodociągowego przeprowadzoną w programie FEFLOW v 5.3. Analizę przeprowadzono dla różnych wariantów, różnicując zarówno powierzchnię otworu, jak i jego lokalizację względem osi przewodu wodociągowego. Uzyskane wyniki zostały poddane empirycznej weryfikacji w oparciu o pomiary laboratoryjne czasu pomiędzy awarią przewodu wodociągowego, a momentem wypływu wody na powierzchnię.

Wyniki przeprowadzonej analizy sugerują, że zarówno rozmiar otworu jak i jego lokalizacja względem osi przewodu, nie wpływają znacząco na czas wypływu wody na powierzchnię. Jednakże, większe wartości czasu były obserwowane dla mniejszych wielkości otworów. Po przeprowadzeniu empirycznej weryfikacji wyników symulacyjnych, zauważono, że bezpośredni związek pomiędzy zmierzonymi i obliczonymi wartościami czasu był odnotowany jedynie dla pierwszego powtórzenia eksperymentu. Należy podkreślić, że zarówno model numeryczny jak i stanowisko laboratoryjne nie odzwierciedlały rzeczywistych warunków w sposób dokładny, ze względu na niezbędne uproszczenia jakie należało przyjąć celem symulacji komputerowej lub fizycznej doświadczenia.

Słowa kluczowe:
awaria przewodu wodociągowego, czas wypływu wody, FEFLOW

Keywords:
water pipe failure, water outflow time, FEFLOW