



Parameters characterizing leakages from damaged water pipes in the aspect of environmental security

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Abstract

Leakages from buried water pipes can result in suffosion posing a threat to the environment and the infrastructure existing in cities. Leakage of water from a pressure pipe into a soil susceptible to suffosion is a very complex phenomenon, characterized by a number of different parameters. Taking into account all parameters in the empirical tests of the buried water pipe leakage is practically impossible. Thus, it is necessary to select them so that on the one hand it is possible to perform a physical simulation of the phenomenon, and on the other to obtain reliable results of investigations. According to the Pareto principle, it can be stated that a small group of factors—about 20%—has a crucial impact on the phenomenon. Therefore, in empirical tests of water outflow from the underground water supply system, it is enough to consider 20% of the parameters affecting the analyzed phenomenon. The purpose of this work was to select these parameters. The selection was based on two types of research—literature research and computer simulations using the FEFLOW v. 5.3 software. The research allowed to select 4 out of 19 parameters which impact on the effects of the phenomenon of water outflow from pressure pipe to a soil susceptible to suffosion turned out to be the most essential: a pressure in the pipe, a leak area, a saturated conductivity coefficient of soil and an uniformity coefficient of soil.

Keywords Buried water pipes · Leakage · Pareto principle · FEFLOW software

Introduction

Failures and breakages of underground water-pipe networks are common problems for water companies all over the world. They cause not only water losses, but also may result in suffosion, which is a process in which fine particles of soil are washed away from the solid matrix and lifted with the water flowing through the soil pores, causing creation of empty spaces below the soil surface and depressions. In urban areas, where they are particularly dangerous due to the density of buildings and underground infrastructure, the most common cause of this type of phenomena are failures of underground pipes (Khomeenko 2006).

Failure of the underground water pipes involving the occurrence of leaks is a very complex phenomenon, characterized by a number of different parameters, that often

depend on each other or change in time or space. Leakage causes that water flowing through the pipe under pressure begins to flow into the soil. In hydraulic calculations, this outflow is usually treated as an outflow to the atmosphere through a small orifice in the bottom of an open tank filled to the height H , corresponding to the hydraulic pressure in water pipe network (e.g. Ferrante 2012; Ferrante et al. 2014; Schwaller and van Zyl 2014). The impact of pressure from the ground is neglected as much lower than the pressure in water distribution networks (van Zyl et al. 2013; van Zyl 2014). Frequently used by practitioners (e.g., Al-Ghamdi, 2011; De Paola and Giugni 2012; Ferrante et al. 2014; Schwaller and van Zyl 2014) relationship between the amount of leakage and the hydraulic pressure in the water pipe (leak law) has the form (Lambert 2001; Thornton 2003; Thornton and Lambert 2005):

$$Q = C \cdot H^{N1} \quad (1)$$

where: Q —leakage flow rate (m^3/s), C and $N1$ —empirical parameters, H —pressure head in a water pipe ($\text{m H}_2\text{O}$).

The relationship (1) is more general form of the well-known Torricelli's law (e.g. Chin 2017):

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$$Q = C_d \cdot A \cdot \sqrt{2 \cdot g \cdot H} \quad (1a)$$

where: C_d —discharge coefficient, taking into account energy losses and jet contraction, A —leak area (m^2), g —standard gravity (m/s^2).

The parameters C and $N1$ in formula (1) are determined by experimental methods. The unit of C depends on the value of $N1$, the exponent $N1$ is dimensionless. Formulas (1) and (1a) coincide only in the special case—if $C = C_d \cdot A \cdot \sqrt{2 \cdot g}$ and $N1 = 0.5$. In general, the coefficient C is affected by the shape of the hole, its surface A and the type of the hole edge. The exponent $N1$ can take values in the range of 0.4–2.79 mainly depending on the material of the pipe and the shape of the hole, as indicated by published research results (Farley and Trow 2003; Greyvenstein and van Zyl 2007; Cassa et al. 2010; Al-Ghamdi 2011; Schwaller and Zyl 2014).

After flowing out through the hole from the pipe, water begins to move in the soil. This movement describes the basic filtration law developed by Darcy for the saturated zone (i.e., below the water table), later extended to the unsaturated zone (e.g., Zaradny 1990; Miyazaki 2005; Hopmans 2011), and the equation of flow continuity. Basing on these relationships, a basic equation of water movement in the soil profile, called the Richards equation, was developed. For isotropic conditions and one-dimensional vertical flow, it can be given as (e.g., Hopmans 2011):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K \cdot \left(\frac{\partial \Psi}{\partial z} + 1 \right) \right] - S \quad (2)$$

where: θ —volumetric water content in the soil, m^3/m^3 , t —time, s, z —vertical coordinate, m, K —unsaturated hydraulic conductivity, m/s, Ψ pressure (capillary) head in soil, m H_2O , S —sink term, taking into account water uptake by plant roots, 1/s.

The conductivity K describes the ability of the bulk soil to transmit water (Hopmans 2011) and can be determined on the basis of the algorithm developed by van Genuchten using the Mualem relationship (Mualem 1976; van Genuchten 1980):

$$K = K_s \cdot \left[\frac{1}{1 + (\alpha \cdot h)^n} \right]^{(1-\frac{1}{n})L} \cdot \left\{ 1 - \left[\frac{(\alpha \cdot h)^n}{1 + (\alpha \cdot h)^n} \right]^{(1-\frac{1}{n})} \right\}^2 \quad (3)$$

where: K_s —saturated hydraulic conductivity (m/s), h —suction head (m), L —dimensionless constant, a parameter that is related to the tortuosity and the connectivity of the soil pores, α —fitting parameter (m^{-1}), n —fitting parameter.

The saturated conductivity K_s is a soil feature dependent on the geometry, distribution and interconnections of the soil pores (Chapuis 2012). The parameter α is a scale

parameter inversely proportional to mean soil pore diameter and is related to the inverse of the air-entry pressure ($\alpha > 0$) (Schaap and van Genuchten 2006; Yang and You 2013). The parameter n is a measure of the pore-size distribution ($n > 1$) and influences the shape of the soil moisture characteristic, i.e., a curve reflecting the relationship between the water content in soil and the soil water potential. Parameters α and n are determined on the basis of the function proposed by Mualem (1976):

$$\theta = \frac{\theta_s - \theta_r}{[1 + (\alpha \cdot h)^n]^{(1-\frac{1}{n})}} + \theta_r \quad (4)$$

where: θ_s , θ_r —saturated and residual, respectively, volumetric water content (m^3/m^3).

The saturated water content θ_s is the amount of water completely filling the pores in a given volume of soil sample. The residual content θ_r is the content of water which is considered to be immobile in soil pores (Hopmans 2011).

Under natural conditions, water flow in the pores of the soil is the most often laminar (Delleur 2006), hence the very wide application of the relationships (2)–(4) in hydrological and hydrogeological practice. Also the outflow of water from a buried water pipe as a result of a failure, at low flow speeds can be treated in studies as laminar (Walski et al. 2006; Fox et al. 2016). However, in soils with large pores or cracks, turbulent flow may occur and the Richards Eq. (2) cannot be applied to describe it. For turbulent flow, the filtration law can be given in the form (e.g., Wieczysty 1982):

$$\text{grad } \varphi = \frac{u_f}{K_s} \cdot (1 + \alpha_n \cdot u_f) \quad (5)$$

where: φ —soil water hydraulic head (m H_2O), u_f —superficial flow velocity (m/s), α_n —factor of filtration nonlinearity (s/m) calculated from the formula:

$$\alpha_n = \frac{a_0}{P^2} \cdot \sqrt{\frac{K_s}{v \cdot g}} \quad (6)$$

where: P —soil porosity (%), v —kinematic viscosity of water (m^2/s), g —standard gravity (m/s^2), a_0 —dimensionless factor dependent on K_s .

The description of the flow of water through the soil becomes more difficult if soil is susceptible to suffosion. Soil may undergo suffosion if two conditions are met—geometric and hydraulic. Soil meets the geometric condition if its granulometric composition and pores size are enough to allow the formation of channels inside the soil along which small particles can move (Kovács and Ujfaludi 1983). Methods for determining the geometrical condition of suffosion developed over the years (Terzaghi 1939; Scherman 1953; Kezdi 1979; Kovács and Ujfaludi 1983; Kenney and Lau

1985, 1986; Burenkova 1993; Li and Fannin, 2008) require knowledge of the characteristic diameters d_x of soil grains (e.g., d_{10} , d_{15} , d_{50}), denoting the diameter of these grains, which together with smaller ones constitute $x\%$ (by weight) of the tested sample. These diameters are determined on the basis of a soil grain size curve. The simple methods of assessing soil susceptibility to suffosion (Istomina 1957; Lubochkov 1965) uses diameters d_{10} and d_{60} in the form of the uniformity coefficient U , defined as:

$$U = \frac{d_{60}}{d_{10}} \tag{7}$$

If water flows in the soil that meets the geometrical condition of suffosion and the flow velocity exceeds a critical value—is high enough to cause washing out the particles from the solid matrix (i.e., the flow velocity meets the hydraulic condition for the occurrence of suffosion), empty spaces may be created in the soil, and consequently land depressions or subsidence may occur. Checking the hydraulic condition of the possibility of the suffosion requires to determine the critical velocity of water flow. In the methods used for many years, the critical velocity is calculated using empirical formulas, that depend on the saturated conductivity K_s (Sichardt 1928; Abramov 1952; Schmieder 1966; Kovács and Ujfaludi 1983).

Summing up the characteristics of the phenomenon of water outflow from a damaged pressure water-pipe, it can be stated that this is a complex process, dependent on many parameters—all occurring in the formulas (1)–(7):

$$Z_{total} = \{C, H, N1, \Psi, S(\theta), K_s, K, h, L, \alpha, n, \theta, \theta_s, \theta_r, \varphi, \alpha_n, u_f, P, a_0, \nu, g, d_{10}, d_{60}, U\} \tag{8}$$

where: Z_{total} —set of parameters occurring in the formulas (1)–(7), C, H, \dots, U —parameters as in the formulas (1)–(7).

The set Z_{total} does not include parameters of the formula (1a) as a special case of the formula (1). The parameter C from the formula (1) depends on the shape of the hole in a water pipe, its surface A and the type of the hole edge. The exponent $N1$ (formula (1)) depends also on the shape of the hole and, in addition, on the material of the pipe. Assuming that the tests are carried out on a specific water pipe, made of a specific material and that one specific type of leak is tested, the exponent $N1$ can be rejected from the set Z_{total} as constant and the parameter C can be replaced in the set Z_{total} with the hole surface A .

The factor α_n from the formula (5) depends on porosity P , kinematic viscosity of water ν , saturated conductivity K_s and factor a_0 . Moreover, the factor a_0 from the formula (6) depends on K_s only. Thus, parameters α_n and a_0 also can be rejected from the set Z_{total} , if parameters P, ν and K_s are left.

There is no need to include each of three parameters U, d_{60} and d_{10} occurring in formula (7) in the set Z_{total} . It is U that is the parameter that is used to determine the geometric condition of the possibility of a suffosion. Therefore, if the set Z_{total} contains the coefficient U , the diameters d_{60} and d_{10} can be omitted from the set Z_{total} .

After rejecting parameters that are dependent on others and after replacing the parameter C with the leak area A , the set of parameters influencing the phenomenon in question can be presented in the form:

$$Z = \{H, A, \Psi, S(\theta), K_s, K, h, L, \alpha, n, \theta, \theta_s, \theta_r, \varphi, u_f, P, \nu, g, U\} \tag{9}$$

where: Z —set of parameters influencing the phenomenon in question, A —leak area (m^2), other parameters as in the formulas (1)–(7).

Description of the elements of the set Z (without the standard gravity g and kinematic viscosity ν) is given in Table.1. The parameters characterizing the soil medium are the vast majority of the set Z .

Among the parameters of the set Z there are parameters that vary both in space (e.g., ψ, K_s), and time (e.g., H, θ), as well as independent parameters (e.g., A and U) or related by equations of different complexity (e.g., K_s and U, θ and α). The empirical studies of such a complex phenomenon, taking into account all parameters affecting this phenomenon, is impossible for methodological reasons. Therefore the purpose of this article is to select those parameters among the elements of the set Z whose inclusion in empirical studies is necessary and sufficient to reliably reflect the actual conditions of the phenomenon in question

on the one hand, and on the other hand—to make the experiment possible to carry out.

Methods

It is practically impossible to consider all elements of the Z set—19 different parameters—in the laboratory tests of the failure of a buried water pipe. Basing on the Pareto (1964) principle, it can be stated that a small group of factors—about 20%—has a decisive impact on the result of a phenomenon. Thus, it is enough to consider 20% of the elements of the Z set in empirical studies of the outflow of water from a damaged water pipe.

The entire research methodology included two integral stages. The first stage was based on literature data and was followed by the second stage based on simulations studies. Both stages were necessary to select parameters with the greatest impact on the analyzed phenomenon.

Table 1 Description of the parameters creating the set Z (9)

Parameter's name	Symbol and unit	No of related formula	Parameter related to	Description of parameter
Hydraulic pressure	HMPa/m H ₂ O	(1)	Pipe	Pressure exerted by water on a pipe at a fixed location
Leak area	A , m ²	(1)*	Pipe	An area on the water distribution pipe where water flows out due to damage of the pipe
Pressure (capillary) head in soil	Ψ , m H ₂ O	(2)	Soil	Pressure equivalent of soil water potential; > 0 in saturated soil, ≤ 0 in unsaturated soil
Sink or source term	S , 1/s	(2)	Soil	Parameter which takes into account the uptake of water from the soil by the plant root system
Saturated hydraulic conductivity	K_s , m/s	(3), (5), (6)	Soil	A quantitative measure of an ability of soil to conduct water when soil pore space is saturated with water; if value of K_s is higher, the soil is more permeable
Unsaturated hydraulic conductivity	K , m/s	(2)	Soil	A quantitative measure describing the ease with which water can move through pore spaces under unsaturated conditions
Suction head	h , m H ₂ O	(3)	Soil	Pressure head which is induced by capillary attraction on the soil voids
Constant	L , –	(3)	Soil	A parameter that accounts for pore tortuosity and pore connectivity
Parameter α	α , 1/m	(3), (4)	Soil	A fitting parameter depending on the inverse of the air entry pressure ($\alpha > 0$)
Parameter n	n , –	(3), (4)	Soil	A fitting parameter depending on the pore-size distribution ($n > 1$)
Volumetric water content	θ , m ³ /m ³	(2)	Soil	The ratio of the volume of water in the soil sample to the volume of this sample
Saturated volumetric water content	θ_s , m ³ /m ³	(4)	Soil	The ratio of the volume of water in the soil sample to the volume of this sample when soil pore space is completely filled with water
Residual volumetric water content	θ_r , m ³ /m ³	(4)	Soil	Water content in the soil sample after roasting the sample at 105°C
Soil water hydraulic head	φ , m H ₂ O	(5)	Soil	The pressure needed to overcome the resistance to water movement when it flows through a specific section of the soil medium
Superficial flow velocity	u_f , m/s	(5)	Soil	Hypothetical velocity of water flow in a soil, calculated as if the water flowed through the entire cross section of the soil sample without solid particles
Porosity	P , %	(6)	Soil	A measure of the void spaces in soil
Uniformity coefficient	U , –	(7)	Soil	A parameter which numerically represents the variety in particle sizes of natural soils

*Leak area A is related to the formula (1) indirectly. The explanation is provided in the text

The first stage of investigations included a review of the literature on the processes associated with the outflow of water from an underground water pipe, in the aspect of inter-relationship between the parameters. The elements of the set Z whose impact on the considered phenomenon occurred the least significant, were rejected. The value characterizing the effect of the failure, to which the impact of particular parameters from the set Z was compared, was the time t_{out} between the moment of water leak from a pipe and the moment of the water outflow on the soil surface.

The elements of the set Z remaining after the first research stage—literature analysis—were evaluated on the basis of the simulations studies. The second research

stage—simulations studies—consisted of the series of computer simulations of buried water pipe failures in the FEFLOW v. 5.3 software (WASY Institute for Water Resources Planning System Research Ltd., Germany) for various values of the examined arguments. The program allows the simulation of liquid, mass and heat transport in saturated and unsaturated porous media (Diersch 2005). It is most often used in research on the movement of natural soil water, but it can also be successfully used to simulate the flow of water flowing from a damaged buried water pipe (Suchorab et al. 2016; Iwanek et al. 2018; Suchorab and Iwanek 2019).

In the simulation studies, it was assumed that the water pipe has a diameter of 100 mm and was laid in natural soil, and the leakage occurs along the entire perimeter of the pipe. The two-dimensional model built in the program, 20 m wide and 5 m deep, covered the cross section of the pipe and the area around it. The input data to the model were the hydraulic parameters of the soil used in the variants of computer simulation. The basic model assumes that the natural soil is sandy soil, for which hydraulic parameters have been taken from the literature data (Kirkland et al. 1992) (Table. 2). As an initial condition for all nodes in the basic model, sand moisture of $0.118 \text{ m}^3/\text{m}^3$, corresponding to the field water capacity, i.e., the maximum amount of water that can be retained by the soil in the aeration zone, despite the force of gravity, was adopted. Evaporation from the soil surface 0.002 m/d was assumed as the upper boundary condition (Neumann’s condition). The lower boundary condition (Dirichlet’s condition) was $\Psi = -10 \text{ kPa}$ (potential for the field water capacity). The Dirichlet’s condition was also adopted in the place of water outflow from the pipe, taking into account the hydraulic pressure inside it assumed as $40 \text{ m H}_2\text{O}$ (0.4 MPa). The hydraulic pressure in water distribution systems in Poland covers the range of $0.25\text{--}0.6 \text{ MPa}$ and the value of 0.4 MPa was assumed as average and relatively often found value in water distribution systems.

During the computer simulation of the buried water pipe failure, the time between the moment of leakage occurrence and the moment of water outflow on the soil was determined. The simulations were divided into groups of variants (series) for which the input data values in the basic model were changed. The range of changes in individual parameters was determined on the basis of literature (Kirkland et al. 1992). In each series the value of one parameter was changed—the one whose impact on the time of water outflow was analyzed in a given series. This impact was assessed on the basis of the difference:

$$\Delta t_{\text{out}} = t_{\text{max}} - t_{\text{min}} \tag{9}$$

where: t_{max} and t_{min} —the largest and smallest value of time of water outflow on the soil surface (t_{out}), respectively, obtained in one series of simulations of water supply failure, when the value of one of the considered parameters changes.

For the purposes of this article, the impact of the parameter assessed in the second research stage was considered significant if the difference Δt_{out} exceeded 5 min (300 s).

Table 2 Hydraulic parameters of sandy soil assumed in the basic model as natural soil (Kirkland et al. 1992)

Parameter	$K_s, \text{ m/s}$	$\theta_s, \text{ m}^3/\text{m}^3$	$\alpha, \text{ 1/m}$	n
Value of parameter	$0.626 \cdot 10^{-4}$	0.366	2.800	2.239

This value was assumed after consulting with practitioners. This is the time when the amount of water lost due to leakage is relatively small—for example, for $H = 60 \text{ m H}_2\text{O}$ and $A = 0.01 \text{ m}^2$ it would be about 20 m^3 . The conducted assessment of the parameters allowed to extract from the set Z those elements that should be included in the research on the effects of an underground water pipe failure.

Results of analysis

The first stage of parameter selection—literature analysis

According to the method, in order to reduce the number of elements of the set Z , relationships between the elements and their influence on the value of time t_{out} were analyzed at first. The first two parameters (H and A) are the only elements of the set Z related to the flow of water in the unsealed distribution pipe. The value of A does not affect the pressure H in the water pipe, but it has been shown that there is an inverse relationship—due to the pressure in the water pipe, the leak area increases linearly (Cassa et al. 2010). In addition, the conducted research indicates that higher values of both H and A cause a reduction in the value of time t_{out} (Iwanek et al. 2016; Iwanek and Suchorab 2017). Therefore, these parameters should remain elements of the Z set as significantly affecting the analyzed phenomenon.

The potential of water in soil Ψ is identified with the amount of suction head h (Zaradny 1990; Hopmans 2011), so $\Psi = h$. If the level of the ground water table is steady, then h has a constant value and it can be assumed that $h \approx \varphi$ (Wieczysty 1982; Puzyrewski and Sawicki 1998). There is a functional relationship $h = f(\theta)$ between suction pressure h and soil moisture θ , represented graphically as a soil water retention curve (Zaradny 1990), approximated by the function (4). Instead of four parameters Ψ, φ, h and θ for further considerations it is enough to take one of them, e.g. θ . Similarly, the changes of values of filtration rate u_f and the hydraulic conductivity coefficient K can be omitted in the empirical tests, because both these parameters are a function of K_s . In the case of u_f it is the Darcy’s law, and in the case of K —the functional relationship (3). The K_s coefficient should remain in the Z set as necessary to take into account in the investigations of the effects of the water-pipe failure, because its value has a significant impact on the fulfillment of the hydraulic condition of the possibility of suffosion (Sichardt 1928; Abramov 1952; Schmieder 1966; Kovács and Ujfaluđi; 1983). The coefficient U has the same meaning in the aspect of meeting the geometrical condition for the occurrence of suffosion (Wieczysty 1982; Houben 2015); therefore, this parameter should also be included in the research on the effects of a water-pipe failure.

The parameter L related to the pattern of pore connections in the soil is sometimes estimated and has different values (e.g., Tuli et al. 2005; Schaap and van Genuchten 2006), however in mineral soils, the fixed value of 0.5 proposed by Mualem (1976) is most often assumed, regardless of the mineral soil type (e.g., Ippish et al. 2006; Lazarovitch et al. 2007; Zhang et al. 2007; Siyal et al. 2013; Widomski et al. 2013). Water distribution networks are usually laid in sand backfill or other mineral soil, so in the study of the water-pipe failure $L=0.5$ can be assumed as constant.

Descriptions of studies in which some parameters are omitted due to the fact that their value is relatively small, can be found in the literature. An example of such a parameter is the sink or source term S . The Richards Eq. (2) without the S term can be found, e.g., in the works of Pop et al. (2004), Schneid et al. (2004), Kuráží et al. (2010, 2014), Cao and Yue (2014). Another example is the residual water content in the soil θ_r , which according to the physical sense is positive. However, its values are usually of the order of a few percent (Vogel et al. 2001; Puhlmann and Wilpert 2012), therefore $\theta_r=0$ may be assumed, as in the works of Tuli et al. (2005) or Widomski et al. (2015).

The saturated water content θ_s equals soil porosity P in saturated zone, for completely saturated soil. However, in unsaturated zone, above the water table, where water-pipes are usually laid, typically $\theta_s \approx 85\% P$ (Hopmans 2011). Thus, taking into account relation between P and θ_s both in saturated and unsaturated zone, one of the two parameters, e.g. θ_s , can be considered in the study of the water-pipe failure.

Water distribution failure tests are carried out in the gravitational field, which can be considered as homogeneous (constant g value). If the water used in the tests has

a constant temperature, then the viscosity ν has a constant value. Thus, the conducted literature analysis allowed to extract from the 19-element set Z an 8-element set Z' :

$$Z' = \{H, A, K_s, \alpha, n, \theta, \theta_s, U\} \tag{10}$$

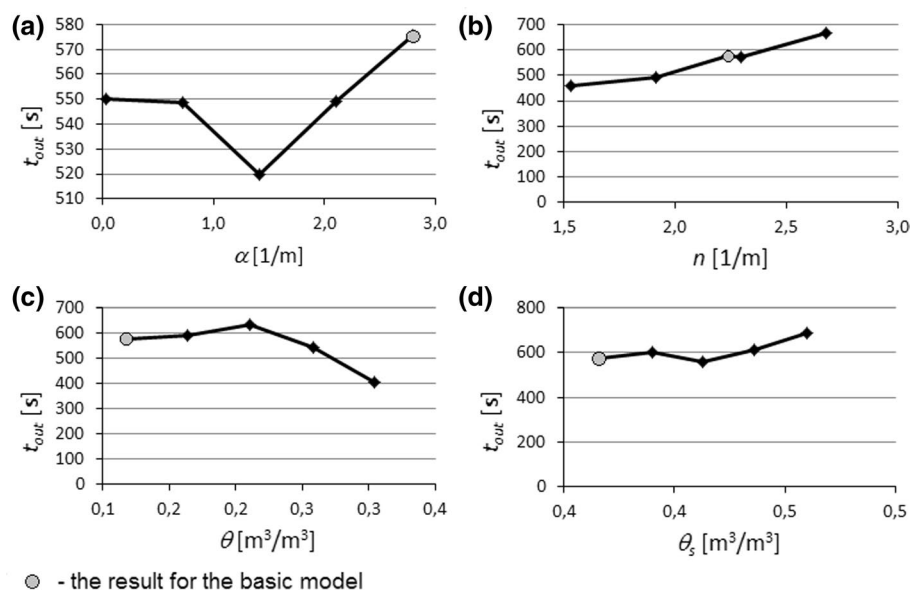
Basing on the analysis of the literature, it can be stated that among the elements of the set Z' , parameters H, A, K_s and U significantly affect the results of underground water supply failure and should be taken into account in the study of this phenomenon, while the remaining parameters $(\alpha, n, \theta, \theta_s)$ should be evaluated by computer simulation studies.

The second stage of parameter selection—computer simulations

To determine the impact of parameters α, n, θ and θ_s on the value of time t_{out} , simulations of a water-pipe failure were carried out in the FEFLOW software. In accordance with the method, a separate series of simulations was carried out for each of these parameters. In one series, simulations were carried out for various values of the tested parameter—varied in the basic model. In the case of parameters α, n and θ_s , maximal and minimal values of the parameter were adopted on the basis of the literature for extremely different soils, and other values (between minimal and maximal) were assumed. In the case of moisture θ , all values were for the sandy soil used in the basic model, with the lowest value corresponding to the field water capacity, and the highest value close to full saturation. The simulation results are shown in Fig. 1.

The difference between the maximum and minimum time of water outflow to the soil surface after an underground

Fig. 1 Graphs of the dependence between the time of water outflow on the soil surface after a failure of a buried water pipe (t_{out}) and the selected parameters: **a** parameter α , **b** parameter n , **c** actual water content in the soil θ , **d** saturated water content in the soil θ_s



water pipe failure, calculated on the basis of the relationship (1), did not exceed the assumed limit value of 300 s for any of the analyzed parameters (Fig. 2). The parameter α clearly showed the smallest impact on the value of t_{out} ($\Delta t_{out} = 56$ s), and the actual water content θ —the largest ($\Delta t_{out} = 226$ s). For comparison, Fig. 3 presents a graph of the dependence of time t_{out} on the saturated conductivity K_s —a parameter considered as significantly affecting the studied phenomenon, after the literature analysis. The difference Δt_{out} in this case was 5150 s (almost 86 min) and was 23 times greater than in the case of the actual water content θ . Therefore,

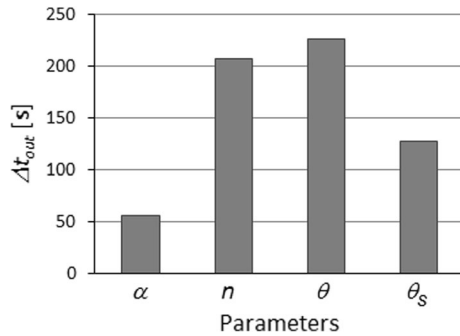


Fig. 2 The differences between the maximum and minimum values of the time of water outflow on the soil surface obtained in the computer simulations of the water pipe failure for the selected parameters

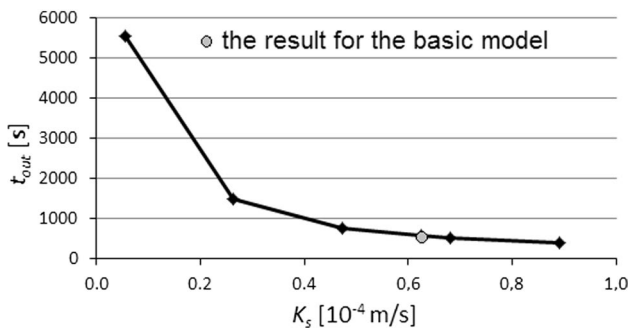


Fig. 3 Graph of the dependence between the time of water outflow on the soil surface after a failure of a buried water pipe (t_{out}) and a saturated conductivity coefficient K_s

the results of simulation tests carried out suggest that the parameters α , n , θ and θ_s may be omitted in the analysis of the effects of the phenomenon in question. Eventually, the four-element set Z' was separated from the 19-element set Z as a set of parameters determining effects of the buried water pipe failure:

$$Z'' = \{H, A, K_s, U\} \tag{11}$$

Discussion

The first two elements of the set Z'' (11)—pressure head H and a leak area A —are parameters related to the water pipe and hydraulic conditions in it, while the others characterize the soil. Parameters H and A are one-sidedly related to each other—increasing the pressure in the pipe increases the leakage area. Both pressure head in a water pipe and a leak area influences the intensity of water outflow from a pipe through a leak according to formula (1) (A influences a coefficient C in formula (1)) and thereby influences the outflow velocity. The value of outflow velocity is important in the aspect of possibility of suffosion occurrence in the soil—if the outflow velocity of water reaches the critical value, washing out the soil particles from the solid matrix is possible. Moreover, lowering the pressure in the water supply system reduces its failure rate (e.g., Lambert 2001; Lambert and Taylor 2010; Zimoch 2012).

Saturated hydraulic conductivity, K_s , describing the ability of the soil medium to conduct water in saturated conditions, is different for different types of soil and also varies widely within one type of soil—typical values for sand cover the range $10^{-6} \div 10^{-3}$ m/s, for silt $10^{-10} \div 10^{-5}$ and for clay $10^{-8} \div 10^{-12}$ (Kardena et al. 2014). The conductivity K_s is the basis for determining the critical flow velocity—value sufficient to cause the fine soil particles to be washed away from the solid matrix. In empirical formulas developed over the years and still used (Table. 3), allowing the determination of the critical flow velocity, the only parameter determining the value of the critical velocity is just the saturated hydraulic

Table 3 Selected formulas for determining the hydraulic condition for the suffosion

Formula	Literature source	Description of parameter
$u_{cr} = \frac{1}{15} \sqrt{K_s}$	Sichardt 1928	u_{cr} —critical flow velocity, m/s
$u_{cr} = 3,2 \cdot 10^{-2} \cdot \sqrt[3]{K_s}$	Abramov 1952	K_s —saturated hydraulic conductivity, m/s
$u_{cr} = 5,0 \cdot 10^{-2} \cdot \sqrt[4]{K_s}$	Schmieder 1966	
$u_{cr}^{(1)} = 0,098 \cdot K_s^{0,356}$	Kovács and Ujfaludi 1983	$u_{cr}^{(1)}$ —first critical flow velocity, for which the fine soil grains start to move, cm/s
$u_{cr}^{(2)} = \frac{1}{3} \cdot \left(1 \pm \frac{f}{3}\right) \cdot \sqrt[3]{K_s}$		$u_{cr}^{(2)}$ —second critical flow velocity, for which micro-channels are created in soil profile, cm/s
		K_s —saturated hydraulic conductivity, cm/s

Table 4 Summary of the influence of the elements of the set Z' (11) on the phenomenon in question

Parameter	The parameter influence on the phenomenon in question
H , MPa/m H_2O	The higher the value of H , the faster the velocity of water outflow from the damaged pipe Increasing the value of H enlarges the area A
A , m^2	The greater the value of A , the greater the amount of water outflowing from the damaged pipe
K_s , m/s	The higher the value of K_s , the higher the value of the critical velocity of water flow, exceeding which causes the occurrence of suffosion possible
U , –	The closer to 1 the value of U , the higher the value of K_s Generally, for $U > 20$ suffosion is possible (geometric condition of suffosion possibility)

conductivity. Thus, K_s is necessary to assess the occurrence of the hydraulic condition for the suffosion.

The last of the elements of the set Z' (11), the uniformity coefficient U is the measure of the uniformity of the soil graining. If the coefficient U is closer to 1, the grain size distribution of the soil is more uniform and its permeability is better. Although the uniformity coefficient is not the only parameter determining the permeability of the soil, this feature is important when considering the possibility of the occurrence of the phenomenon of suffosion in the soil in the aspect of the hydraulic condition. Moreover the uniformity coefficient can be used to evaluate the geometric condition of suffosion possibility. According to Istomina (1957) if $U < 10$, then suffosion will not occur, and if $U > 20$, then suffosion is possible. The case of $10 < U < 20$ should be considered as intermediate conditions. Wieczysty (1982) gives the same conditions as Istomina (1957), and also suggests the possibility of suffosion occurrence for $2 \leq U \leq 10$, if the sandy soil is displaced due to the upward flow of water.

Summary of the influence of the elements of the set Z' (11) on the effects of the buried water-pipe failure is given in Table. 4.

Summary and conclusions

The literature studies carried out as a part of this paper have shown that the failure of a water-pipe involving leaks is a very complex phenomenon, progressing over time, characterized by 19 independent or related parameters, sometimes varying in time or space. Among the 19 parameters there are two parameters related to the flow of water in the pipe, 15 parameters characterizing the soil or hydraulic conditions in the soil and 2 universal parameters (v and g).

It is practically impossible to take into account such a large number of factors during empirical research, but according to the Pareto principle, most of them can be ignored, leaving only the most important ones. Basing on the literature review, 11 parameters were excluded from the 19-parameter set, mainly because of functional relationships between parameters or parameter values close to 0. The

significance of four parameters of a 19-element set was confirmed by the literature data. The impact of the other four parameters on the time of water outflow onto the soil surface after a leakage from a water pipe was evaluated using the computer simulation tests. Ultimately, this allowed the selection of 4 out of 19 parameters which impact on the effects of the phenomenon under consideration turned out to be the largest—two parameters related to the flow of water in the pipe: a pressure head in the pipe H and a leak area A , as well as a saturated conductivity coefficient K_s characterizing hydraulic conditions in the soil and an uniformity coefficient U characterizing the soil. The impact of all these parameters on water leakage from a distribution pipe in the aspect of suffosion possibility is essential— H , A , and K_s are necessary to evaluate the hydraulic condition of suffosion, whereas U can be used to evaluate the geometric condition. The effects of water supply leaks related to suffosion are particularly dangerous in urban areas, threatening the environment and the stability of the existing infrastructure. Taking into account that leaks occur in all water distribution systems all over the world, during the whole period of their maintenance, the problem seems to be actual now and in future.

The literature review showed that the investigation of this kind, connected with selection of parameters that has a decisive impact on the results of water pipe leakage connected with the suffosion problem, has not been presented yet. The results of the theoretical analyzes presented in the article constitute the first stage of the characterization of the phenomenon of water outflow from the damaged water pipe to the soil, necessary to carry out empirical research. Taking into account the adequate number of factors affecting the phenomenon is a very important task. The consideration of too few parameters may cause the phenomenon characteristics to be unreliable. However, too many parameters can make tests impossible to carry out.

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Availability of data and material The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The author declares no conflict of interest.

Ethical approval Not applicable.

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