Periodica Polytechnica
Civil Engineering

61 (4), pp. 700–705, 2017
https://doi.org/10.3311/PPci.9728

RESEARCH ARTICLE

Suffosion Holes as the Results of a Breakage of a Buried Water Pipe

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Received 15 July 2016; Revised 05 December 2016; Accepted 19 December 2016

Abstract
The result of a breakage of a buried water pipe is the water movement in soil, which can cause that fine soil particles are washed out from the solid matrix and transported through pores (suffosion process). It is widely known that the most hazardous suffosion effects in urban areas relate to water-engineering structures. Holes, that can form on the soil surface by water outflowing after a failure of a buried pipeline (suffosion holes), are in different shapes and sizes. Recognition of factors influencing holes shapes and sizes would facilitate the prevention of hazardous suffosion effects connected with failures of water distribution systems. In the range of the presented article, the influence of selected parameters on the dimensions of suffosion holes was analyzed. The basis of the analysis was results of laboratory investigations of the controlled leakage from a buried water pipe. The vast majority of values of suffosion holes areas, selected according to area of leak and hydraulic pressure head in a pipe, occurred normally distributed. The tendency of average area of suffosion holes to be higher with rising pressure head in a pipe was clearly visible, but we were as yet unable to select one regression model fitting measured and calculated data better than others. Moreover, no tendency was observed between the biggest probable area of suffosion hole and pressure head in a pipe.

Keywords
suffosion holes, water pipe failure, water outflow

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1 Introduction

Depressions or holes creating on the soil surface as a result of suffosion can be very dangerous, especially in urban areas. It is widely known that the most hazardous phenomena of this kind relate to water-engineering structures [1,2,3]. It stems from the fact that failures and damages of pipes occur in water, sewage and storm water systems all over the world during their operation [4,5,6]. Even the high-tech methods of pipes condition assessment do not enable to prevent leakages occurrence, because of their random character and multiplicity of their reasons [7,8,9]. Still insufficient knowledge about them [10] is caused by many different, both static (pipe and soil parameters) and dynamic (hydraulic working conditions), factors [11,12,13,14,15]. Creation of suffosion holes is a phenomenon specially typical and onerous for water supply systems of a high intensity rate placed in internally unstable soils. The result of a breakage of a buried water pipe is the water movement in soil, which can cause that fine soil particles are washed out from the solid matrix and transported through pores (suffosion process) [16,17,18,19,20,21]. As a result, depressions or holes can form on the soil surface. Holes creating on the soil surface by water outflowing after a failure of a buried pipeline (suffosion holes), are in different shapes and sizes.

Recognition of factors influencing holes shapes and sizes would facilitate the prevention of hazardous suffosion effects connected with failures of water distribution systems. In the range of the presented article, the influence of pressure head in a water pipe on dimensions of suffosion holes was analysed. The basis of the analysis was results of laboratory investigations of the controlled leakage from a buried water pipe.

2 Material and methods

Investigations of water outflow on the soil surface after a buried water pipe failure were conducted on the laboratory setup reflecting natural condition scaled 1:10. The scheme of the laboratory setup is presented in figure 1. The laboratory setup consisted of an intentionally damaged water pipe (2) buried in medium sand filling a cuboid box (1). The pipe was supplied by water form a container (4) located on the assumed height. Internal water pressure head in the pipe (H) varied in the range: 3.0÷6.0 m H_2O, depending on the height of the container and the water level in it. The width of the leak between a spigot end and a socket end of the pipe equalled 15 mm for each experiment repetition, while the inner pipe diameter changed (20 mm, 32 mm, and 40 mm). Laboratory tests were conducted for 3 different leak areas ensuing due to loosening of the pipe connection: 9.42 cm^2, 15.07 cm^2 and 18.84 cm^2. Each experiment was repeated 7 times in the same conditions of pressure head and leak area in a pipe, according to standard procedures of statistical calculations of minimum number of samples (e.g. [22]). Details about the laboratory setup, parameters of sand filling the box and realization of the experiment are given in the article [23].

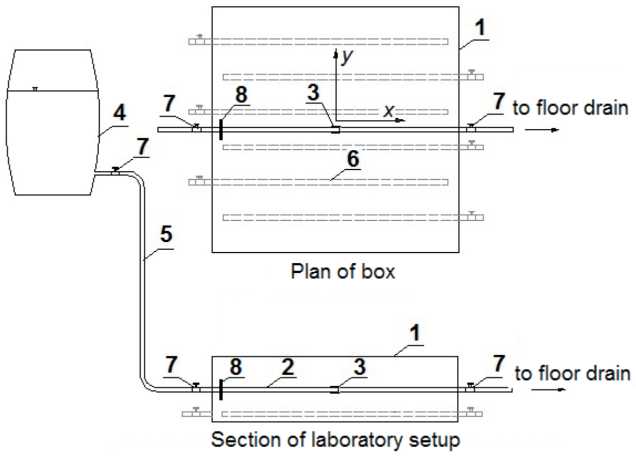

Fig. 1 Scheme of laboratory setup for physical simulation of water supply failure [23]: 1 – sand-filled cuboid box, 2 – water pipe, 3 – bell-and-spigot connection (place of leakage), 4 – container, 5 – hose, 6 – drainage system, 7 – valves, 8 – holder

During laboratory investigations, the shape and size of suffosion holes were determined. The average dimensions of suffosion holes created in the sand surface by water outflowing from a damaged buried pipe were measured in accordance to methodology presented in figure 2. Basing on dimensions measurements, holes were selected according to a shape. The holes area was determined using the AutoCAD software. Values of the hole area obtained in laboratory tests correspond to values for real conditions by multiplying by 100, according to geometrical similarity. The normality of the results distribution was verified with the Shapiro-Wilk test, at significance level $\alpha = 0.05$. Next, the representative values of suffosion holes areas were determined for individual cases of pressure head and leak area in a water pipe, taking a type of data set distribution into account. Relationships between the average suffosion holes area and pressure head in a pipe were estimated on the basis of the regression analysis, using exponential, linear, logarithmic and power models.

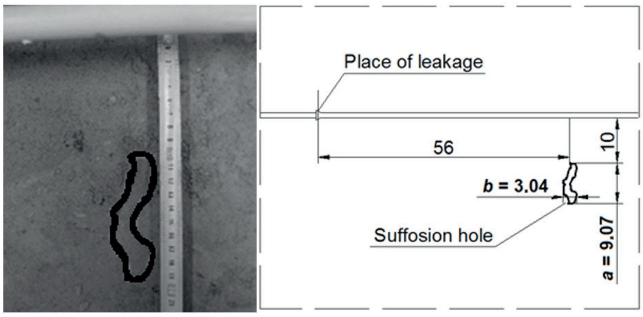

Fig. 2 Suffosion hole created on the sand surface by water outflowing from a damaged pipe

The next step in the analysis was evaluation of a biggest probable area of the suffosion hole for individual cases of pressure head and leak area in a damaged water pipe. To this end, 90% tolerance intervals were determined with the confidence level of 95% for suffosion holes areas data, considering a type of data set distribution. The possibility that the outflow on the soil surface would never occur, was assumed in the calculations. The effect of this assumption is that the lower tolerance limit always equals 0 independently of the calculations results and the upper tolerance limit corresponds to a biggest probable area of the suffosion hole. Relationships between the biggest probable suffosion holes area and pressure head in a damaged pipe were estimated as for average values of the area. All parameters needed in the investigations were calculated with Statistica 12 (StatSoft, Inc.) and MS Excel software.

3 Results and discussion

During the physical simulation of a water pipe failure, the creation of suffosion holes was observed. For a leak area A = 9.42 cm^2 there were 23 experiments with a single observed suffosion hole (23 holes together), 17 experiments with 2 holes observed (34 holes together), 6 experiments with 3 holes (18 holes together), 1 experiment with 4 holes and 2 experiments with 5 holes (10 holes together). Total number of created holes for a leak area A = 9.42 cm^2 was equal 89. Analogically, the amount of holes was calculated for other leak areas (A = 15.07 cm^2 – 91 holes, A= 18.84 cm^2 – 93 holes). Total number of suffosion holes equalled 273 (Fig. 3).

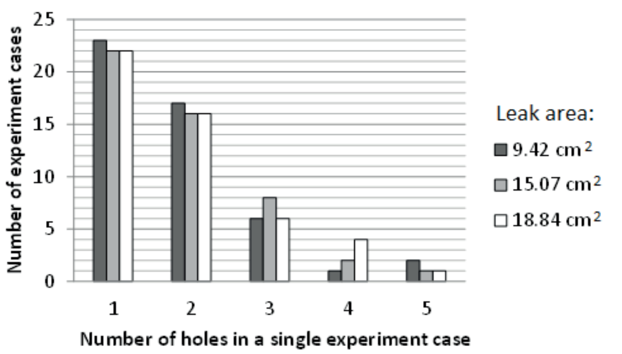

Fig. 3 Number of suffosion holes occurred during experiments

Maximal number of holes appearing on the soil surface in a single repetition of the experiment was 5. For each area of leak in a pipe, one hole was observed in a single experiment case the most frequently.

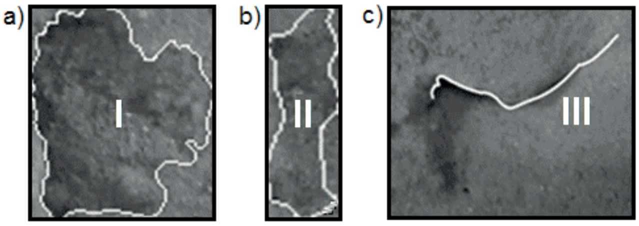

Fig. 4 Types of suffosion holes: a) type I, b) type II, c) type III

During investigations, 3 types of suffosion holes were singled out: I – compact holes, for which a length is smaller than triple width (Fig. 4a), II – elongated holes, for which a length equals at least triple width and the width is measurable (Fig. 4b), and III – cracks with the length as characteristic dimension and small width, difficult to determine (Fig. 4c). Percentage of the respective types in the obtained number of holes creating during experiments for each pressure head in the pipe as well as the total holes number, without selection, is given in Fig. 5 – 7. For all considered leak areas, for all but one case of pressure head in a water pipe ($A = 9.42$ cm^2, $H = 6.0$ m H_2O), prevalence of type II suffosion holes was observed. More than 50% of type II holes occurred for 3 cases of $A = 9.42$ cm^2, for all but one case of $A = 15.07$ cm^2 and for all cases of $A = 18.84$ cm^2. For the cases of $A = 15.07$ cm^2 and $H = 6.0$ m H_2O as well as $A = 18.84$ cm^2 and $H = 4.5$ m H_2O the suffosion hole of type II was the only which occurred on the soil surface. The highest percentage of the type I and type III holes were observed for the cases of $A = 9.42$ cm^2 and $H = 4.0$ m H_2O (38.89%) as well as $A = 9.42$ cm^2 and $H = 6.0$ m H_2O (90.91%), respectively.

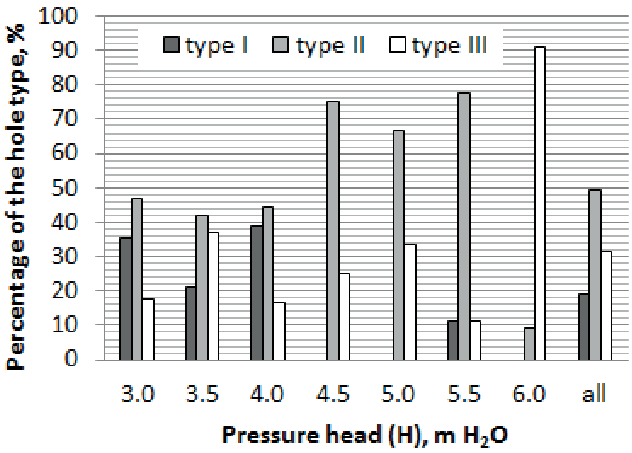

Fig. 5 Percentage of the I, II and III hole types for leak area of 9.42 cm^2

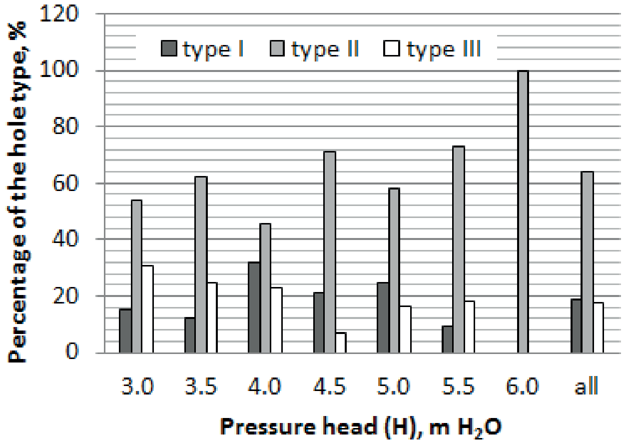

Fig. 6 Percentage of the I, II and III hole types for leak area of 15.07 cm^2

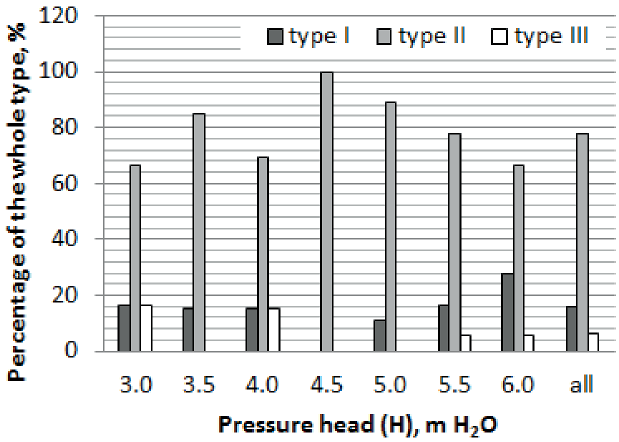

Fig. 7 Percentage of the I, II and III hole types for leak area of 18.84 cm^2

For the reason of clear dominance of the type II suffosion holes in our investigations, results of the consecutive analyses are presented for these holes type only. The next stage of the investigations was assessment of normality of distribution of data obtained as results of suffosion holes areas measurement. The conducted calculations indicated that only 2 of 21 data files, selected according to both leak area and hydraulic pressure head were not characterized by normal distribution (Tab. 1). For cases with normal data distribution, a mean was taken as an average value of the suffosion holes areas. A mean was also taken as an average value for the case of $A = 9.42$ cm^2 and $H = 3.0$ m H_2O, but it should be emphasized that a mean is not an efficient estimator for this case, because of irregular data distribution. Analyzing right-asymmetrical data distribution, a mode was treated as an average value for the case of $A = 15.07$ cm^2 and $H = 3.0$ m H_2O.

Table 1 Amount of data and type of data set distribution (N – normal, IR – irregular, R-AS – right-asymmetrical)

H (m H_2O) / A (cm^2)	3.0		3.5		4.0		4.5		5.0		5.5		6.0	
	Amount of data / type of data set distribution													
9.42	8	IR	8	N	8	N	9	N	7	N	7	N	10	N
15.07	7	R-AS	5	N	10	N	10	N	7	N	8	N	11	N
18.84	8	N	11	N	9	N	10	N	8	N	14	N	12	N

Average values of the type II suffosion holes areas are given in figure 8. The lowest suffosion hole area (A_s) was obtained for the case of A = 15.07 cm^2 and H = 3.0 m H_2O (0.92 cm^2), whereas the highest for A = 18.84 cm^2 and H = 6.0 m H_2O (8.85 cm^2). For all leak areas, the tendency of the area of suffosion holes to increase with rising pressure head in a water pipe was observed (Fig. 8) and confirmed by positive coefficients in regression equations (Tab. 2). For A = 9.42 cm^2, all analyzed regression models gave satisfactory or good fit of calculated and measured results – the lowest value of determination coefficient R^2 = 0.65 was obtained for linear regression model and the highest (R^2 = 0.84) for power model. For A = 15.07 cm^2, using exponential and linear models resulted in unsatisfactory fit of calculated and measured results ($0.5 < R^2 < 0.6$), whereas logarithmic and power lines fitted the data satisfactorily (R^2 = 0.73). For A = 18.84 cm^2, on the contrary, exponential and linear models gave satisfactory results ($R^2 > 0.6$), whereas logarithmic and power – unsatisfactory (R^2 = 0.55).

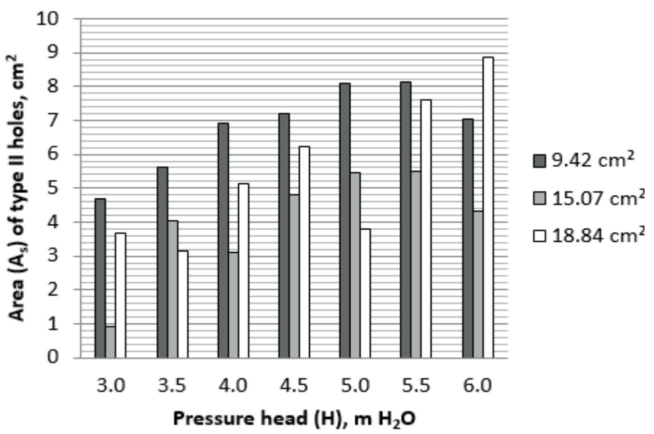

Fig. 8 Average value of type II holes areas

Table 2 Characteristics of regression models for average values of the type II holes areas

Regression model	A (cm^2)	Regression equation	R^2
Exponential	9.42	$A_s = 4.9521e^{0.0755H}$	0.6613
	15.07	$A_s = 1.5461e^{0.208H}$	0.5119
	18.84	$A_s = 2.8463e^{0.1472H}$	0.6472
Linear	9.42	$A_s = 0.4727H + 4.9186$	0.6545
	15.07	$A_s = 0.5532H + 1.8064$	0.5537
	18.84	$A_s = 0.8281H + 2.1714$	0.6803
Logarithmic	9.42	$A_s = 1.6672\ln(H) + 4.7791$	0.8181
	15.07	$A_s = 2.0054\ln(H) + 1.577$	0.7312
	18.84	$A_s = 2.3564\ln(H) + 2.6142$	0.5535
Power	9.42	$A_s = 4.826H^{0.2693}$	0.8445
	15.07	$A_s = 1.3668H^{0.7845}$	0.7315
	18.84	$A_s = 3.0409H^{0.4292}$	0.5529

A power regression model fitted calculated and measured data the best in cases of A = 9.42 cm^2 and A = 15.07 cm^2. Nevertheless, it can not be recommended to reflect dependence between area of suffosion hole and pressure head in a damaged water pipe at the current stage of investigation, because in the case of A = 18.84 cm^2 the model occurred unsatisfactory. Thus, selection of one fitting model independent of an area of leak in a pipe, requires further investigations, for higher number of leak areas.

Analyzing the areas of type II suffosion holes obtained in laboratory experiments it is possible to determine the biggest probable area of the hole, calculating tolerance intervals. Results of calculation of upper limits of 90% tolerance intervals at the 95% confidence level are given in figure 9. Calculated values denote areas covering at least 90% possible areas of type II suffosion holes, with the confidence level of 95%. No tendency was observed between the biggest probable area of the hole and pressure head in a water pipe for A = 9.42 cm^2. For the rest cases of leak area in a pipe, some tendency of the biggest probable area of suffosion holes to increase with rising pressure head in a water pipe was noticed, but the tendency was disappointing ($R^2 < 0.5$ for all analysed regression models) and not as clear as during analysis of average values of the suffosion holes areas. The highest value was obtained for the case of A = 9.42 cm^2 and H = 4.5 m H_2O (26.56 cm^2) and the lowest for A = 15.07 cm^2 and H = 3.0 m H_2O (2.82 cm^2). Considering methodology of tolerance intervals calculation, big discrepancy of the results as well as lack of the tendency can be caused by different dispersion and range of laboratory results for individual conditions of pressure head and leak area in a water pipe.

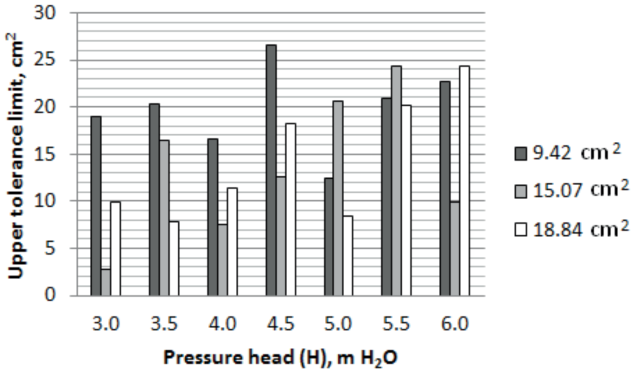

Fig. 9 Upper limits of tolerance intervals for areas of type II suffosion holes (cm^2)

4 Conclusions

During investigations, area of suffosion holes occurred on the soil surface after a failure of a buried water pipe in laboratory tests was analyzed. In one repetition of the experiment 1–5 holes of I, II or III type created on the surface. Taking into account all results of laboratory tests, the number of type II holes was distinctly the highest, so this type of the holes was the subject of the consecutive analysis.

The effects of the Shapiro-Wilk test calculations indicated that 19 of 21 data files, including values of the type II suffosion holes areas selected according to both leak area in a pipe and hydraulic pressure head during laboratory investigations were characterized by normal distribution. For these files, a mean was treated as a representative value of the suffosion hole area. The tendency of the average area of suffosion holes to increase with rising pressure head in a water pipe was observed for all cases of leak area in a pipe, but a regression line fitting calculated and measured data the best, was not of the same type for respective cases of leak area in a pipe. Apart from average values, the biggest probable area of the hole, which covered at least 90% possible areas of type II suffosion holes, with the confidence level of 95%, was determined. On the contrary to the average values, no clear tendency was occurred between the biggest probable area of the hole and pressure head in a pipe.

A large number of parameters influencing direction and velocity of soil particles movement during subsurface water flow as well as connections between these parameters cause that investigation of suffosion holes shape and size is a complex and difficult task. The results of the conducted analysis occurred promising, thus investigations of water network pipe breakages will be continued in the aspect of suffosion holes creation, concerning previous conclusions and including analysis of influence of parameters other than pressure head in a water pipe, on the process of suffosion holes forming. Moreover, it is highly recommended to verify the laboratory results by in-situ experiments in real conditions.

Acknowledgement

The project presented in this article was financed by statutory activity of the Faculty of Environmental Engineering, Lublin University of Technology.

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