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APPROACH TO ASSESSING THE CONSEQUENCES OF EMERGENCIES IN SEWER TUNNELS

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Abstract
The paper deals with the approach to assessing the consequences of emergencies in sewer tunnels based on multicriteria analysis. A detailed analysis was performed of tendencies of research interests and areas in the world concerning the issue of the reliability of sewer networks. The main causes of deterioration of sewer tunnels resulting in the occurrence of emergencies were identified. A classification was proposed of the factors of their deterioration according to the following groups: production factors; factors of durability of materials of linear portions of a network; organizational and technological factors; operational factors; factors of the external operating environment. The main groups of consequences caused by emergencies were classified; in particular, the following groups were identified: ecological, economic, technical, social, innovative. The method was proposed for determining ranks of consequences of an emergency by means of the corresponding scale of ranks developed by the authors and the system of their determination. The main criteria and the range of their values were determined according to which an assessment is given and a rank is determined according to the emergency.

Keywords: **Consequences; Corrosion; Demolition; Emergency; Sewer tunnel.**

1. INTRODUCTION

The evaluation of the technical condition and sustained operating environment of the public utility distribution sewer systems in Ukraine have recently become a matter of national significance. As shown by a comprehensive analysis of the occurrence of emergencies in the wastewater disposal networks, sewer tunnels, sewers and inspection shaft structures fail to function before their statutory service life. The research into the trouble-free operation of sewerage distribution networks clearly shows that approximately 80–90% of accidents are caused by structural deterioration due to biogenic corrosion. Chemical reactions occurring in the free space of a sewer network form an aggressive environment with respect to its structures.

The dynamics of occurence of emergencies at sewer facilities in Eastern Europe shows the following.

Over the last 5 years, the number of emergencies in the wastewater disposal networks, which were laid in the 80–90s of the last century, is almost 5 times higher than in 2014.

The most vulnerable to deterioration are reinforced concrete structures of sewer tunnels, sewers and inspection shafts. In recent years, many of the accidents have occurred in the wastewater disposal network with a diameter of more than 1500 mm. Sewer tunnel – a distribution network of wastewater, the diameter of which is more than 1500 mm. The ecological component of the operation of sewer tunnels and sewers should also be highlighted, as accidents and

failures result in obvious economic, environmental and social consequences, which is unacceptable in the context of Ukraine's European integration within the framework of the European environmental requirements and the Protocol on Water and Health of the United Nations (UN) and the Water Framework Directive of the European Union (EU). The economic component of ensuring the efficient operation of utility networks and wastewater disposal facilities is particularly acute in the conditions of limited financial resources of Ukrainian operating companies. Therefore, the matter of investigating into the consequences of emergencies in sewer tunnels is of topical interest.

2. LITERATURE DATA ANALYSIS AND ARTICULATION OF THE ISSUE

Recently, increasing attention has been paid to trouble-free operation and issues of increasing the operational life of building structures and wastewater disposal system structures, primarily by improving their performance data. Researchers focus on the issues concerning the probable prediction of pipeline operational failure and the investigation of the consequences of an emergency in sewer tunnels; to achieve this, typically, a deterministic method of life factor is used, the basis of which is the assessment of factors that reduce the reliability of sewer facilities [1, 2]. In the works [1–3], when studying the factors affecting the operational life of distribution networks and technical and economic performance of carrying out of works, particular attention was paid to the protection of reinforced concrete sewers from the effects of corrosion processes; however, it is reasonable to investigate into the specificity of the behavior of corrosion processes in the structures of distribution wastewater disposal networks, which will make it possible to predictly arrange a set of organizational and technological measures to extend the life time of sewer tunnels and sewers and mitigate the consequences of an emergency. The research [3] deals with the protection of reinforced concrete sewers from the effects of corrosion processes. The analysis of the issue of biogenic corrosion as a major factor in the deterioration shows that the process of studying biogenic corrosion occurs through theoretical [4] and experimental studies [5]. Generally, experimental studies are performed by immersing the samples in an aggressive environment (full-scale or laboratory) to further identify the characteristics of the pipeline material [6]. Foreign scientists are constantly improving methods of trenchless rehabilitation of pipes in order to improve their efficiency. The work [7] describes the improvement of the ecological component of the use of trenchless technologies and clarifies the ecological component of the use of trenchless technologies; however, according to the authors, this is not enough: emergencies in sewer tunnels and sewers are similar to an ecological catastrophe, so it is reasonable to study this issue within the Environmental Policy of the European Union and the European Environmental Requirements. Studies on the operational reliability of pipelines indicate that as of today, preference is given to trenchless (NO-DIG) rehabilitation technologies [8], which are more cost-effective than traditional (involving earthwork). The work [9] deals with pipe spot repair by means of Quick Lock polymeric mechanical sleeves, thus ensuring reliable operation and minimizing the consequences of emergencies. Much attention is paid to modeling the processes of repair and operation of pipelines; in the work [10], a model of failure of sustained operation of distribution networks was proposed for its further prediction. Despite the described improvements, the implementation of most of these advanced NO-DIG technologies for the operating companies in Ukraine is inaccessible owing to their high cost. All the abovementioned products, analogues and prototypes have their own specificities for the foreign conditions of carrying out rehabilitation works in the adequate funding conditions. Complex studies into the service life of sewer networks of different diameters were presented and comprehensively studied by scientists [11–19]. In the studies [11–13] of the life cycle of sewer networks, particular attention was paid to a comprehensive approach for its assessment, but it would be reasonable to approach each individual case on a more individual basis, taking into account the results of continuous monitoring of operation reliability and the corresponding consequences of damage.

The literature data analysis shows that as of today, there is a constant search for solutions to the issue of increasing the operational life of sewer tunnels, sewers and engineering structures. However, the introduction of innovative technologies for the rehabilitation of sewer networks usually occurs when there is the very fact of an accident. This contradicts the basic provisions of Ukraine's water policy. The main focus of Ukraine's water policy is to ensure water security for sustaining human life and a healthy environment. According to the United Nations official regulations, water security under the conditions of peace and

political stability is a state's ability to maintain sustained access to sufficient quantities of acceptable quality water for the purposes of: provision of means of subsistence, human well-being and socio-economic development; preservation of aquatic ecosystems and the environment.

The operation reliability of sewer tunnels and sewers is an integral part of ensuring water safety for humans in all EU countries and states governed by the Association Agreement [14]. The main obligation under the Protocol on Water and Health with the implementation of Directive 91/271/EC dated 21 May 1991 on urban wastewater treatment involves the solution to issues of ensuring sanitary well-being through the sustained functioning of wastewater disposal and wastewater treatment facilities in all settlements and industrial sites, and ensuring the safe operation of sewer system facilities. The Directive also sets high standards for the treatment of wastewater and trouble-free operation with reference of significant consequences [14].

To solve the issue of accident-free operation of sewer tunnels and facilities and introduce repair techniques before the occurrence of an emergency, it is necessary to have a clear idea of the consequences after its occurrence in different directions of life support. This issue is important and has not been properly investigated to date.

3. THE PURPOSE AND OBJECTVES OF THE RESEARCH

The purpose of this work is to propose an approach to assess the effects of accidents in sewer tunnels.

To achieve the purpose of the research, the following objectives were defined:

- to identify the main causes of deterioration of sewer tunnels provoking the occurrence of emergencies;
- to identify the consequences of emergencies in sewer tunnels;
- to propose a comprehensive approach to assess the consequences of occurrence of emergencies in sewer tunnels using a rank scale that provides information on the extent of the consequences according to the rank of the emergency in each individual case.

4. APPROACH TO DETERMINING THE CONSEQUENCES OF EMERGENCIES IN SEWER TUNNELS

The main methods of conducting the paper are as follows: imperial research methods; analysis and synthesis of statistical data; classification and clustering; expert assessment method; elements of the multicriteria analysis method. A method of comparative analysis of existing regulatory documents on the issue of assessing the consequences and supplementing their generalization by the example of the operation of sewer tunnels.

The existing regulatory documents include issues of determining the class of facility. For building structures of various purposes, including sewer tunnels and sewers, it is mandatory to determine the importance class of the facility, which shows the extent of the consequences of its failure. The term "failure" means the condition of a facility under which it cannot be used for functional purposes [11].

According to the regulatory documents, the consequence class for the construction facility is determined independently by the specific characteristics of the possible consequences of the failure of the facility:

- potential hazard to the health and life of people who are permanently at the facility;
- potential hazard to the health and life of people who are periodically at the facility;
- potential hazard to the life of people outside the facility;
- the amount of potential economic loss;
- possibility of losing cultural heritage sites;
- possibility of discontinuation of tranport and utility infrastructure.

The consequence class is determined for each linear tranport and utility infrastructural facility on an individual basis. According to the provisions, the importance class of a construction facility is determined by the highest characteristic of the possible consequences resulting from the calculations [11].

The characteristics of the possible consequences of failure of a facility are the basis for the classification of facilities, including sewer tunnels, into three consequence (importance) classes:

- minor consequences (CC1);
- medium consequences (CC2);
- significant consequences (CC3).

Sewer tunnels and facilities have a CC3 consequence

class, as their failure in operation is of national importance. The characteristics specified in the regulatory document are general and obligatory for the facilities and do not depend on their functional purpose. This fact indicates that for sewer facilities, the determination of the consequences of the failure requires the use of not only the characteristics specified in the standard, but also additional definitions and rankings.

5. CLASSIFICATION OF THE CONSEQUENCES OF EMERGENCIES OCCURRENCE IN SEWER TUNNELS

Comprehensive studies of the main causes of the disruption of the sustained operation of sewer tunnels clearly show that the main cause of their deterioration is corrosion processes [11–13] resulting in the presence of air holes, cracks, fractures in the sewerage distribution networks. The cause of corrosion is the thermodynamic instability of structural materials to the effects of substances being in contact with their environment. Furthermore, trouble-free operation of a sewer tunnel is often complicated by defects arising from the construction and non-observance of technological regulations for the use of the public sewer system, which leads to emergencies, complete or partial cessation of the sewage liquor movement through the pipelines and its penetration into the ground surface or in groundwater [15–17].

The authors of the work investigated (based on the analysis of literature sources [14, 15]) into the main causes of deterioration of sewer tunnels that cause emergencies, and classified them into the following groups: production factors; factors of durability of materials of linear portions of a network; organizational and technological factors; operational factors; factors of the external operating environment.

The production factors of the deterioration of sewer tunnels are primarily due to the process of production of pipes and fittings such as:

– variations in the thickness of the wall due to the displacement of the cast core, shrink shells of various types and sizes;
– typical defects (incorrect mounting accessories, laying pipes on an unprepared base, backfilling with soil, poor-quality butt joints, etc.) arising from the manufacture of pipes made of polymeric materials;
– deterioration of corrosion resistance and mechanical properties of pipes due to the use of low quality material;
– insufficient corrosion protection;
– unadequate pipe joint designs.

During the operation of sewer tunnels, the process of technical aging of materials and structures leads to their deterioration; therefore, the factors of durability of materials of the linear portion of the network are as follows: corrosion of pipe material and joints due to corrosive media; fatigue and fragility of artificial materials; decay of organic materials; weakening of the stabilizing force of rubber seals.

When laying and installing a sewer tunnel, the technological process of construction may be not observed, which in the course of operation leads to a decrease in its operational life. Therefore, the main organizational and technological factors that influence the process of deterioration of sewer tunnels are identified as follows:

– general violations of technological regulations for pipe installation;
– implementation of butt joints of pipes with technology breaches;
– errors during pipe assembly and transportation;
– insufficient corrosion protection of the pipeline inside and outside;
– errors in pipe laying and grounding.

During the operation of sewer tunnels, their working conditions are influenced by their operating conditions, both from the standpoint of the centralized wastewater disposal system (operating factors) and from the standpoint of operating conditions. Therefore, the operational factors are as follows:

– Servie life of the pipeline;
– Change in the volume of wastewater. Fluid pressure drops in the pipeline;
– Corrosion of pipe material and joints due to the effects of microorganisms;
– Corrosion of pipe material and joints due to the effects of wandering currents;
– Insufficient prevention of pressure drop, for example, lack of compensating units;
– Insufficient ventilation and/or too rapid filling, for example, restoration after preventive or repair work;
– Poor water preparation for pipeline materials caused by unauthorized emissions, for example, lack of equilibrium in carbon lime content (increased corrosion of metal or dam water with low carbon content aggressive for cement);
– Too high flow rate (loss of corrosion resistance of

Table 1.
Group of ecological consequences of emergency occurrence in a sewer tunnel

Sphere of impact	Nature of impact	Consequences
Atmosphere	Release of hydrogen sulfide, mercaptan, sulfur dioxide, carbon dioxide, methane and the like	Intense man-caused environmental load, which is a source of significant environmental hazards for urban areas, especially if the exceedance of maximum allowable concentrations for substances of hydrogen sulfide, mercaptan, sulfur dioxide, carbon dioxide, methane and the like [15]
Hydrosphere	Penetration into groundwater	Changing the chemical composition of water and the appearance of other undesirable components that threatens environmental safety
	Penetration into surface water of sources	Dangerous increase of concentrations of substances and pollution of the main sources of water supply
Lithosphere	Flooding of territories and disturbance of water exchange	Increase in the level of groundwater and their aggressivity as a result of feces water contamination causes the impact on existing karst voids, which leads to the formation of karst holes, which threate ns facilities, the deterioration of the body of foundations, corrosion of reinforcement and concrete; deterioration of soil mechanical properties (shear resistance decreases)
	Soil degradation	Deterioration of soil beneficial properties and fertility due to the allocation of hydrogen sulfide which is highly toxic
	Suppression of plant complex	Reduced seed germination, slow growth of plants, abnormal development of root systems, chlorosis, withering, plant death
	Contamination of the topsoil with heavy metals	Toxic, even in minimal amounts, heavy metals are not susceptible to decomposition processes, but are only able to be redistributed between natural environments; therefore, they are concentrated in living organisms, causing different pathologies.

Table 2.
Group of economic consequences of an emergency occurrence in a sewer tunnel

Sphere of impact	Nature of impact	Consequences
Macroenvironment of the operating company	The need to allocate additional funds from the budget for carrying out work	Destabilization of the financial environment of the local budget
Microenvironment of the operating company	The need to eliminate the emergency	Allocation of funds for temporary stoppage of wastewater disposal, local elimination of consequences of an emergency
	The need for temporary provision of uninterrupted operation of the wastewater disposal distribution system	Allocation of funds for the installation of a wastewater bypass line, pumping equipment, etc.
	The need to overhaul a worn-out sewer tunnel or build a new one	Allocation of funds for the development and approval of the complete set of design, budget and as-built documentation; carrying out construction works for the rehabilitation of an existing or construction of a new sewer tunnel

material, cavitation of the shape, deformation of the pipe surface);

– Damages due to emergencies of sewerage supply networks, at pumping stations.
– The factors of the external operating environment include:
– Swelling and shrinkage of soil due to natural conditions;
– Increased transport load;
– Damage due to emergency situations on adjacent networks.

Appearance of long sedimentary seams on the slopes of the mountains, in the areas of slopes, on the banks of rivers with a strong flow of groundwater and in places with frequent changes in the level of groundwater.

The impact of each of the above factors, to one extent or another, may not lead to the complete deterioration of the sewer tunnel within the given time frame. However, the combined impact of several factors in each group results in irreversible consequences for both the operating company and the community.

After analyzing the decrease in the operational life of sewer tunnels, the main groups of consequences caused by emergencies are classified by the authors, in particular the following groups are identified: ecological; economic; technical; social; innovative.

Table 3.
Findings of the survey of experts in the field of sewer system

Item	Criterion	Expert						Score
		1	2	3	4	5	6	
C1	Technical characteristics of the emergency section	5	5	6	6	6	5	33
C2	Impact aureole of the sewer tunnel on the environment	4	3	3	3	3	4	20
C3	Population coverage	2	1	2	2	1	1	9
C4	Extent of damage or deterioration and maintenance of temporary (or permanent) wastewater disposal system	3	4	4	4	4	3	22
C5	Cost of complete elimination of consequences	1	2	1	1	2	2	9
C6	Organizational and technological measures of restoration of sustained operation of the sewer tunnel	6	6	5	5	5	6	33

The group of ecological consequence includes the effects on the atmosphere, lithosphere, and hydrosphere (Table 1). The group of economic consequences covers the macroenvironment and the microenvironment of the operating company (Table 2).

The group of technical consequences of emergency occurrence in a sewer tunnel includes the following: violation of stability of functioning of the wastewater disposal system; stopping continuous operation of wastewater disposal process; search for alternative wastewater disposal solutions; additional load on redundant lines and pumping equipment.

A significant impact on the population is due to the inconveniences caused by the disruption of the centralized wastewater disposal system. The social group of consequences of occurrence of an emergency in a sewer tunnel includes: deterioration of a state of health of people as a result of influence of poisonous gases in air; disruption of the life support system [14] due to the interruption of the centralized water supply and wastewater disposal systems; inconvenience due to the temporary wastewater disposal process; high probability of occurrence of foci of infectious diseases; danger to the population due to ground collapses and damage to the road surface; violation of the normal functioning of the city transport system; aesthetic inconvenience for the population.

However, the occurrence of an emergency in a sewer tunnel provokes an innovative group of consequences, which involves searching for innovative solutions to minimize losses. The innovative group includes: development of alternative solutions for centralized wastewater disposal; development of innovative organizational and technological solutions for rehabilitation of distribution networks; modernization of emergency sections of sewer tunnels; use of modern materials with anticorrosive properties; conducting research on the sustained operation of the wastewater disposal system; implementation of a system for monitoring the sustained operation of sewer tunnels.

6. MULTI-CRITERIA ANALYSIS RESULTS OF THE CONSEQUENCES OF EMERGENCIES IN SEWER TUNNELS

Based on studies of operational practices and statistics on the occurrence of emergencies, the authors have identified six criteria by which one can assess the consequences of the occurrence of emergencies in a sewer tunnel (C1-C6). Using the method of expert evaluation by experts in the field of sewer system (representatives of urban operating enterprises “Kievvodokanal”, “Kharkovvodokanal”), the criteria are ranked in the order of increasing or decreasing depending on the level of impact of the criterion on the consequences of an emergency [20]. When determining the level of impact, the expert gave an assessment (from 1 to 6) to each of the criteria in the order that they deem to be the most rational, particularly: when assigning a score of 1, the criterion receives the highest level of significance, and a score of 6 means the lowest one. Therefore, the order scale resulting from the ranking should meet the condition of equality of the number of ranks “6” to the number of the ranking factors “n” [20]. The obtained expert data are summarized in the table of ranks (Table 3).

As a result of the analysis of the table of standardized ranks and the calculations performed, a Multiple Rank Correlation Coefficient equal to 0.917 was obtained, which indicates a high degree of concordance of opinions in the selected expert group [20].

The criteria for population coverage and cost of complete elimination of consequences of an emergency are the most important parameters in assessing the consequences of an emergency in sewer tunnels. The technical and technological criteria (C1, C6) have less impact on the consequences, but they are directly affected by the cost of elimination of an emergency on the whole. According to the performed research, the authors proposed a scale of ranks of consequences of the occurrence of an emergency in a sewer

Table 4.
Determining the rank of the consequences of occurrence of an emergency in a sewer tunel

Criterion	Parameter value according to the rank of consequences		
	I	II	III
Technical characteristics of the emergency section (C1)*: diameter of the tunnel, mm depth, m damage area, rm	1500 to 2000 Up to 5 Up to 5	2000 to 2500 5 to 12 5 to 15	Over 2500 Over 12 Over 15
Impact aureole of the sewer tunnel on the environment (C2)	Up to 50 m, no pollution of water resources	50 to 150 m, no pollution of water resources	over 150 m, there is pollution of water resources
Population coverage (C3), thous. people	up to 5	5 to 25	over 25
Extent of damage or deterioration and maintenance of temporary (or permanent) wastewater disposal system (C4)	Switching over to the redundant wastewater disposal line	Arrangement of a temporary wastewater disposal system by means of pumps and temporary ground wastewater disposal lines	Inability to arrange a temporary wastewater disposal system and shutdown of water supply
Cost of complete elimination of consequences (C5), thous. of € (in equivalent to the national currency in Ukraine)	Up to 20	20 to 40	Over 40
Organizational and technological measures of restoration of sustained operation of the sewer tunnel (C6)	Typical measures to restore the operation of a sewer tunnel	Organizational and technological measures of increased complexity	Innovative measures for the complete reconstruction of the existing tunnel and facilities or construction of new ones
*When determining the criterion rank under different values, the highest value is taken			

tunnel and an appropriate system for determining the rank. With reference to the criteria of C1-C6 the range of their values is determined, according to which an assessment is given following to the emergency situation, particularly:

– Technical characteristics of an emergency section of the sewer tunnel (diameters of the tunnel are of 1500 to 2000 mm, 2000 to 2500 mm, more than 2500 mm; depths are up to 5 m, 5 to 12 m, more than 12 m; damage areas are up to 5 m, 5 to 12 m, more than 12 m – the ranges of values are based on documents and regulations that are based on operating experience [14]);
– Impact aureole on the environment;
– Population coverage (up to 5 thousand people, 5 to 15 thousand people, more than 15 thousand people – the ranges of values are based on documents and regulations that are based on operating experience [14]);
– Extent of cost for eliminating the damage or deterioration and ensuring the functioning of a temporary (or permanent) wastewater disposal system;
– Cost of complete elimination of consequences.

The emergency situation is understood to be an accident in a sewer that has emerged or may result according to the results of the survey for reliability and stability of operation.

Table 4 shows the procedure for determining the rank of the consequences of an emergency in a sewer tunnel.

Table 4 describes the procedure for determining the rank of the consequences of occurrence of an emergency in a sewer tunnel for each individual emergency that occurred in a sewer tunnel and facility. It should be noted that subject to different rank values according to the definition criteria, the mean value is calculated and a higher value is selected.

7. CONCLUSIONS

In order to determine the necessary rank of the consequences of an emergency in a sewer tunnel, it is necessary to have the result of a comprehensive study of each individual section or facility. Conventionally, after the diagnostics of the functioning of the selected section of the sewer tunnel in Kharkiv, Ukraine [14], the following parameters are obtained: the diameter of the tunnel is 2000 mm; the tunnel is laid at a depth of 7 meters; the length of the technically worn section is 8 running meters (rm); at a distance of 150 rm it does not have any surface water

resources; the protection zone of operation does not exceed 150 rm; the area of influence of the sewer tunnel covers more than 50 thousand inhabitants of the city; due to the dense development of the city, provided the tunnel is damaged, it is almost impossible to arrange a temporary wastewater disposal solution; in case of damage to the sewer tunnel, non-conventional repair methods should be used as a result of the lack of possibility of cessation of wastewater runoff, dense development and structural characteristics. Therefore, according to Table 4, rank II of consequences is chosen based on two criteria; rank III of consequences is chosen basce on three criteria. In this case, subject to different rank values according to the definition criteria, the mean value is calculated and a higher value is selected relative to the factor that has more influence (according to experts indicated in Table 3). Figure 1 shows a graphical representation of the methodology for determining the rank of the consequences of an emergency in a sewer tunnel.

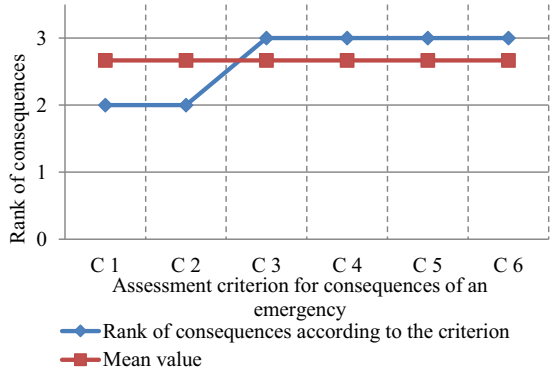

Figure 1.
Determining the rank of the consequences of occurrence of an emergency in a sewer tunnel

An important issue for operating companies is to evaluate the probable consequences of an emergency occurring in a sewer tunnel, or when planning measures to be taken upon occurrence of an emergency. When planning major and scheduled repairs and selecting priority sections for rehabilitation work, it is important to justify the cost of repairs. The approach to assessing proposed by the authors is a significant tool in the system of monitoring the sustained operation of sewer tunnels and facilities. On the basis of certain definite consequences, it is possible to build a program of reconstruction of sewer tunnels and facilities for the future.In the course of the a multicriteria analysis into the consequences of occurrence of emergencies in sewer tunnels, a number of scientifically justified findings were obtained, specifically:

– The main causes of deterioration of sewer tunnels resulting in the occurrence of emergencies were determined and the classification of the factors of their deterioration was elaborated according to the following groups: production factors; factors of durability of materials of linear portions of a network; organizational and technological factors; operational factors; factors of the external operating environment;
– The consequences of emergencies in sewer tunnels on the person, the operating company and the environment were identify;
– An approach to assessing was proposed for determining the consequences of emergencies in sewer tunnels using a rank scale that provides information on the extent of the consequences according to the rank of the emergency in each individual case.

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