Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2020.55.2349

UDC 621.79101.670

Experimental studies of long-term fatigue of steel sewer structures

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The results show that the experimental studies of long-term fatigue (strength) of steel structures of underground sewage structures in a chemically aggressive environment, simultaneously containing chemical ingredients and biologically aggressive bacteria. It is established that long-term fatigue (strength) of steel structures of underground sewage structures is significantly reduced during long-term operation, and especially when exceeding 20 years or more, in chemically aggressive environments of domestic sewage, which often leads to corrosion and mechanical damage. It is shown that in the course of long service life the indicators of long-term fatigue of reinforcing steel rods of reinforced concrete structures are significantly reduced, which causes the formation of cracks in the connection "reinforcement - concrete", which usually leads to the destruction of reinforced concrete pipes and structures as a whole.

Keywords: underground sewerage structure, steel structure, chemically aggressive environment, crack resistance, deformation, fluidity, tensile strength, viscosity.

Експериментальні дослідження тривалої втомленості сталевих каналізаційних конструкцій

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Наведено результати експериментальних досліджень тривалої втомленості (міцності) сталевих конструкцій каналізаційних підземних споруд у хімічно-агресивному середовищі, які одночасно містять хімічні інгредієнти та біологічно-агресивні бактерії. В лабораторних випробуваннях використано арматурні стрижні діаметром 32 мм зі сталі марки 20ГС. Отримано нові емпіричні залежності між концентрацією гетеротрофних бактерій (ГТБ) у розчині та спротивом втомленості сталевих зразків, вирізаних із арматури залізобетонних конструкцій каналізаційних споруд, при їх циклічних випробуваннях на згин і кручення. Для порівняння аналогічні дослідження виконано для умов розчинів хлористого натрію. Встановлено, що тривала втомленість (міцність) сталевих конструкцій каналізаційних підземних споруд значно зменшується при тривалій експлуатації, а особливо при перевищенні терміну 20 років і більше, в хімічно-агресивних середовищах побутово-господарських стоків, що призводить часто до корозійно-механічних руйнувань. Доведено, що в процесі тривалого терміну експлуатації суттєво знижуються показники тривалої втоми арматурних сталевих стрижнів залізобетонних конструкцій, що спричиняє утворення тріщин в з'єднанні «арматура – бетон», яке, як правило, призводить до руйнувань залізобетонних труб і конструкцій в цілому. Отримані результати пояснено тим, що в процесі тривалої експлуатації каналізаційного устаткування відбувається окрихчення та деградація металу.

Ключові слова: каналізаційна підземна споруда, сталева конструкція, хімічно-агресивне середовище, тріщиностійкість, деформація, текучість, межа міцності, в'язкість

Introduction

When constructing sewer systems, steel profile rolled products (pipes, T-shaped and I-beams, angles, etc.) are often used as the main type of structures [1].

In Ukraine, their share is about 90% [2, 3] and in the near future, this percentage will not change significantly, due to increasing service life of such structures sharply increases the wear of steel structures and corrosion damage of reinforcement in reinforced concrete structures, and therefore only pliable steel structures will be able to provide in most cases a satisfactory operational condition of underground sewage engineering structures [2]. The almost unique ability of these structures is to adapt to changing loads and therefore the force and temperature factors, without collapsing, allows us to consider them as the safest [3].

Review of the research sources and publications

Significantly reduces the efficiency of steel reinforced concrete structures and constructions, their corrosion ability, in particular reinforcing bars [2-9].

Corrosion aggressiveness of sewage effluents is caused by the presence of chlorine ions, sulfuric acid anions, magnesium and calcium ions, anions of chloride salts and acids. In particular, in the sewerage systems of Kyiv, Chernihiv, Odesa, Kharkiv in domestic and industrial effluents there are (mg·dm^3/eq) Cl^- 1200-2100; SO_4^{2-} 15-25; $Mg^{2+}+Ca^{2+}$ 120-300; HCO^{3-}10-25. Moreover, the coefficient of corrosion is on average 10-16, and the aggressiveness of the metal is $SO_4^{2-}+Cl^- > 3$ g/l.

Corrosion (destruction of metal) is the result of the interaction of the environment with metals. From the point of view of the mechanism of the corrosion process, corrosion happens chemical, electrochemical, and biochemical. Under industrial conditions, sewage structures can often be biological corrosion with a gradual transition to the electrochemical type of corrosion.

Definition of unsolved aspects of the problem

Analysis of literature sources [10 – 12] shows that to date there is no information on long-term fatigue (strength) of steel pipe structures, especially reinforcing rods of reinforced concrete sewers during a long life in aggressive chemically active environments, which simultaneously contains chemical ingredients and biologically aggressive bacterias.

Problem statement

The purpose of the work is to establish quantitative dependencies to reduce long-term fatigue (strength) of steel structures of underground sewers under the conditions of their operation in chemically aggressive environments of domestic and industrial effluents.

Material and methods of research

Samples for experimental tests for prolonged fatigue (strength) are shown in Fig.1. All samples were made of steel structures directly on the objects of sewage underground structures.

a)

b)

c)

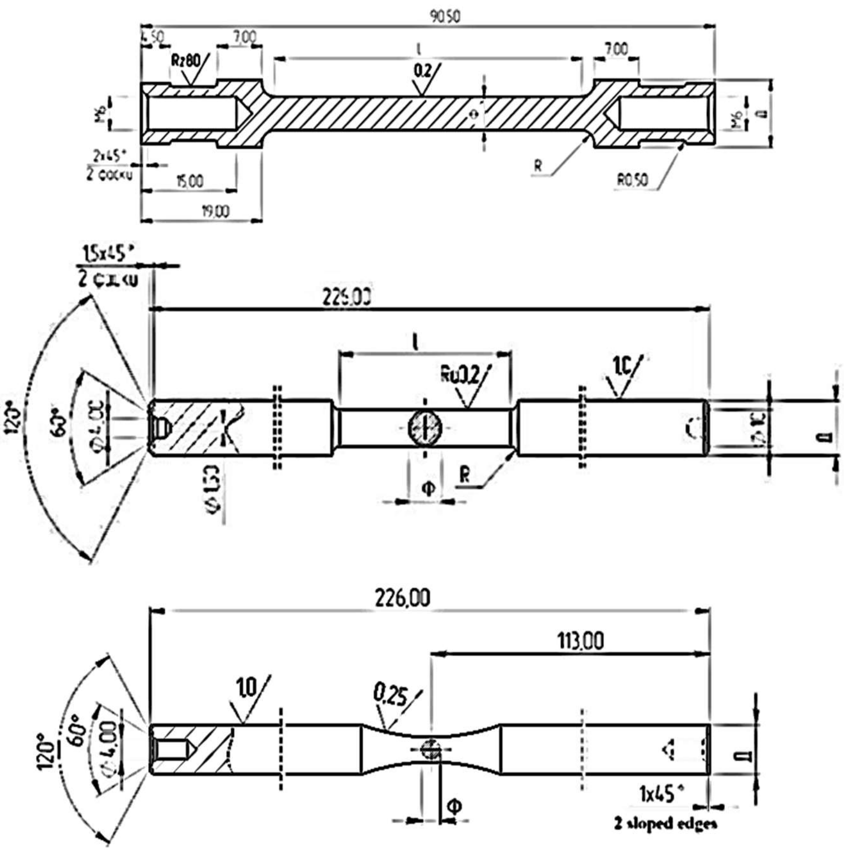

Figure 1 – Samples for fatigue (long-term) strength tests:
a – sample for torsion tests; b – sample for tests under axial loading;
c – a sample for bending tests during rotation

For the research were used carbon-low-alloy steel grade 08G2S with 0.07-0.092% C with the following characteristics: σ_B = 470-560 MPa; $\sigma_{0.2}$ = 315 MPa ($\sigma_{0.2min}$ = 245 MPa) for ambient temperatures -20…-40^{0}C. The carbon equivalent was CE = 0.21-0.32; KCV = 28 J (equivalent to FISI 1035 steel) [1, 7].

After normalization with heating to 860 ^{o}C and holding for 30 min from such steels made samples, which are shown in Fig.1. The samples were polished with a sanding skin with a grain size of 3/0, and then subjected to tempering in a vacuum chamber at 620 °C for 30 min to relieve residual stresses.

Experimental tests for corrosion fatigue (long-term strength) were performed under different types of loads.

The samples were tested on the setpoint of the Instron model (Great Britain). In particular, the tests were performed on a bend with zero average voltage and a cycle frequency of 20 Hz. The tests were performed in salt solutions with concentrations from 0.5% to 10%. To compare the results, tests were sometimes performed in the air.

Bacteria of the species of heterotrophic bacteria (GTB) were introduced into the water in the following quantities (in cells / ml):
$6.2\cdot10^6 - 2.2\cdot107$ - $3.1\cdot!0^8 - 25\cdot10^8$ - $1.5\cdot10^9$;
and bacteria such as sulfate-reducing (CBD) in the amount (in cells/ml):
$1.0\cdot10^2 - 1.5\cdot10^2 - 1.5\cdot10^3 - 2.5\cdot10^4 - 1.5\cdot10^5 - 2.0\cdot10^6$.

It should be noted that the samples made of industrial steels according to the requirements (Fig. 1) were the day before completely immersed in aqueous saline or bacterial solution circulating at a rate of 2.5 l / min between the test chamber (with a capacity of 1 l) and the reservoir, and kept for 720 h according to the requirements of the Specification of the International Corrosion Association (Specification TenquizOil and Gas Plant // ProzessPlant-Lurgi code: 65102-00-MAL-TENGUIZ II.Specification №.SPC-62900-XP-007) [1, 7, 12].

The volume of solution used for the experiments was 10 l, and after each test, the solution was replaced with a new one. The temperature of the solution during the tests was kept at 22 ^{o}C thanks to an electric automatic regulator. The dissolved oxygen content was not controlled.

During the operation of sewage systems, reinforced concrete gallery walls are in direct contact with moisture, in particular, chemically active waters and the surrounding atmosphere.

As a result, steel tubular and reinforced concrete structures (in particular, reinforcing bars) are subject to various types of corrosion, among which are atmospheric, underwater, underground, hydrogen, oxygen, gas and sulfuric acid, chloride, and microbiological (bacterial).

According to surveys and practice, corrosion processes of several types can occur simultaneously in sewer structures, in particular:

1. Atmospheric corrosion is particularly intense when the air temperature reaches 40 ^{o}C, the airflow is characterized by a significant air flow rate and relative humidity, often equal to 100%.

2. Underwater corrosion is the destruction of metal immersed in water. Under the water are the elements of the foundation attachments, which are adjacent to the drainage ditches and submerged products, the system of reservoirs, pipelines, etc. The presence of impurities of salts and acids in the water accelerates the process.

3. Underground corrosion occurs when reinforced concrete is exposed to underwater biologically aggressive environments and mineral particles. Hydrogen and gas types of corrosion are characteristic of metal structures in sewer structures.

In underground sewer conditions, metal corrosion is also classified by the nature of the destruction. Uneven corrosion is the most dangerous.

It is necessary to pay attention to the role of rolled scale and rust in processes of corrosion of metal designs, especially reinforcing cores of reinforced concrete designs in sewer conditions of long service life.

It is known that rust, in contrast to scale, occurs in the presence of moisture when t <100 °C, and therefore consists mainly of hydrated iron oxides. In general, the chemical composition of rust is expressed by the formula [12 – 15]: $(FeO)_n \bullet (Fe_2O_3)_m \bullet (H_2O)_k$.

Dissolved salts of iron and other cations are usually found in the rust layer. Due to the loose structure on the surface of the rust, moisture is retained for a longer time, which appears as a result of groundwater drainage, and therefore the corrosion rate increases.

As a result of the aggressive influence of underground sewer conditions, getting on separate parts of metal designs, water accumulates, forming stagnant zones (sites) that lead to their fast corrosion.

It is practically established those thin membranes of a liquid act more actively and aggressively, and therefore when narrow hair gaps are observed between metal parts. Then the corrosion processes are more intense.

The corrosion rate in hydraulic and sewage conditions is also affected by the temporary (carbonate) hardness of natural waters. Iron is corroded faster in soft water. Hard waters tend to precipitate insoluble salts, such as $CaCO_3$ (especially in cathode regions), which prevents the diffusion of oxygen to the metal. [4 – 6, 13].

At the same time, easily soluble salts (chlorides, sulfates), which are in the soil or dissolved in groundwater, increase the corrosive aggressiveness of wastewater, accelerating the development of corrosion processes. This is due to the metal activation by presented ions in it. especially chlorine ions, which, adsorbing on the steel surface and displacing oxygen, contribute to the destruction of oxide membranes and make it difficult for the passivation of the surface.

An important role in this process is played by particles suspended in water, which by their corrosion activity can be divided into three groups:

1. Corrosion-active particles. These are in most cases particles of salts, such as sodium chloride, sodium sulfate, ammonium sulfate.

2. Corrosive-inactive particles adsorbing corrosive-active gases from the air. These are the particles of siltation of the bottom near aeration stations and observation wells, the presence of which on the metal greatly accelerates its corrosion.

3. Corrosion-inactive particles that do not adsorb harmful gases.

In some conditions of the sewer landscape, there is a phenomenon when the particles of solid waste and mineral rocks, in the absence of water inflow from the environment, create a protective membrane, under which corrosion processes are temporarily suspended.

The above-mentioned operating conditions of sewage equipment and various engineering metal structures change insignificantly within the sewage structures of Ukraine.

However, it should be noted that aggressive wastewater is the most corrosive and active in relation to the metal equipment, highly mineralized, containing a significant amount of ions Cl^- and SO^{2-}_4. Their total stiffness varies within 5…10 mg / eq, and alkalinity – pH = 6…7.2.

The content of mineral salts (sulfates and chlorides) in groundwater has a significant impact on the development of corrosion of metal structures, which ultimately affects their load-bearing capacity.

As a rule, the problem of ensuring the stability of already corroded areas of steel and reinforced concrete structures of sewer structures are solved one way – replace the old, corroded equipment with new ones. The optimal solution to this problem requires a detailed study of the corrosion process of engineering structures in the sewer (full-scale) conditions.

It should be noted that to assess the internal stresses in the existing metal structures of hydraulic structures was used a device model "Stresscan" company "Argosy Technologies" (USA), the principle of which is based on the properties of magnetoelasticity of ferromagnetic materials (Barkhausen noise). This device allows you to detect the parameters of the stress-strain state of the metal in the experimental location. Also, to quantify their danger, as well as identify areas with final plastic deformations and welding stresses. The principle of operation of this device is described in more detail in [3].

Research results and their discussion.

The results of experimental studies of long-term fatigue of various steel structures (steel 09G2) of sewer structures are shown in Fig. 2 – 7. In particular, in fig. 6 – 7 the data of fatigue strength of reinforcing cores of reinforced concrete constructions of sewer constructions are stated.

In the experimental tests were used reinforcing rods with a diameter of 32 mm made of steel grade 20GS.

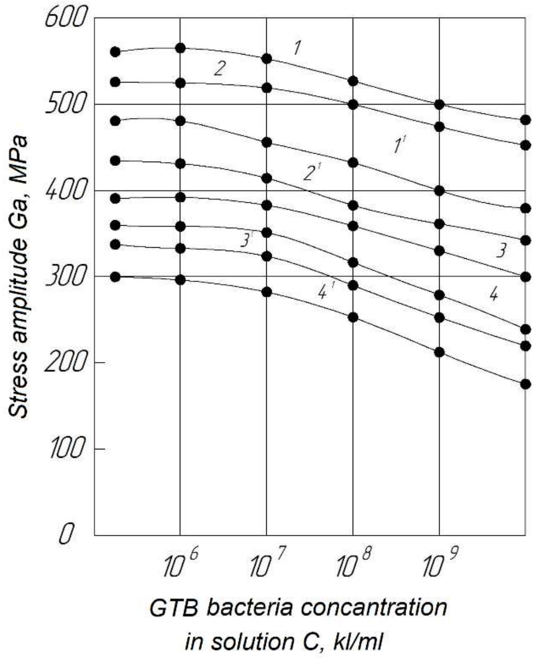

Figure 2 – Curves of dependence between the concentration of GTB bacteria in solution and fatigue resistance at the base N=10^7 cycles when tested by bending deformation during rotation.

Designation: operation of sewer pipe structures (years): 1 – 10; 2 – 20; 3 – 30; 4 – 40; 1', 2', 3', 4' – (GTB solution +5% NaCl)

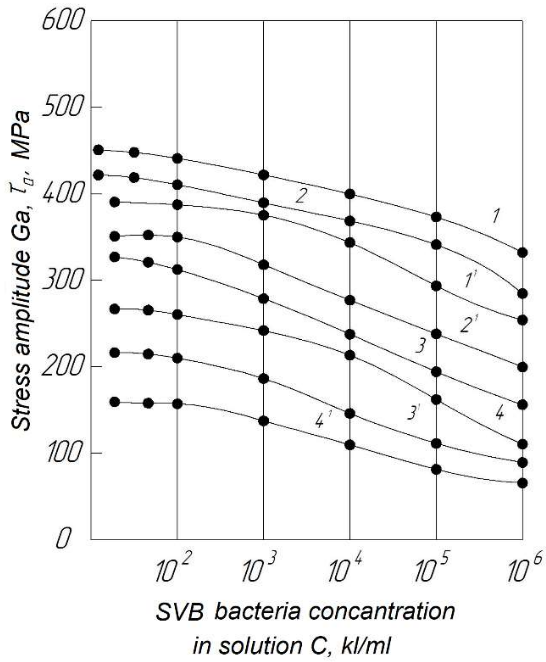

Figure 3 – Curves of dependence between the concentration of CBS bacteria in solution and fatigue resistance at the base N=10^7 cycles when testing samples by torsional deformation.

Designation: operation of sewer pipe structures (years): 1 – 10; 2 – 20; 3 – 30; 4 – 40; 1', 2', 3', 4' – (GTB solution +5% NaCl)

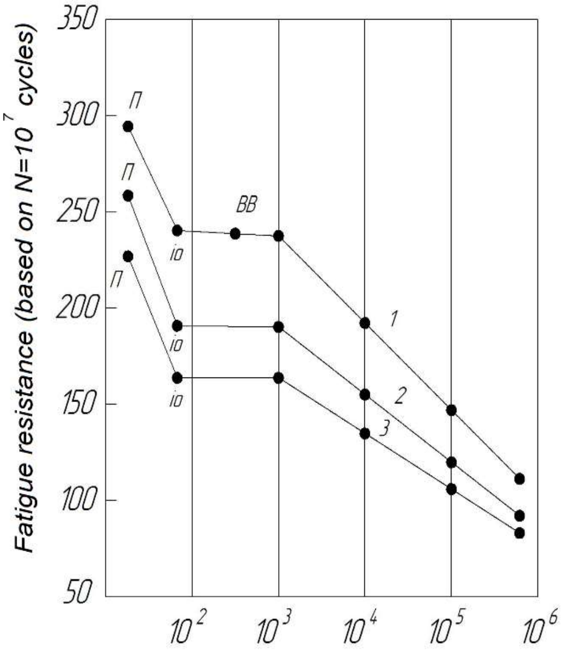

Figure 4 – Curves of dependence between the concentration of bacteria of SVB in solution and resistance of fatigue on base N=10^7 cycles during operation of sewer pipe structures lasting 40 years.

Marking: 1 – bend during rotation;
2 – axial load; 3 – torsion;
BB - tap water; П – air; io - ion exchange water

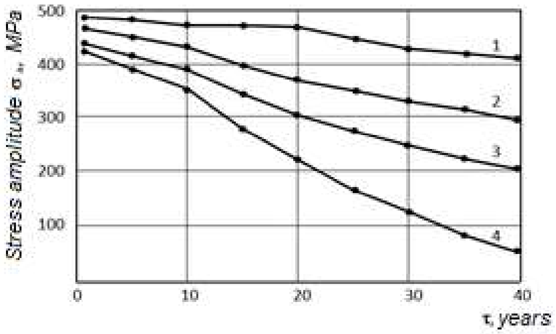

Figure 6 – Graphs of dependence when testing for bending deformation of samples cut from the reinforcement of reinforced concrete structures of sewer structures.
Fatigue tests at the base N=10^7 cycles.

Marking: 1 – air test;
2 – test in an environment with 3% NaCl;
3 – tests in the environment with GTB bacteria ($2.5 \cdot 10^6$ cells); 4 – tests in the environment with CKD bacteria ($5 \cdot 10^7$ cells).
Fittings with a diameter of 32 mm,
steel of the 20GS brand

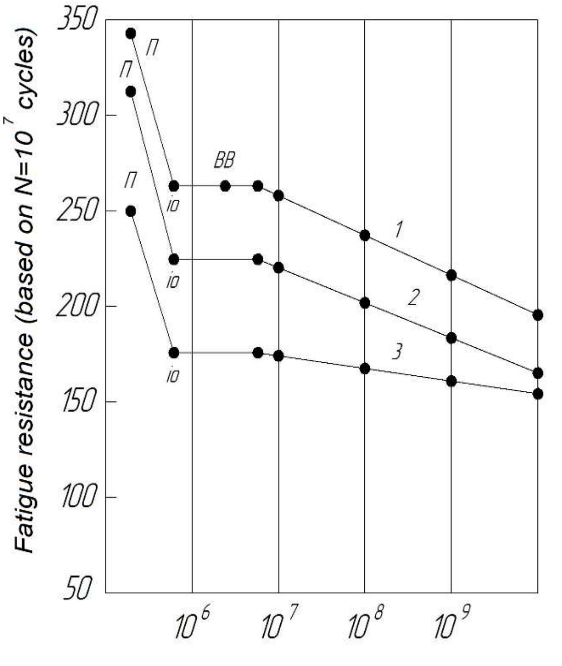

Figure 5 – Curves of dependence between the concentration of GTB bacteria in solution and fatigue resistance at the base N=10^7 cycles during operation of sewer pipes of drainage duration of 40 years.

Marking: 1 – bend during rotation;
2 – axial load; 3 – torsion;
BB – tap water; П – air; io – ion exchange water

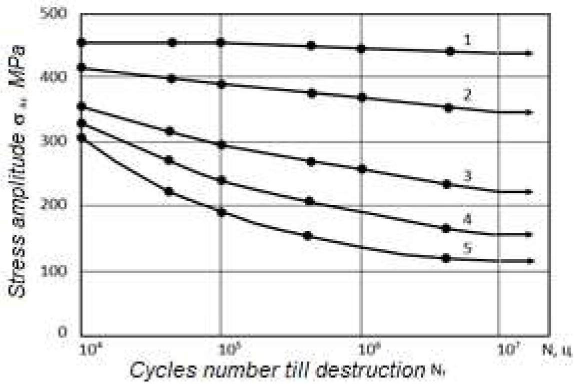

Figure 7 – Graphs of dependence when tested in saltwater (NaCl -3% =30g/l) on deformation of axial loading, 20 Hz, the samples cut out of armature of reinforced concrete designs on constructions of sewer systems.

Designation of service life of reinforced concrete structures (years):
1 – 15; 2 – 25; 3 – 35; 4 – 40 5 – 50;
Fittings with a diameter of 32 mm,
steel of the 20GS brand

Analysis of the data is shown in Fig. 2 – 7, indicates that prolonged fatigue of steel and reinforced concrete structures of various sewage structures is significantly reduced when reaching 20 years or more, especially in an environment containing CBS bacteria, which, in turn, cause severe corrosion damage to the main pipe structures for sewage disposal in comparison with other simulated environments (Fig. 2 – 7).

Moreover, it is noteworthy that the samples, which are cut from metal with a long service life in hydraulic and sewer conditions (more than 20 years), are characterized by low long-term strength (Fig. 2 – 5).

The data presented in Fig. 7, clearly showed a sharp decrease in metal fatigue resistance in saline solutions, especially after 10 – 20 years of operation of steel reinforcing bars of reinforced concrete sewer structures. This result can be explained by the fact that in the process of long-term operation of metal structures, as well as in general sewage equipment is metal degradation caused by flooding, which, in turn, causes its embrittlement and, consequently, fragile destruction [10, 11].

Conclusions

1. Thus, it is established that long-term fatigue (strength) of steel structures of underground sewage structures is significantly reduced during long-term operation (more than 20 years) in chemically aggressive environments of domestic sewage, which often leads to corrosion and mechanical destruction.

2. It is proved that in the process of long service life the indicators of long-term fatigue of reinforcing steel rods of reinforced concrete structures are significantly reduced, which causes the formation of cracks in the connection "reinforcement - concrete", which usually leads to the destruction of reinforced concrete pipes and structures as a whole.

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