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Factors affecting extended avalanche destructions on long-distance gas pipe lines: Review

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A R T I C L E I N F O

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A B S T R A C T

Avalanche destructions in long-distance gas pipe lines are of great importance in the uninterrupted transport of commercial gas on an international and national scale in the Republic of Kazakhstan. In the study, an analysis of pipe line accidents showed that such incidents can lead to large casualties and cause enormous economic damage. The statistics of damages in pipe line transport showed that a significant part of accidents occur due to corrosion of the pipe material, concentration of stresses and structural defects, as well as due to external actions. In the work, all these reasons were analyzed and, as a solution for localization or control of avalanche destructions, the authors proposed the prestressing method, which has been studied by the authors for a long time in various problems. As the review showed, the solution of such a problem has an international and national scale, which undoubtedly emphasizes the relevance of the direction. The purpose of this article is to study and fill the gap in the issue of the features of the propagation of destructions in long-distance gas pipe lines and the development of sound methods and techniques for assessing the resistance of pipes to destructions.

1. Introduction

Possessing large reserves of natural gas, oil and gas condensate, an extensive network of gas supply and pipe line transport, the

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Republic of Kazakhstan can have a serious impact on the world energy market development. The creation of a dynamically developing, sustainable and balanced system of pipe line transport is a necessary condition for stabilizing and boosting the economy, ensuring the integrity of the country, and improving the living standards of the population. Its role is even more enhanced in the context of the world economy globalization, leading to a significant increase in interstate economic ties.

The annual growth in gas production and the increase in its share in the country's fuel and energy balance and in export deliveries to international markets predetermined the high growth rates of the construction of a network of long-distance gas pipe lines (Fig. 1) [1], which, according to the data of the national operator Qazaqgaz in the field of gas and gas supply of the Republic of Kazakhstan, is currently the main way to transport large volumes of gas from fields to places of consumption.

In total, the Qazaqgaz group of companies operates gas pipe lines with a total length of about 79.6 thousand km, of which 20.6 thousand km are long-distance, and 59 thousand km are distribution gas pipe lines. Fig. 2 shows a map of the long-distance gas pipe lines of the Republic of Kazakhstan [1].

Considering these data, there is a need to increase the requirements for ensuring the safe operation of gas pipe lines or other storage facilities [2–5], reducing the risks of severe accidents, which are caused by threats of large-scale fires, explosions, soil and water pollution in case of gas or oil leaks in conditions of the objective impossibility of completely eliminating destructions. An analysis of foreign and domestic sources shows [6–10] that accidents of various kinds occur in long-distance gas pipe lines for various reasons, especially with an increase in their throughput due to an increase in pipe line diameters and operating pumping speeds, as well as an increase in operating pressure, lead to high damage and destructibility, Fig. 3.

Thus, according to the data source "European gas pipeline incident data group" (EGIG), which is the owner of the statistical data of seventeen operators of the gas transmission system in Europe, including information on failures and accidents on gas pipe lines that have occurred since 1970–2019 shows that during this period 1411 failures were recorded on European gas pipe lines over a total length of 142 711 km of gas pipe lines. Total failure rate for the period 1970–2019 equals 0.29 incidents per year per 1000 km. An analysis of the causes of failures showed the main causes: external loads or actions, material corrosion, imperfection or design defect (Fig. 3a) [6].

The United Kingdom Onshore Pipeline Operators Association (UKOPA), whose total length of gas networks at the end of 2020 amounted to 23 587 km, on which since 1962–2020, 205 accidents on gas pipe lines were recorded. The overall failure rate for the period from 1962–2020 is 0.201 incidents per year per 1000 km. The main factors contributing to accidents from the UKOPA report include material corrosion, external actions or weld defects (Fig. 3b) [7].

According to the US Pipelines and Materials Safety Administration (PHMSA), which is responsible for developing and ensuring the reliable operation of pipe line transport, compliance with safety regulations, and also uses data to track the frequency of failures, incidents and accidents. According to the management, between 2003 and 2022, 661 accidents occurred on gas pipe lines in the United States, where corrosion, external actions, and design defects were also the main causes of failure [8].

According to the Rostekhnadzor data, the analysis of the Russian gas transmission system for the period 2005–2019 showed that the main reasons for the failure of the operation of gas pipe lines are also material corrosion, construction defects, design flaws (product defects), mechanical impacts, and others, Fig. 3c [9].

An analysis of the domestic gas transmission system showed that the Intergas Central Asia (ICA), out of the entire system of the national operator Qazaqgaz JSC, occupies more than 80 % of the long-distance pipe line transport, and therefore the failure analysis was carried out on the ICA data basis, where the main causes of accidents were also corrosion, mechanical damages and defects in welds, Fig. 3d [10].

Given the fact that any of the above reasons can serve as the cause of avalanche destruction (Fig. 4), the design, construction,

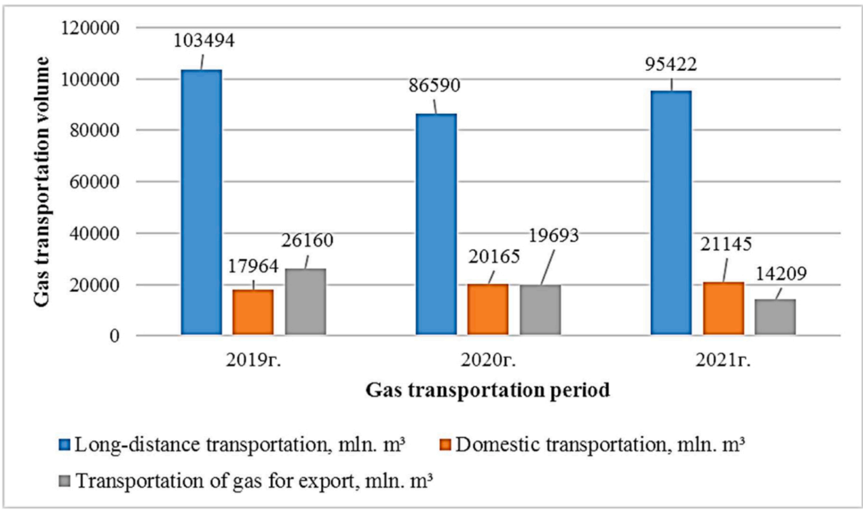


Fig. 1. Gas transportation volumes of the Republic of Kazakhstan [1].

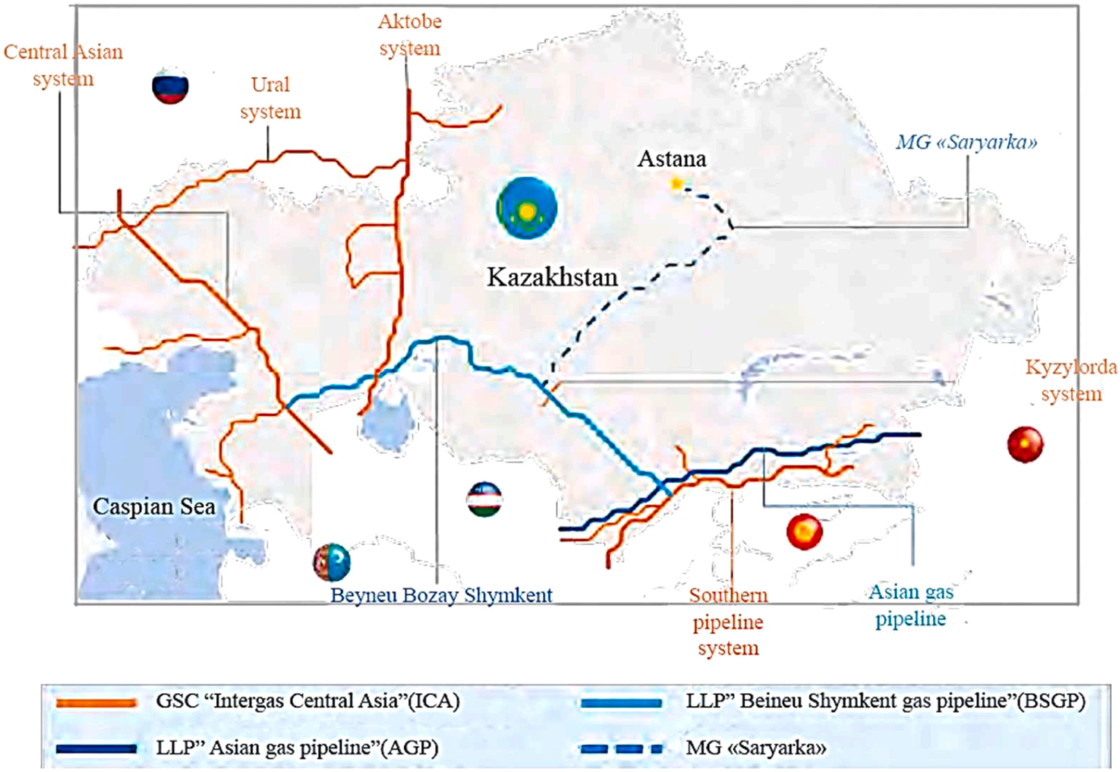


Fig. 2. Map of long-distance gas pipe lines of the Republic of Kazakhstan [1].

reconstruction, strengthening and operation of gas pipe lines in order to avoid human casualties [11–18] should be based on strictly scientific, technically feasible and economically justified solutions using improved and new engineering design methods, which requires additional comprehensive research.

As the calculation models of the mechanism of extended destruction of the gas pipe line have not been developed enough, today there are no reliable methods for quantifying the resistance to destruction, choosing the parameters that most strongly affect the conditions for extended destruction and searching for their optimal values. In conditions when, for objective reasons, it is impossible to completely exclude the destruction of long-distance gas pipe lines, studies aimed at preventing the spread of destruction or managing their length are of great importance. In this regard, conducting comprehensive studies to develop scientific foundations for assessing the resistance of gas pipe lines to extended destruction is necessary today.

The purpose of this research is to study the features of the propagation of destruction in long-distance gas pipe lines and develop sound methods and techniques for assessing the resistance of pipes to destruction, which is a very urgent task, both at the international and national levels, especially since the wear of existing gas pipe lines in the Republic of Kazakhstan is more than 70 %, the service life of which has exceeded 30 years [19].

2. Methodology

In general, the authors reviewed 135 sources of scientific and scientific-technical literature, including reports from competent specialized companies, of which 76 scientific articles are the main causes of avalanche destructions in pipe lines (gas pipe lines or oil pipe lines) [28–103], 23 articles are not related to the problem under consideration [113–135], and the rest of the literature in the amount of 36 refers to standards, reports of competent companies and statistical data [1–27,104–112].

The methodology for selecting relevant literature is summarized in Fig. 5 below.

3. Review of works related to the destruction of long-distance pipe lines, conducted by researchers around the world

From the analysis of accidents on gas pipe lines (Fig. 3), it can be seen that, to a greater extent, the initiator of the failure is the corrosion of the pipe material, then the concentration of stresses and structural defects (welds, etc.), as well as external actions. To improve the strength characteristics, in the norms [20–27], two fundamental approaches to solving the problem of preventing extended destructions of gas pipe lines are mainly described. The first is related to the exclusion of the energy conditions for maintaining the process of stationary crack movement along the pipe line by choosing the parameters of the gas pipe line material. The second is associated with the use of various technological solutions (for example, choosing the depth and nature of the backfill,

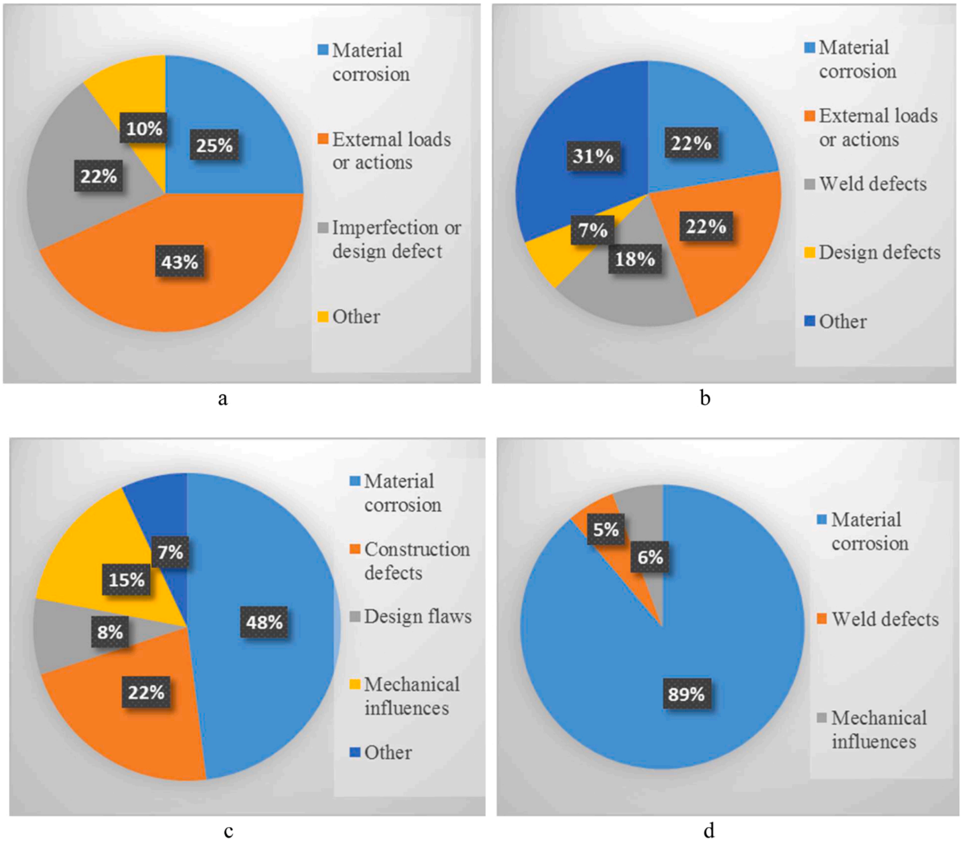


Fig. 3. Damage analysis on gas pipe lines of foreign and domestic sources: a – European gas pipeline incident data group; b – United Kingdom Onshore Pipeline Operators Association; c – Rostekhnadzor; d – Intergas Central Asia.

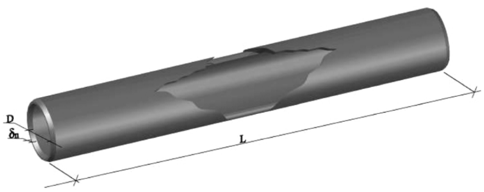


Fig. 4. An example of avalanche destruction on a large-diameter gas pipe line: D – gas pipe line diameter, δ_n – gas pipe line wall thickness, L – gas pipe line length.

changing the mode of operation and maintenance of the gas pipe-line), as well as special structural elements – destruction dampers.

3.1. Studies related to pipe failure due to corrosion

The authors of works [28–30] showed that most accidents on long-distance gas pipe lines occur due to stress corrosion, where in some sections of pipe lines during operation, cracks reach the middle of the wall thickness, which corresponds to the exhaustion of all the safety margins provided for by the projects. After that, a pipe rupture occurs, gas is released under high pressure, spontaneous combustion with a flame height of up to tens of meters. Basiev K.D. et al. [31] carried out the influence of the gas elastic energy reserve on corrosion and stress-corrosion destructions of long-distance gas pipe lines and proposed a model for the development of surface defects depending on the elastic energy reserve of the compressed gas. It was found that the elastic energy of the compressed gas in the long-distance gas pipe line is 4.25 times greater than the energy in the oil pipe line, depending on the diameter and pressure, while the tendency to stress-corrosion damages to gas pipe lines increases with increasing pipe diameter. An increase in the elastic energy reserve in the gas pipe line contributes to the accumulation of damage and activates the processes of stress corrosion cracking. The relationship between the specific elastic energy value of the compressed gas and the growth rate of the crack parameters is revealed. The results obtained allow to predict the degree of danger of cracks and determine the margin of safety of a defective pipe. An analysis of the

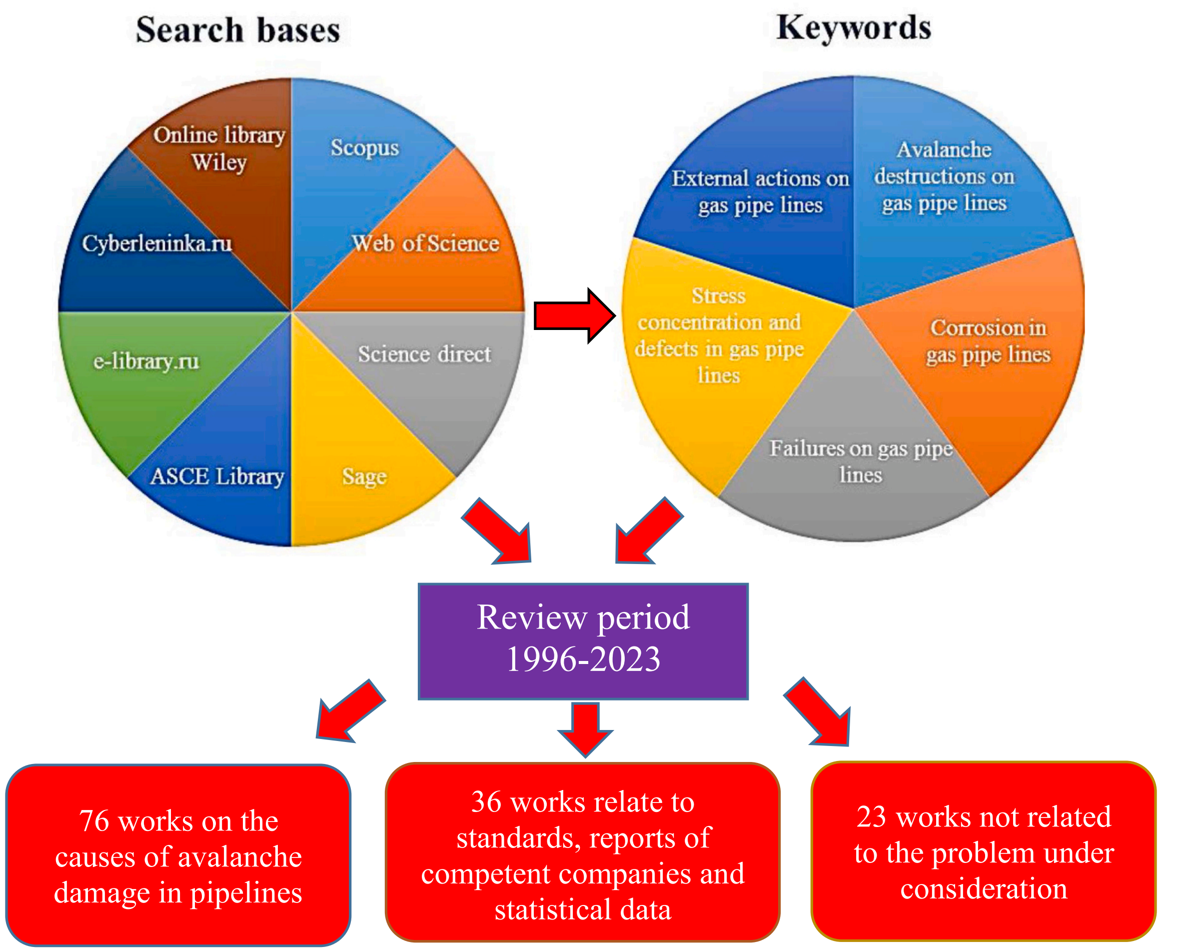


Fig. 5. The methodology for selecting relevant literature.

results indicates that pipe lines with a diameter of 1220 and 1420 mm are more prone to stress corrosion, which may be due to the large accumulated energy of the compressed gas.

In [32], Juntao Yuan et al. showed that in the oil pipe line a large number of corrosion centers was distributed in the lower part of the pipe line, and a significant local decrease in wall thickness was observed, and the authors of [33–35] conducted a simulation of the gas pipe line for internal corrosion with an accuracy of 93.22 %, where they showed that 58 % corrosion is formed as a result of deposits, and 48 % as a result of the action of microorganisms, where they also showed the frequency of failures with an increase in internal corrosion. A review of works related to deposits that negatively affect corrosion in the oil and gas industry was carried out in [36]. The localization of corrosion on gas pipe lines and oil pipe lines was studied by Aeshah H. and Angalev A. [37,38], and the study of forecasting taking into account the risks of the technical condition of gas pipe lines is shown in [39–42].

Hasan F. et al. [43] studied cases of failure of high-pressure gas pipe lines in Pakistan due to stress corrosion cracking, which were observed after about 15–20 years of operation. Based on metallurgical studies performed on the ruptured pipe, the damage was characterized as stress corrosion failure that began with a longitudinal "stress buildup". This stress buildup, which was in fact a manufacturing defect, was a longitudinal "step" on the pipe surface resulting from improper trimming of the weld flash. Thus, the results of this study highlight the need for care when removing the weld flash. Ahammed M. et al. in [44] describe a probabilistic method for estimating the suitability of corroded pipe lines to work under pressure. The method takes into account the uncertainties of variables affecting suitability with application to some typical examples. Ahammed M. in [45] presented a methodology for estimating the remaining life of a pressure pipe line containing active corrosion defects. In this methodology, a probabilistic approach is adopted, and the associated variables are represented by normal or non-normal probability distributions. The methodology can be applied to an example pipe line and the remaining life of that pipe line is estimated. A method based on the analysis of the fault tree of failures of oil and gas pipe lines is given in [46].

Černý I. [47] showed the effects of steel varieties on stress corrosion cracking in pipe lines, where he studied two types of pipe line steels – carbon pipe line steel and high-strength thermomechanically treated steel X60 – in carbonate solution. As a result, it was found that X60 steel was more sensitive to the stress corrosion cracking process compared to carbon steel. It is known that a number of solutions was developed to assess the residual strength of corroded pipe lines, which mainly depend on the properties of the material and the geometry of the pipe line [48,49]. Also, Choi J.B. et al. [50] conducted a series of tensile tests with various types of machined recesses and showed the effects of the defect depth and length, as well as the geometry of the pipe line, on the failure as a whole [51–54].

An analysis of the above works shows that the appearance of corrosion on high-pressure gas pipe lines may well serve as the initial cause of the formation of a crack, which can subsequently lead to an extended (avalanche) destruction of a large-diameter gas pipe line. Summarizing Section 2.1, Table 1 provides a summary of the work carried out at the international level.

3.2. Studies related to pipe failure due to stress concentration and structural defects

Otegui J.L. et al. [55] analyzed three failures in a gas pipe line where the root cause was due to poor manufacturing procedures. The material used to make the sleeves was old and had low transverse strength. In this case, cellulose electrodes with high heat capacity were used for welding field joints, which was facilitated by relatively high circumferential stresses and defects in the absence of melting [56,57]. Cosham A. et al. [58,59] showed that denting reduces the static and cyclic strength of the pipe, where simple dents, weld dents and dents were considered [2–5].

Zhang D. et al. [60] based on the creation of a three-dimensional finite element model of a welded joint of a pipe with unequal wall thickness showed the effect of the length and shape of the transition on the crack resistance of welded joints of a pipe line with unequal wall thickness. Also, on this basis, the influence of the geometric parameters of the transition section and the ratio of wall thicknesses, pipe diameter and the coefficient of conformity of the strength of the welded joint on the force of cracking in welded joints with unequal wall thicknesses was obtained. As a result, a method was proposed for obtaining a section of the minimum transition length and preventing the destruction of the circumferential weld. Wu K. et al. [61] reviewed the current state of research on codes and standards related to weld strength requirements in the pipe line industry. The result showed that in almost all standards, the lower tensile strength of the pipe is considered as a requirement for assessing the strength of the weld for specimens subjected to a transverse weld rupture test at the weld site, which is contrary to the original intention to ensure a uniform or excessive fit of the weld to the girth of the pipe line. The Monte Carlo Method [62] was then used to investigate the change in circumferential weld strength fit factor and pipe line failure probability at various high and low misalignments, fracture toughness and standard deviations of the pipe strength distribution. As a result, based on the requirement of a certain target reliability and deformation requirements, a semi-empirical model for predicting the critical strength compliance factor for engineering applications was proposed. Also, in numerical studies [63–65], based on numerical results, a new strain-based J-integral prediction formula was proposed, and Kibey S. et al. [66] presented the required input parameters, their applicability limits, and simplified equations for determining tensile strength. It was shown that the equation can be used to properly determine the material properties of welds and pipes, select a design concept, and develop full-scale tests to evaluate a strain-based design. The equations can also serve as the basis for codified procedures for critical evaluation of the design of welded pipe lines, taking into account deformations [67,68].

Table 1
Studies related to pipe destruction due to corrosion according to study type and year of publication.

№	Reference	Year	Study type	Research objectives
1	[44]	1996	Theoretical	The suitability of corroded pipe lines for work under pressure was assessed
2	[45]	1998	Theoretical	The remaining life of a pressure pipe line containing active corrosion defects was assessed
3	[51]	2002	Theoretical	The propagation of longitudinal cracks on the outer surface of the pipes was analyzed
4	[50]	2003	Theoretical	Tensile test was carried out with various types of machined recesses based on finite element modeling
5	[47]	2004	Experimental	The effect of steel grade on corrosion cracking was studied
6	[46]	2005	Theoretical	Development of a gas pipe line failure analysis method
7	[48]	2005	Experimental	Assessment of steel grades used in the manufacture of pipe lines
8	[43]	2007	Theoretical	Analysis of gas pipe line failures
9	[42]	2009	Theoretical	Investigation of the causes and consequences of pipe line accidents
10	[39]	2009	Theoretical	Forecasting the technical condition of pipe lines
11	[29]	2010	Experimental	Investigation of gas pipe line cracks as a result of corrosion
12	[49]	2013	Theoretical	Overview of high-strength pipe steel grades
13	[38]	2015	Experimental	Building a system of stress-corrosion protection of technological pipe lines
14	[41]	2015	Theoretical	Risk assessment to predict breakdowns and consequences of pipe line failures
15	[36]	2016	Theoretical	Analysis of the frequency and consequences of pipe line failures
16	[31]	2018	Experimental	Development of a method for assessing the propensity of pipe steels and welded joints to the initiation of corrosion cracks
17	[30]	2019	Theoretical	Peculiarities of operation of pipe lines during natural gas transportation were considered
18	[53]	2019	Theoretical	Development of a methodology for assessing the degree of danger of corrosion damages to gas pipe lines
19	[37]	2020	Theoretical	Discussion of future problems and research directions related to localized corrosion of gas pipe lines
20	[54]	2020	Theoretical	Study of the morphology and dynamics of the development of manufacturing defects on a steel pipe
21	[35]	2021	Experimental	Study of internal corrosion in gas pipe lines
22	[28]	2022	Experimental	Study of the corrosion behavior of gas pipe line steel
23	[34]	2022	Theoretical	Development of a methodology for assessing gas pipe lines
24	[40]	2022	Theoretical	Development of a method for predicting pipe line operation
25	[32]	2023	Experimental	Investigation of an oil pipe line suffering from severe internal localized corrosion after a short period of maintenance
26	[33]	2023	Experimental	Investigation of the causes of internal corrosion in gas pipe lines
27	[52]	2023	Theoretical	Assessment of the reliability index and / or probability of failure of a corroded pipe line

Zhao J. et al. [69] conducted a systematic review of various assessment methods and standards for dents in pipe lines, including the combination of a dent with other defects. As a rule, the methods, available today, are not sufficiently accurate and reliable for evaluating dents in pipe lines, especially combinations of dents and defects. For simple pipe line dents, both depth-based and strain-based criteria are commonly used in engineering. Their main concerns include inaccuracy and conservatism. For a dent in combination with other defects, the existing evaluation methods are not perfect enough to give reliable results [2–5,70–74]. Alashti A. R. et al. [75] carried out experimental and numerical studies on the effect of plastic damage on the behavior of a dented steel pipe subjected to internal pressure. In a numerical study, the plastic behavior of pipes under indentation was studied using the theory of continuous damage mechanics and elastic-plastic analysis by the finite element method. The proposed damage plasticity model includes the influence of four parameters that play an important role in predicting the onset of failure, namely: damage rule, softening effect, hydrostatic pressure, and dip angle. To confirm the numerical calculations, a series of experimental tests was carried out on a pipe at atmospheric pressure. After verification, numerical calculations were performed for various ranges of internal pressures with and without damage effect and the results were compared. It was shown that damage plays an important role in the bearing capacity of a pipe or shell with recesses [2–5,76–79].

The above works in Section 2.2 are also the causes of gas pipe line failures, which can subsequently give rise to extended (avalanche) destruction in high pressure gas pipe lines, where the main information of works carried out at the international level is given in Table 2.

3.3. Studies related to the destruction of pipes due to external actions

Shabarchin O. et al. [80] performed a seismic risk assessment that was used for a pipe line infrastructure located in northeastern British Columbia, Canada. Spatial clustering analysis was used for earthquakes previously recorded in a region to identify areas that are particularly prone to seismic activity. The state-of-the-art ground motion prediction equation for induced seismicity was applied in the Monte Carlo Method modeling [62] to obtain a stochastic field of seismic intensity. Based on data on the seismic fragility of pipe lines, as well as their mechanical characteristics and corrosion conditions, using a geospatial information system, spatial and probabilistic distributions of the repair rate and failure probability were obtained and visualized. Also, the results of the work of Wang Y. et al. show [81] that the potential impact of seismic damages on a corroded pipe line is very significant [82–85]. As a dynamic protection of pipe lines, a prestressing method was proposed, which optimizes the amplitude-frequency values and the logarithmic oscillation decrement by an order of magnitude [86], the issue of the influence of temperature [87] and prestressing parameters [88,89] was also considered. The issue of prestressing of vertical shells was studied in [90–93].

Long-distance gas pipe lines located in mountainous areas with hazardous geological processes are often subject to various geodynamic phenomena, which in turn can lead to emergencies [94]. In this connection, Tkachenko I.G. et al. [95] outlined the design features of a hardware-software complex that allows monitoring the stress-strain state of surface and underground sections of gas pipe lines, as well as remote monitoring of gas pipe lines [96,97]. The issue of accidents as a result of natural phenomena was also studied, as lightning strikes into a gas pipe line was considered in [98,99]. Sukharev M.G. et al. [100], conducted research in the field of statistical analysis of the accident rate of gas distribution systems and came to the conclusion that the main causes of accidents and incidents on aboveground gas pipe lines are anthropogenic impacts up to 80 %, and on underground steel pipe lines, the causes of

Table 2
Studies related to pipe destruction due to stress concentration and structural defects according to study type and year of publication.

№	Reference	Year	Study type	Research objectives
1	[55]	2001	Theoretical	Investigation of pipe line defects affecting the destruction
2	[56]	2001	Theoretical	Method for predicting a gas pipe line weld
3	[57]	2003	Theoretical	Investigation of pipe line imperfections
4	[72]	2003	Theoretical	Study of the reliability of gas pipe lines
5	[58]	2004	Experimental	Assessment of pipe line defects
6	[67]	2004	Experimental	Investigation of the destruction of pipe line welds
7	[73]	2004	Theoretical	Design reliability study
8	[68]	2006	Theoretical	Structural deformation study
9	[74]	2008	Theoretical	Development of a method for predicting the failure of a gas pipe line
10	[66]	2010	Theoretical	Development of a method for calculating the strength of gas pipe lines
11	[71]	2011	Theoretical	Improvement of the calculation method
12	[76]	2012	Theoretical	Assessment of a pipe with dents for strength characteristics
13	[75]	2015	Experimental	Study of the effect of plastic damages on the bearing capacity of the pipe
14	[77]	2018	Theoretical	Study of strength characteristics taking into account the internal pressure of the pipe line
15	[78]	2019	Theoretical	Study of the stress-strain state of a pipe with a dent
16	[63]	2020	Theoretical	Investigation of the integrity of the circumferential weld for the strength of the pipe line
17	[64]	2020	Theoretical	Study of load-bearing capacity of pipe line weld
18	[61]	2021	Theoretical	Investigation of the integrity of the circumferential weld for the strength of the pipe line
19	[65]	2021	Theoretical	Examination of welded joints of the pipe line
20	[79]	2021	Theoretical	Study of the reliability of oil pipe lines, taking into account dents
21	[69]	2022	Theoretical	Investigation of pipe line dents
22	[70]	2022	Theoretical	Analysis of the reliability of pipe lines with dents
23	[59]	2023	Theoretical	Development of a method for assessing a damaged natural gas pipe line
24	[60]	2023	Theoretical	Analysis of the failure behavior of welded joints in pipe lines with unequal wall thicknesses

accidents are external corrosion (48 %) and anthropogenic impacts (43 %) [101–103].

As the above brief review of accidents and destruction of gas pipe lines showed, external impacts on gas pipe lines of a natural or anthropogenic nature also serve as possible causes of incidents, where the main descriptions of the works presented in Section 2.3 are presented in Table 3.

4. The proposed method for solving the problem of avalanche destruction and its justification

The creation of pipe lines of high throughput and reliability is possible only on the basis of fundamentally new design solutions. In this connection, the method proposed by the authors for controlling avalanche destructions in long-distance gas pipe lines consists in winding a high-strength profile (wire, steel tape, and wrappings made of composite or nanocomposite materials) in one or several layers onto the surface of large-diameter pipes manufactured by industry using conventional technology [104–108], where the design feature of such a design is that, using a high-strength winding, it is possible to redistribute the forces in the shell and increase its efficiency due to equalization of longitudinal and hoop stresses in the pipe, which increases the strength and reliability of the vessel, tank or pipe line. The profile can be wound in the transverse direction at an angle or perpendicular to the longitudinal axis of the pipe, evenly or with some variable pitch, distributed along the shell, as well as with some given force, in accordance with Fig. 6 [87–93], where the winding and gas pipe line materials will be taken in accordance with [109–112].

A schematic diagram of the operation of a prestressed shell in the form of a diagram is presented in accordance with Fig. 7.

According to the operation diagram of a prestressed shell (Fig. 7), when the casing is compressed by a stretched wrapping, the shell wall is compressed, and the wrapping is stretched. When exposed to internal pressure, the shell and wrapping work together in the annular direction. As the internal pressure increases, the prestress in the shell changes from compressive to tensile. The compressive stresses arising from the prestressing go to the reserve of the bearing capacity of the structures. Longitudinal forces during ring winding are perceived only by the shell, therefore, when working under pressure, a biaxial stress state occurs in the shell. The prestressed shell is made of materials that are dissimilar in terms of mechanical characteristics: the shell is made of plastic material and the wrapping is made of high-strength relatively brittle metal. As a result, the limit of the bearing capacity of a prestressed shell is characterized by the value of the internal pressure in it, at which the stresses in the shell reach the yield point, and the stresses in the wrapping make up a certain part of the ultimate strength of the wire.

Previously, the issue of applying prestressing was widely covered by the authors in [87–93], where this method was used as a way to increase the bearing capacity (increase strength), dynamic (seismic) protection of the pipe line and reservoir. It was also proposed to replace a thick wall with a relatively thin one wrapped with high-strength wire, which facilitates the design, saves metal, simplifies the technology and reduces the cost of its manufacture, which served as a justification for studying the issue of applying prestressing as a method of controlling avalanche destructions in long-distance gas pipe lines.

The mechanism of the influence of velocity during avalanche destruction of a gas pipe line on the nature of crack propagation and the conditions for the development of extended fracture will be investigated on the basis of the classical theory of fracture mechanics and by studying the features of the destruction of gas pipe lines. The computational experiments will be carried out in the ANSYS finite element analysis software system, and the verification of the research results will be carried out with experimental data. To study the stress-strain state of the crack tip zone, a boundary value problem for a cylindrical thin-walled shell with a cut will be solved based on the theory of elasticity, taking into account the action of the inertia forces of the turn of the crack edges that arise in the process of stationary movement of the cut along the shell body. The stress-strain state of the fracture zone and the dependence of the fracture rate and on the geometric and operating parameters of the gas pipe line will be studied by experimental studies of gas pipe line models. The reliability of the results will be based on the application of standard methods for testing structures and ensuring that the data obtained are compared with the results of theoretical studies based on the use of fundamental theories of fracture mechanics. A general methodology for assessing the resistance of gas pipe lines to extended fractures will be developed taking into account the results of theoretical and experimental studies.

The proposed method for localizing and stopping extended destructions of long-distance gas pipe lines using a wire wrapping or a composite pad will be developed taking into account the nature of crack propagation and stopping in the gas pipe line, as well as the operation features of pre-cylindrical shells with adjustable parameters (wrapping pitch, force, thickness and angle).

5. Conclusion

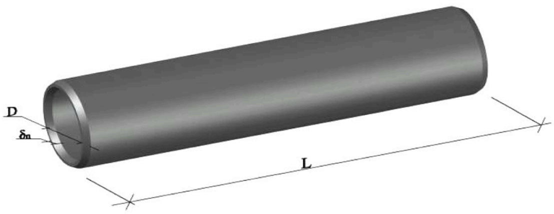
This article describes the research work carried out around the world on the causes of failures in gas pipe lines, which can be the main initiators of avalanche destructions. At the same time, the review of standards and studies shows only traditional methods of strengthening gas pipe lines: choosing the parameters of the gas pipe line material or using various technological solutions that may not be economically efficient, and are also not acceptable for gas pipe lines under pressure (operation). The main information about the causes of accidents and destructions on gas pipe lines is given in Tables 1–3. At the same time, based on the results of the review of works carried out in the framework of this study, the following can be noted as the main conclusions:

- The paper provides extensive statistical information of international and national companies on failures in gas pipe lines, where it is possible to mention such reputable companies as: “European gas pipeline incident data group” (EGIG) [6]; the United Kingdom Onshore Pipeline Operators Association (UKOPA) [7]; the Pipelines and Materials Safety Administration (PHMSA) [8]; Rostekhnadzor [9]; the Intergas Central Asia (ICA) [10].

International and national standards for the design and construction of large diameter gas pipe lines were considered [20–27], which basically describe two fundamental approaches to solving the problem of destruction of gas pipe lines: choosing the parameters

Table 3
Studies related to pipe destruction due to external actions according to study type and year of publication.

№	Reference	Year	Study type	Research objectives
1	[84]	1999	Theoretical	Study of the influence of dynamic loads in the form of earthquakes on the integrity of pipe lines
2	[100]	2010	Theoretical	Analysis of accidents on gas pipe lines
3	[83]	2011	Theoretical	Study of the impact of earthquakes on the integrity of pipe lines
4	[99]	2011	Theoretical	Investigation of pipe line accidents
5	[101]	2015	Theoretical	Analysis of the impact of natural and anthropogenic or man-made phenomena on the safety of pipe lines
6	[82]	2016	Theoretical	Analysis of accidents due to external actions
7	[95]	2016	Theoretical	Development of a monitoring system for the condition of gas pipe line sections
8	[98]	2016	Theoretical	Studies of lightning strikes on the integrity of the gas pipe line
9	[80]	2017	Theoretical	Studies of the influence of seismic effects on the pipe line
10	[96]	2017	Theoretical	Development of methods for monitoring gas pipe lines
11	[85]	2019	Theoretical	Study of the influence of seismic impacts on the gas pipe line
12	[81]	2020	Theoretical	Investigation of the influence of seismic impacts on a corroded pipe line
13	[94]	2020	Theoretical	Analysis of accidents on pipe lines as a result of external actions
14	[86]	2021	Experimental	Development of a method for dynamic protection of a gas pipe line
15	[97]	2021	Theoretical	Analysis of pipe line safety computer control
16	[87]	2022	Experimental	Study of the effect of temperature on the strength characteristics of prestressed shells
17	[88]	2022	Experimental	Studies of the influence of prestress parameters on the strength of the shell
18	[90]	2022	Theoretical	Investigation of the influence of prestressing as a method of protection against dynamic loading of vertical shell structures
19	[91]	2022	Theoretical	Investigation of the influence of prestressing as a method of protection against dynamic loading of vertical shell structures
20	[102]	2022	Theoretical	Analysis of natural gas leakage and the impact on the failure of the gas pipe line
21	[89]	2023	Theoretical	Development of a method for calculating the strength characteristics of shells taking into account the prestressing parameters
22	[92]	2023	Theoretical	Investigation of the influence of prestressing as a method of protection against dynamic loading of vertical shell structures
23	[93]	2023	Theoretical	Investigation of the influence of prestressing as a method of protection against dynamic loading of vertical shell structures
24	[103]	2023	Theoretical	Analysis of accidents taking into account the damage caused



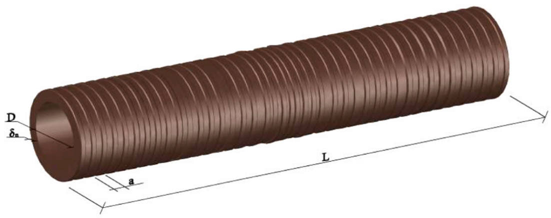


Fig. 6. Scheme of winding a high-strength profile onto a shell: a – traditional pipe line; b – prestressed pipe line with winding a wrapping perpendicularly and with a certain pitch .

of the gas pipe line material or using various traditional technological solutions that are not economically justified.

- Based on the statistical data of international companies, the main causes of failures affecting the extended (avalanche) destruction of gas pipe lines were determined, for which a review of international works was carried out, sections 2.1–2.3;.

- The authors proposed a method for managing avalanche destructions in long-distance gas pipe lines, which consists in winding a high-strength profile (wire, steel tape and wrappings made of composite or nanocomposite materials), Section 3.

Informed consent statement

Not applicable.

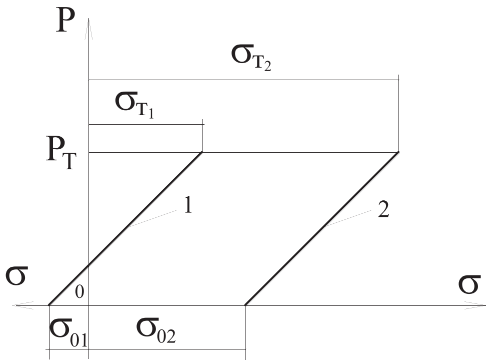


Fig. 7. Diagram of the operation of the prestressed shell technology: 1 – pipe line; 2 – steel or composite wrapping [87–93,104–106].

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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