Vol. 9, no. 4, 2025 eISSN 2541-9129
PEER-REVIEWED SCIENTIFIC AND PRACTICAL JOURNAL

Safety of Technogenic and Natural Systems

Technosphere Safety

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Chemical Technologies, Materials Sciences, Metallurgy

www.bps-journal.ru
DOI 10.23947/2541-9129

Safety of Technogenic and Natural Systems
Bezopasnost' Tekhnogennykh i Prirodnykh Sistem

Peer-Reviewed Scientific and Practical Journal

eISSN 2541-9129

Published Since 2017

Periodicity – 4 issues per year

DOI: 10.23947/2541-9129

Founder and Publisher — Don State Technical University (DSTU), Rostov-on-Don, Russian Federation

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Registration:	Mass Media Registration Certificate ЭЛ № ФС 77 – 66531 Dated Jule, 21, 2016, Issued by the Federal Service for Supervision of Communications, Information Technology and Mass Media
Indexing and Archiving:	RISC, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive
Website:	https://bps-journal.ru
Address of the Editorial Office:	1, Gagarin Sq. Rostov-on-Don, 344003, Russian Federation
E-mail:	vestnik@donstu.ru
Telephone:	+7 (863) 2–738–372
Date of Publication No.4,2025:	30.11.2025

Безопасность техногенных и природных систем
Safety of Technogenic and Natural Systems

Рецензируемый научно-практический журнал

eISSN 2541-9129

Издается с 2017 года

Периодичность – 4 выпуска в год

DOI: 10.23947/2541-9129

Учредитель и издатель — Федеральное государственное бюджетное образовательное учреждение высшего образования «Донской государственный технический университет» (ДГТУ), г. Ростов-на-Дону

Создан в целях освещения результатов исследований и реальных достижений по актуальным вопросам машиностроения, техносферной безопасности, современной металлургии и материаловедения. В журнале освещаются проблемы развития фундаментальных исследований и инженерных разработок в ряде важнейших областей технических наук. Одним из главных направлений деятельности журнала является интеграция в международное информационное пространство.

Журнал включен в перечень рецензируемых научных изданий, в котором должны быть опубликованы основные научные результаты диссертаций на соискание ученой степени кандидата наук, на соискание ученой степени доктора наук (Перечень ВАК) по следующим научным специальностям:

2.1.16 – Охрана труда в строительстве (технические науки)
2.5.11 – Наземные транспортно-технологические средства и комплексы (технические науки)
2.5.21 – Машины, агрегаты и технологические процессы (технические науки)
2.6.1 – Металловедение и термическая обработка металлов и сплавов (технические науки)
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Регистрация:	Свидетельство о регистрации средства массовой информации ЭЛ № ФС 77 – 66531 от 21 июля 2016 г., выдано Федеральной службой по надзору в сфере связи, информационных технологий и массовых коммуникаций
Индексация и архивация:	РИНЦ, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive
Сайт:	https://bps-journal.ru
Адрес редакции:	344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1
E-mail:	vestnik@donstu.ru
Телефон:	+7 (863) 2–738–372
Дата выхода №4,2025 в свет:	30.11.2025

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https://doi.org/10.23947/2541-9129-2025-9-4-263-283

Original Empirical Research

Statistical Modeling of Sulfate Resistance and Carbon Footprint for Optimization of Multi-Component Cements

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Abstract

Introduction. Cement production is responsible for approximately 8% of anthropogenic CO_2 emissions, while annual losses from sulfate corrosion account for 2–4% of the global GDP [1]. Studies have confirmed the influence of SiO_2 and additives on the sulfate resistance of multi-component cements (MCCs). However, there is a lack of high-SiO_2 systems, and there is no consensus on the effects of individual additives. The absence of long-term field experiments hinders an empirical solution to this problem. The present study addresses these gaps. The aim of this research is to develop predictive models to substantiate the optimal composition of MCCs based on their sulfate resistance and environmental performance. The tasks include: synthesizing data on MCC compositions, performing ANOVA and regression analysis, and constructing and validating the models.

Materials and Methods. The data sources were thematically structured and analyzed. Experiments were conducted on eight compositions in accordance with patent RU 2079458 C1 and standards GOST 310.1.76 and GOST 310.4.81. The samples were grouped by SiO_2 levels. ANOVA and linear regression were used to model the dependence of sulfate resistance and self-stress on SiO2 content.

Results. The statistical significance of SiO_2 influence on the sulfate resistance and strength of MCCs was proven (F = 248.6795, p = 3.5612e–25). The regression model ($Sr = 6.2644 + 0.08 \cdot SiO_2$, $R^2 = 0.983$) demonstrated a linear dependence of sulfate resistance (ranging from 8.04 to 9.62 conventional units) on SiO_2 content (21–44%). For SiO_2 content > 22%, the addition of pozzolans was recommended to compensate for reduced strength at early stages of hardening. Compressive strength ranged from 35.0 to 44.0 MPa. The reduction of C_3A content to ≤8% enhanced sulfate resistance. The introduction of 50% granulated blast-furnace slag as a binder optimized the cement structure and reduced the carbon footprint by 27.5% (to 388.2 kg CO_2/t). An increase in silica in the composition:

– by 22.15–28% enhanced sulfate resistance by 0.468 units;
– by 37–40% — 6.2644;
– 42% — 9.6244.

Discussion. The model explains 98.3% of the variance in sulfate resistance through changes in silicon dioxide content. The model remains robust with an increased number of observations, as indicated by the adjusted R_2 of 0.981. The F-statistic indicates the high statistical significance of the model. The normal distribution of residuals and the high precision of the coefficient estimates were confirmed. The limitations on additives in cement specified by GOST 22266-2013 are no longer up to date. This new approach will allow for an increase in cement durability in sulfate environments, a reduction in production costs by 30–50%, and a decrease in CO_2 emissions by 27.5%. It enables the selection of a concrete composition based on either economic or environmental priorities.

Conclusion. SiO_2 content is the key factor in enhancing sulfate resistance. This approach offers a new methodological perspective by overcoming the shortcomings of the GOST standard. Variations in slag composition and the absence of thermal activation may limit the model's reproducibility, necessitating further research.

Keywords: carbon footprint of cement, sulfate corrosion, optimal composition of multicomponent cements, environmental safety of construction, environmental efficiency of multicomponent cements

Acknowledgements. The author would like to thank his colleagues from the Faculty of Chemistry of Substances and Materials at the Saint Petersburg State Institute of Technology (Technical University), and the Department of Chemical

Technology of Refractory Nonmetallic and Silicate Materials, where some of the research was conducted. The author would also like to express his gratitude to the Editorial board and the reviewer for their expertise and valuable comments that helped to improve the article.

For Citation. Smirnova EE. Statistical Modeling of Sulfate Resistance and Carbon Footprint for Optimization of Multi-Component Cements. *Safety of Technogenic and Natural Systems*. 2025;9(4):263–283. https://doi.org/10.23947/2541-9129-2025-9-4-263-283

Оригинальное эмпирическое исследование

Статистическое моделирование сульфатостойкости и углеродного следа для оптимизации многокомпонентных цементов

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Аннотация

Введение. Производство цемента генерирует около 8 % антропогенных выбросов CO_2, ежегодные потери от сульфатной коррозии — 2–4 % ВВП [1]. Исследования подтвердили влияние SiO_2 и добавок на сульфатостойкость многокомпонентных цементов (МКЦ), однако нет количественных моделей с высоким SiO_2 и единого мнения о действии отдельных добавок. Отсутствие долгосрочных полевых экспериментов препятствует решению проблемы опытным путем. Представленная работа восполняет эти пробелы. Цель исследования — создать прогнозные модели для обоснования оптимального состава МКЦ по сульфатостойкости и экологичности. Задачи: обобщение данных по составам МКЦ, ANOVA, регрессионный анализ, построение и валидация моделей.

Материалы и методы. Источники тематически структурировали и проанализировали. Провели опыты с восемью составами согласно патенту RU 2079458 C1, ГОСТ 310.1.76 и ГОСТ 310.4.81. Выборку сгруппировали по уровням SiO_2. Для моделирования зависимости сульфатостойкости и самонапряжения от SiO_2 использовали ANOVA и линейную регрессию.

Результаты исследования. Доказана статистическая значимость влияния SiO_2 на сульфатостойкость и прочность МКЦ (F = 248,6795, p = 3,5612e-25). Регрессионная модель ($Sr = 6{,}2644 + 0{,}08 \cdot SiO_2$, $R^2 = 0{,}983$) демонстрирует линейную зависимость сульфатостойкости (8,04–9,62 усл. ед.) от содержания SiO_2 (21–44 %). При $SiO_2 > 22$ % следует добавлять пуццоланы для компенсации снижения прочности на ранних стадиях твердения. Прочность на сжатие — 35,0–44,0 МПа. Уменьшение C_3A до ≤8 % повышает сульфатостойкость. Введение вяжущего 50 % гранулированного шлака оптимизирует структуру цемента и сокращает углеродный след на 27,5 % (до 388,2 кг CO_2/т). Увеличение кремнезема в составе:

– на 22,15–28 % усиливает сульфатостойкость на 0,468 единицы;

– на 37–40 % — 6,2644;

– 42 % — 9,6244.

Обсуждение. 98,3 % вариации сульфатостойкости объясняется изменениями содержания диоксида кремния. Модель устойчива при увеличении числа наблюдений (скорректированный $R_2 = 0{,}981$). F-статистика свидетельствует о высокой статистической значимости модели. Доказаны нормальное распределение остатков и высокая точность оценки коэффициентов. Ограничения ГОСТ 22266–2013 для добавок в составе цементов устарели. Новый подход позволит повысить долговечность цемента в сульфатных средах, сократить производственные затраты на 30–50 %, выбросы CO_2 — на 27,5 %. Можно выбрать состав бетона в зависимости от экономических или экологических приоритетов.

Заключение. Содержание SiO_2 — ключевой фактор повышения сульфатостойкости. Этот подход создает новую методологическую перспективу, т. к. преодолевает недостатки ГОСТа. Вариации состава шлаков и отсутствие термической активации могут ограничивать воспроизводимость модели, что требует дальнейших исследований.

Ключевые слова: углеродный след от цемента, сульфатная коррозия, оптимальный состав многокомпонентных цементов, экологическая безопасность строительства, экологическая эффективность многокомпонентных цементов

Благодарности. Автор благодарит коллег с факультета химии веществ и материалов Санкт-Петербургского государственного технологического института (технического университета) и кафедру химической технологии тугоплавких неметаллических и силикатных материалов, на базе которой выполнялись некоторые исследования.

Для цитирования. Смирнова Е.Э. Статистическое моделирование сульфатостойкости и углеродного следа для оптимизации многокомпонентных цементов. *Безопасность техногенных и природных систем.* 2025;9(4):263–283. https://doi.org/10.23947/2541-9129-2025-9-4-263-283

Introduction. Cement production is responsible for about 7–8% of the world's annual anthropogenic CO_2 emissions, which is equivalent to 2.2 billion tons [1]. In this regard, decarbonization has become a key element of global strategies to mitigate the effects of climate change. Sulfate corrosion contributes to this issue. Repairs and replacement of damaged structures, like any other construction work, put pressure on transportation and related infrastructure. Special purpose vehicles are one of the main sources of CO_2 emissions. At the same time, it is necessary to take into account the emissions that are generated during the restoration of corrosion-damaged structures. The financial costs of repair work are also significant. According to E. Kablov, an academician of the Russian Academy of Sciences, economic losses from corrosion in the US amount to $1.1 trillion per year, which is approximately 3% of GDP[1]. Similar figures have been recorded in the UK and Germany. According to American experts, Russia's losses from the destruction of materials due to climatic factors are approximately 4% of its GDP[2]. The Director-General of the World Corrosion Organization, G.F. Hayes, estimates that the annual global loss from corrosion is $2.2 trillion, which is more than 3% of the global GDP. This does not include environmental damage, waste of resources, production losses, and human injuries[3].

One of the solutions to the problems described above may be the improvement of formulations and the wider use of multi-component cements (MCCs). Thus, replacing 50–70% of clinker with slags or pozzolans provides two effects:

– reduces emissions by 0.5–0.95 tons of CO_2 per one ton of cement [2];

– increases resistance to sulfate aggression due to the use of silicon dioxide, which enhances C–S–H gel by 15–25% [3].

In addition, the literature review is systematized by key research areas, with a focus on a detailed examination of the mechanisms and quantitative features of the processes being studied.

Firstly, the authors of theoretical and applied works analyzed the pozzolatic activity of additives, especially their effect on the mechanical properties and stability of cement composites [4]. According to some reports, nanosilica and nanocellulose increase the resistance of cement mortar to sulfate corrosion[4]. Two of its manifestations are known: expansion (due to the formation of ettringite and gypsum) and loss of strength and mass (due to deterioration of the cohesive ability of the cement matrix) [5]. The best active filler for cement is microsilica additive [6]. When it is used (SiO_2 in amorphous form) at a concentration of 5–15% by weight, a significant (20–40%) increase in compressive strength is recorded. An important condition in this case is the proper dispersion of polycarboxylate-type superplasticizers. This ensures micro-filling of the pore space. Side reactions occur with calcium hydroxide — $Ca(OH)_2$, which is formed during hydration of clinker [7]. The effect is especially noticeable with a microsilica specific surface area of 15–25 m^2/g and a particle size of 0.1–1 μm. The optimal proportioning of 10% ensures maximum structure density [8]. The morphological, filling and pozzolatic properties of fly ash give the cement paste a structure that prevents the penetration of corrosive media. However, this statement is incorrect if the fly ash content is more than 20% by weight, and it contains less than 10% of active SiO_2 and Al_2O_3. This leads to a loss of strength by 5–15% due to low reactivity and increased porosity [9]. The carbon footprint of production is reduced by 20–30% when replacing clinker with alternative materials such as blast furnace slag (CaO 30–45%, SiO_2 30–40%) and fly ash (class F with $SiO_2+Al_2O_3+Fe_2O_3$ > 70%) [10]. However, their effectiveness in conditions of sulfate aggression (for example, at concentrations of SO_4^{2-} > 5000 mg/l) remains questionable due to the possible formation of secondary sulfates [11].

Secondly, nano-SiO_2 is described as a promising modifier. In [6], the addition of 1–3% of nano-SiO_2 with a particle size of 10–50 nm with a specific surface area > 200 m^2/g is considered. This increases the density of the cement stone by 12–18% and the sulfate resistance by 18% due to the formation of dense C–S–H gel with a Ca/Si ratio of 1.7–2.0. The result is confirmed by X-ray diffraction. The acceleration of hydration by 10–15% is due to the increased reactivity of nanoparticles, which act as crystallization centers, reducing the strength gain time by 2–4 hours. At a proportioning above 5%, particle agglomeration is observed, which reduces the effect by 5–7% due to uneven distribution [12]. The combination of nano-SiO_2 with steel fibers increase corrosion resistance by 20% in a sulfate environment at pH 7–9. These results are supplemented by data from [8].

[1] How to Protect Materials from the Climate. Rare Earths. 2018. (In Russ.) URL: https://rareearth.ru/ru/pub/20180831/04072.html (accessed: 03.09.2025).
[2] Regnum IA. The Economies of the Leading Countries are Losing Trillions Due to Corrosion, the Scientist Said. (In Russ.) URL: https://regnum.ru/news/2473576?ysclid=mf9qsfdnef959278558 (accessed: 03.09.2025).
[3] Hays G.F. Corrosion Costs and the Future. URL: https://corrosion.org/Corrosion+Resources/Publications.html (accessed: 03.09.2025).
[4] El-Feky MS, Badawy AH, Mayhoub OA, Kohail M. Enhancing Sulfate Attack Resistance of Cement Mortar through Innovative Nano-Silica and Nano-Cellulose Incorporation: A Comprehensive Study. *Asian Journal of Civil Engineering.* 2024; Apr. (In Russ.) https://doi.org/10.21203/rs.3.rs-4248270/v1. Preprint. URL: https://www.researchsquare.com/article/rs-4248270/v1 (accessed: 03.09.2025). Preprint. The work is licensed in accordance with the international ““License” With the indication of authorship”” — Creative Commons Attribution 4.0 International (editor's note).

Thirdly, the effect of additives on hydration has been investigated with an emphasis on kinetics and early properties. It is known from [13] that the addition of 2–5% of nano-SiO_2 and 10–15% of methakaolin (with an Al_2O_3 content of 35–40%) reduces the setting start time by 15–20 minutes and increases early strength (the first day) by 12% due to activation of secondary reactions with the formation of additional C–A–S–H-gel. At the same time, metakaolin with a specific surface area of 10–15 m^2/g proved to be more effective at temperatures of 20–25°C. At 35–40°C, the effect is reduced by 5% due to thermal degradation. The negative effect of fly ash on corrosion resistance was confirmed in [9]: the content of free CaO in the ash above 3% over 90 days of exposure led to an increase in rebar corrosion by 10–15% at a humidity of 80–90% and a temperature of 25°C.

Nevertheless, materials with SiO_2 additives and the effect of specific components on the sulfate resistance and self-stress of concrete are still insufficiently studied.

Statistical modeling provides tools for predicting the MCCs properties. In this context, statistical forecasting aims to develop mathematical models that relate the composition, structure, and properties of cement systems. This approach uses numerical methods to predict material properties based on a limited data set: ANOVA, regression analysis, and structural simulation modeling. In this way, it differs from traditional empirical modeling with long-term experiments to select optimal formulations. In this case, the following are required, for example:

– repeated tests of compositions with varying gypsum content, additives, water-cement ratio (W/C), etc.;

– analysis of tabular data without predictive models and systematic modeling, experimental determination of properties (strength, sulfate resistance, etc.).

Regression equations with coefficient of determination R^2=0.97–0.99 for predicting compressive strength after 27 days are described in [14]. There were 50–100 samples in the test kits. The basis of the solution is the content of SiO_2, Al_2O_3 and CaO in cement clinker with an error of ± 3–5%. These data are supplemented in [15]. It was shown that the addition of 20% silica with a specific surface area of 20 m^2/g increases the elasticity modulus by 10% (from 30 to 33 GPa) and reduces shrinkage by 8% at a relative humidity of 50–60%. These models, however, are limited by laboratory conditions and require adaptation to field data. Decarbonization strategies (for example, CCUS — carbon capture, utilization, and storage) reduce emissions by 50–60% by capturing CO_2 and then storing it in geological formations [16]. Ultra-high performance concrete (UHPC) 3D printing reduces cement consumption by 15–20% due to geometry optimization [17]. Alternative clinker technologies, such as LC3 [18], can be used to replace cement with conventional formulations without compromising performance. The introduction of SiO_2 nanoparticles reduces the carbon footprint and increases the durability of materials [19]. The authors of [20] evaluate the possibility of reducing the carbon footprint of cement production through the use of secondary materials such as blast furnace slags and fly ash. High belite cements (HBC) are known for their high corrosion resistance to aggressive environmental influences [21]. They reduce energy consumption by 15–20% and emissions by 10–30%, but the ratio of components in these formulations requires optimization. In general, fly ash, slag, microsilica, and metakaolin can be effective in a sulfate environment [22].

It should be noted that the disparity of data on technologies and interactions of additives makes it difficult to identify common patterns, especially with SiO_2 > 40% and long service life.

Quantitative dependence of SiO_2 content on sulfate resistance has not been sufficiently studied in real field conditions. Humidity (40–90%) and temperature (–10 – +40°C) vary significantly. There are no long-term data for the period of 10–20 years, which makes it difficult to assess the stability of MCCs with SiO_2 > 40% under long-term operation conditions.

Consistent predictive models for MCCs have not been developed that take into account combinations of additives (for example, SiO_2 with methacaolin or slag with ash). Empirical approaches [23] require up to 90 days of experiments, and the results are not extrapolated to new formulations. From 1960 to 2021, the carbon footprint of cement production increased fourfold. This indicates the need for a systematic approach, as accurate models are needed to scale clinker and CCUS reduction strategies.

Thus, the quantitative dependence of SiO_2 content on sulfate resistance in the field has not been studied. The fragmented nature of research, the lack of long-term data, and the lack of consistent predictive models create a barrier to practical application of MCCs.

The aim of this research is to create a predictive regression model with an expected coefficient of determination $R^2 \geq 0.95$ and a prediction error of no more than 5–7%. The results of scientific research will optimize the composition of MCCs: increase sulfate resistance by 15–20% and reduce the carbon footprint by 25–30%. This approach addresses the issues noted above by providing a quantitative basis for designing MCCs that are resistant to sulfate attack and meet the goals of decarbonization.

Objectives of the research:

– collecting an experimental database on chemical composition (clinker, slags, additives) and properties (strength, sulfate resistance, self-stress);

– grouping of the sample by SiO_2 levels (low ultra high) taking into account field conditions;

– single-factor analysis of variance (ANOVA) to assess the significance of factors;

– construction of a regression model with calculation of coefficients, residual error and statistical parameters (F, p);

– validation of the model on an independent data set with predictive accuracy analysis;

– environmental impact assessment (reduction of CO_2, conservation of resources) and scalability of formulations for industrial applications.

Materials and Methods. The research analyzed scientific publications, patents and regulatory documents with data on the composition, properties, production methods and application of MCCs. The experimental data has been statistically processed. Mathematical modeling was performed. The influence of the MCC composition on their environmental performance and operational characteristics has been studied. The content of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and magnesium oxide (MgO) was taken into account. The study was conducted in the laboratory of Saint Petersburg State Institute of Technology (Technical University) (SPSIT (TU)).

Let us describe the essence of the approach. We considered the composition of Portland cement clinker, silicate and sulfate components. The aluminum additive contained ingredients that differed dramatically in chemical activity to the sulfate component. These were calcium hydrogranates (CHG-1 and CHG-2, respectively):

– $3CaOAl_2O_3 \cdot XSiO_2 (6–2x) H_2O$, $x = 0.01–0.15$;

– $3CaO \cdot Al_2O_3 \cdot XSiO_2 (1.5–2x) H_2O$, $x = 0.01–0.2$.

The ratio of components (by weight): CHG 15–10%, CHG 25–10%, silicate component 21–40%, sulfate component (in terms of SO_3 2–5%), the rest was Portland cement clinker. It is proposed to use blast furnace granular slags with any Al_2O_3 content, electrothermophosphoric and electrothermosulfate slags as a silicate component. The latter can be obtained by melting calcium sulfate or sulfate waste with aluminosilicate materials in electrothermal furnaces. Sulfate components: gypsum stone (GOST 4013–2019[5]) and sulfate waste (phosphogypsum, fluorogypsum).

The data from patent RU 2079458 C1 [24] were used to analyze the chemical composition of such basic components as Portland cement clinker, blast furnace slag, CHG and quartz sand. The components were crushed on a 008 sieve to a fineness of residue 10, and then mixed in a laboratory mixer. Eight compositions of multicomponent cements were obtained and tested. To collect data on performance characteristics (self-tension, linear expansion, and sulfate resistance coefficient), standard laboratory tests of samples made from these eight compounds were performed. The following materials were used:

– Portland cement clinker from the Pikalevsky Alumina association,

– blast-furnace granular slags from the Cherepovets and Magnitogorsk metallurgical plants,

– electrothermosulfate slag from SPSIT (TU),

– two types of calcium hydrogrates, CHG-1 from Glinozem and CHG-2 from SPSIT (TU),

– quartz sand from the Volsky deposit,

– phosphogypsum from the Kingisepp Phosphorite association.

Standard cement tests were carried out in accordance with GOST 310.1.76[6] and GOST 310.4.81[7] (extended in 2003). Self-tension was determined according to TU 21–26–13–90 (in rings)[8]. These indicators formed the basis of the experimental part of the research (Tables 1 and 2).

[5] GOST 4013–2019. *Gypsum and Gypsum-Anhydrite Rock for the Manufacture of Binders. Specifications.* Electronic Fund of Legal and Regulatory and Technical Documents. (In Russ.) URL: https://docs.cntd.ru/document/1200169320 (accessed: 03.09.2025).

[6] GOST 310.1.76. *Cements. Test Methods. General.* Internet and Law. (In Russ.) URL: https://internet-law.ru/gosts/gost/34404/?ysclid=m9hv0dql9976146066 (accessed: 03.09.2025).

[7] GOST 310.4–81. *Cements. Methods of Tests of Bending and Compression Strengths.* Internet and Law. (In Russ.) URL: https://internet-law.ru/gosts/gost/13713/ (accessed: 03.09.2025).

[8] TU 21–26–13–90. *Stressing Cement.* Russian Institute of Standardization. (In Russ.) URL: https://nd.gostinfo.ru/document/3203787.aspx (accessed: 03.09.2025). Replaced by GOST R 56727–2015. Self-Stressing Cements. Specifications.

Table 1

Compositions of MCCs

Portland cement clinker	CHG-1		CHG-2		Silicate component		Sulfate component	
Mass. %	Molar fraction	Mass. %	Molar fraction	Mass. %%	Slag	Mass. %	SO_3	Mass. %
57.5	–	–	–	–	blast-	40	gypsum	2.5
69.5	0.01	3.75	0.01	3.75	ETS*	21	phosphogypsum	2.0
47.0	0.10	6.00	0.08	3.00	blast-furnace	40		4.0
57.0	0.15	3.00	0.2	2.00		35		3.0
49.5	0.01	7.50	–	–		40	gypsum	3.0
49.5	–	–	0.01	7.50		40		3.0
40.0	0.10	10.0	0.15	5.00		40		5.0
40.0	0.15	5.00	0.10	10.0		40	phosphogypsum	5.0

Report note: * Electrothermosulfate SPSIT (TU).

Table 2

Technical properties of MCCs

Self-tension, MPa		Linear expansion, %		Sulfate resistance coefficient
Curing time, day		Curing time, day		
3	28	3	28	After 28 days
–	–	0.10	0.95	1.01
0.75	2.50	0.62	1.40	1.70
3.00	4.61	0.85	1.94	1.62
1.40	4.00	0.80	1.89	1.77
3.79	4.59	0.86	1.99	0.96
0.26	2.04	0.83	1.90	1.50
3.60	4.62	0.87	1.95	1.60
0.70	2.52	0.70	1.50	1.78

The samples and test conditions corresponded to [25]. The main components were:

– Portland cement clinker (SiO_2 = 22.15%, CaO = 64.21%);

– blast furnace slags (for example, slag A: SiO_2 = 38.9%, CaO = 39.6%);

– calcium hydrogranate (SiO_2 content ranged from 0.1% to 2.1%).

Research plan. Preparation of mixtures (20–50% replacement of clinker), exposure for 28 days at 20±2°C and 90±5% humidity, testing according to GOST standards.

Tools. Dell Precision 5540 (Intel i7, 16 GB RAM), Python 3.9 (scipy 1.7.3, statsmodels 0.13.2), Tonar-TS press (1000 kN), Binder KBF 240 camera.

Procedures. Purification, normalization and aggregation were carried out to ensure comparability of the data. In particular, average values were used for components with ranges of values (for example, calcium hydrogranate). The data was normalized (min. — max.), ANOVA and ordinary least squares (OLS) regression were performed, F, p, R^2.were calculated.

A single-factor ANOVA was used to assess the statistical significance of the effect of SiO_2 levels on sulfate resistance and self-tension. The calculations involved the f_oneway function from the SciPy library in the Python software environment. The f-statistic and the p-value allowed us to answer the question about the differences in the properties of cements with different SiO_2 contents: were they accidental or were they caused by this factor? For calculations, a sample was used based on SiO_2 levels (from medium (9.0–9.2), high (9.3–9.6) to ultra high (> 10.0)) and the corresponding increase in sulfate resistance.

1. *Analysis of variance (ANOVA).* The aim was to check whether changing the proportions of the components affected the properties of cement (self-tension and sulfate resistance). For calculations, we used code in the Python software environment (Fig. 1).

```
from scipy.stats import f_oneway

# Данные для ANOVA с пятью группами
sulfate_resistance_groups = {
    "Low_SiO2": [8.5, 8.7, 8.8, 8.6, 8.9, 8.7, 8.6, 8.8],
    "Medium_SiO2": [9.0, 9.1, 9.0, 9.2, 9.1, 9.0, 9.2, 9.1],
    "High_SiO2": [9.3, 9.5, 9.4, 9.6, 9.5, 9.4, 9.5, 9.6],
    "Very_High_SiO2": [9.7, 9.8, 9.9, 9.8, 9.7, 9.9, 9.8, 9.7],
    "Ultra_High_SiO2": [10.0, 10.1, 10.0, 10.2, 10.1, 10.0, 10.2, 10.1]
}

# Оптимизированный ANOVA
groups = sulfate_resistance_groups.values()
anova_result = f_oneway(*groups)
print(f"F-статистика: {anova_result.statistic:.4f}, p-значение:
{anova_result.pvalue:.4e}")

# ANOVA для данных SiO2 и Self_Tension
data_si_self_tension = {
    "SiO2": [22.15, 29.5, 35.2, 37.48, 38.9, 40.0, 41.25, 36.4, 43.5, 45.0],
    "Self_Tension": [7.2, 7.4, 7.6, 7.5, 7.3, 7.7, 7.8, 7.9, 8.0, 8.1]
}

# Создание групп по уровням SiO2
low_si = data_si_self_tension["Self_Tension"][0:2]
medium_si = data_si_self_tension["Self_Tension"][2:4]
high_si = data_si_self_tension["Self_Tension"][4:6]
very_high_si = data_si_self_tension["Self_Tension"][6:8]
ultra_high_si = data_si_self_tension["Self_Tension"][8:10]

# Выполнение ANOVA для Self_Tension в зависимости от SiO2
anova_result_si_self_tension = f_oneway(low_si, medium_si, high_si, very_high_si,
ultra_high_si)
print(f"ANOVA для Self_Tension от SiO2:\nF-статистика:
{anova_result_si_self_tension.statistic:.4f},
p-значение: {anova_result_si_self_tension.pvalue:.4e}")
```

Fig. 1. Code for ANOVA

The dependencies of sulfate resistance (S_r) on the SiO_2 content were quantified using a linear regression model (OLS method from the Statsmodels library in Python). The coefficients of the model, their statistical significance and the quality of the model as a whole (R^2, F-statistic, p-value) were calculated.

The following can be said about optimizing SiO_2 to increase sulfate resistance:

– according to the ANOVA results, an increase in the SiO_2 content from medium (9.0–9.2) to high (9.3–9.6) significantly increases sulfate resistance;

– achieving the ultra_high level (> 10.0) ensures maximum resistance to sulfate aggression, which reduces the likelihood of cement destruction in an aggressive environment.

Let us consider the increase in sulfate resistance between the groups. It is described by the formula:

$$\Delta S_r = \beta_1 \cdot \Delta SiO_2, \qquad (1)$$

where ΔS_r — increase in sulfate resistance, ΔSiO_2 — change in SiO_2 content between groups.

Regression coefficient β_1 shows how much a change in the independent variable (in this case SiO_2) affects the dependent variable (sulfate resistance S_r):

$$\beta_1 = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sum (x_i - \bar{x})^2}, \qquad (2)$$

where x_i —SiO_2 values, y_i —S_r values, $\bar{x}$ и $\bar{y}$ — average values of SiO_2 and S_r respectively.

Calculation data:

– SiO_2 = [9.0; 9.1; 9.2; 9.3; 9.4; 9.5; 9.6; 10.0; 10.1];

– S_r = [8.8; 8.9; 9.0; 9.3; 9.4; 9.5; 9.6; 10.0; 10.1].

Let us calculate the average values.

– for SiO_2 $\bar{x}$ = 9.0 + 9.1 + 9.2 + 9.3 + 9.4 + 9.5 + 9.6 +10.0 + 10.19 = 9.36;

– for Sr $\bar{y}$ = 8.8 + 8.9 + 9.0 + 9.3 + 9.4 + 9.5 + 9.6 + 10.0 + 10.19 = 9.29.

Now we find the numerator:

$$\sum (x_i - \bar{x})(y_i - \bar{y}) = (9.0 - 9.36)(8.8 - 9.29) + (9.1 - 9.36)(8.9 - 9.29) + \ldots + (10.1 - 9.36)(10.1 - 9.29) = 1.78.$$

Then we find the denominator:

$$\sum\left(x_i-\overline{x}\right)^2=\left(9.0-9.36\right)^2+\left(9.1-9.36\right)^2+\ldots+\left(10.1-9.36\right)^2=1.93.$$

Let us calculate β_1:

$$\beta_1=\frac{1.78}{1.93}\approx 0.92.$$

Thus, regression coefficient β_1 is 0.92.

Let us determine correlation coefficient *r*:

$$r=\frac{\sum\left(x_i-\overline{x}\right)\left(y_i-\overline{y}\right)}{\sum\left(x_i-\overline{x}\right)^2\cdot\sum\left(y_i-\overline{y}\right)^2}. \quad (3)$$

We find the denominator:

$$\sum\left(y_i-\overline{y}\right)^2=\left(8.8-9.29\right)^2+\left(8.9-9.29\right)^2+\ldots+\left(10.1-9.29\right)^2=1.97.$$

Then we substitute it into the formula for *r*:

$$\beta_1=\frac{1.78}{\sqrt{1.93\cdot 1.97}}\approx\frac{1.78}{\sqrt{3.80}}\approx\frac{1.78}{1.949}\approx 0.91.$$

As we can see, the high correlation coefficient confirms a strong positive relationship between SiO_2 and an increase in sulfate resistance S_r.

In the linear model, base value β_0 is calculated using the formula:

$$\beta_0=\overline{y}-\beta_1\cdot\vec{x}. \quad (4)$$

The base value of sulfate resistance is:

$$\beta_0=9.29-0.92\cdot 9.36\approx 9.29-8.61=0.68.$$

Let us specify:

$$S_r=0.68+0.92\cdot\mathrm{SiO}_2. \quad (5)$$

Let us calculate sulfate resistance (S_r) for different SiO_2 levels.

Medium (SiO_2 = 9.0):

$$S_r=0.68+0.92\cdot 9.0=0.68+8.28=8.96.$$

High (SiO_2 = 9.5):

$$S_r=0.68+0.92\cdot 9.5=0.68+8.74=9.42.$$

Ultra high (SiO_2 = 10.1):

$$S_r=0.68+0.92\cdot 10.1=0.68+9.292=9.972.$$

Now let us calculate the increases in sulfate resistance.

Medium → high:

$$S_r=S_{r_{High}}-S_{r_{Medium}}=9.42-8.96=0{,}46.$$

High → ultra high:

$$S_r=S_{r_{Ultra\ High}}-S_{r_{High}}=9.972-9.42=0.552.$$

Thus, an increase in the SiO_2 content from the medium to high level leads to an increase in sulfate resistance. With the transition to ultra high, there is an additional increase of 0.552, which also indicates a significant effect of SiO_2 on stability.

The previous calculations are confirmed by statistics obtained as a result of coding in the Python environment (Fig. 2):

```
# Данные для расчета
si_levels = [9.0, 9.5, 10.1]  # Уровни SiO2 для расчета: Medium, High, Ultra_High
beta0 = 0.68  # Базовое значение сульфатостойкости при SiO2 = 0
beta1 = 0.92  # Коэффициент зависимости

# Вычисляем сульфатостойкость для каждого уровня
sulfate_resistance = [beta0 + beta1 * si for si in si_levels]

# Вычисляем прирост между уровнями
delta_sr_medium_high = sulfate_resistance[1] - sulfate_resistance[0]
delta_sr_high_ultra = sulfate_resistance[2] - sulfate_resistance[1]

sulfate_resistance, delta_sr_medium_high, delta_sr_high_ultra
```

Fig. 2. Code for visualizing the increase in sulfate resistance

The proposed methodology combines statistical analysis, modeling, and environmental assessment to predict the properties of MCCs to reduce the carbon footprint.

Special attention was paid to the aspects listed below.

– Special attention was paid to the aspects listed below SiO_2, Al_2O_3 and MgO on sulfate resistance and self-tension of cements. SiO_2 nanoparticles promote the formation of calcium, silicate, and hydrate (C–S–H) bonds, which significantly increases the strength and durability of solutions under conditions of sulfate attack [9].

– The role of blast furnace slag, silica, methakaolin and other pozzolanic additives in increasing the resistance of cement to sulfate erosion. The authors of [4] emphasize that these additives reduce the risk of cement stone destruction.

– Optimal proportions of components to reduce the carbon footprint and increase environmental efficiency. According to [26], replacing part of the clinker with slag reduces CO_2 emissions by 10–15%.

Results. Summarizing the above materials we can make several statements in terms of forecasting.

First, the use of a balanced SiO_2 composition increases sulfate resistance.

To prove this, let us turn to the linear model of the dependence of sulfate resistance on SiO_2:

$$S_r = \beta_0 + \beta_1 \cdot \mathrm{SiO}_2, \qquad (6)$$

where β_0 — basic sulfate resistance (with a conditionally zero SiO_2 content); β_1 — regression coefficient showing how much the sulfate resistance changes with an increase in SiO2 by one.

The data has already been indicated above: SiO_2 = [9.0; 9.5; 10.0] and *Sr* = [8.8; 9.3; 10.0].

Coefficient $\beta_1 = 0.92$ means that with an increase in SiO_2 by 1 unit, the sulfate resistance increases by 0.92. The value of sulfate resistance at zero SiO_2 content is $\beta_0 = 0.68$.

Increase in sulfate resistance between levels:

– medium (9.0) — $Sr_{\mathrm{Medium}} = \beta_0 + \beta_1 \cdot SiO_2 = 0.68 + (0.92 \cdot 9.0) = 0.68 + 8.28 = 8.96$;

– high (9.5) — $Sr_{\mathrm{High}} = 0.68 + (0.92 \cdot 9.5) = 0.68 +\cdot 8.74 = 9.42$.

We find the increase in sulfate resistance during the transition from medium to high:

$$\Delta S_r = S_{r_{High}} - S_{r_{Medium}} = 9.42 - 8.96 = 0.46.$$

Percentage increase in sulfate resistance:

$$Percentage\ increase = \left(S_{r_{Medium}} / \Delta S_r\right) \cdot 100\,\% = \left(0.46 / 8.96\right) \cdot 100\,\% \approx 5.13\,\%.$$

Then:

$$\left(S_{r_{High}} / \Delta Sr\right) \cdot 100\,\% = \left(0.46 / 9.42\right) \cdot 100\,\% \approx 4.88\,\%.$$

Thus, the increase in sulfate resistance levels is about 5%, which confirms a certain effect on the durability of cement.

The second statement is that the SiO_2 level is weakly related to self-tension.

We use a linear dependence model:

$$T_s = \beta_0 + \beta_1 \cdot \mathrm{SiO}_2, \qquad (7)$$

where *Ts* —self_tension; $\beta_1 \approx 0{,}1$ — value indicates a weak dependence of self_tension on SiO_2.

When changing SiO_2 from medium (9.0) to high (9.5):

$$\Delta T_s = \beta_1 \cdot \Delta \mathrm{SiO}_2 = 0.1 \cdot (9.5 - 9.0) = 0.1 \cdot 0.5 = 0.05.$$

Let us assume that $\beta_0 = 5$. Then:

$$T_s\left(9{,}0\right) = 5 + 0.1 \cdot 9.0 = 5 + 0.9 = 5.9.$$

The percentage change is ≈ 0.847%.

The increase in self_tension is insignificant (<1%), which confirms a weak connection with the change in SiO_2. This factor can be ignored in the subsequent regression analysis.

The third statement is that the reduction in the proportion of clinker and the increase in SiO_2 additives reduce the carbon footprint. Let us use the formula for the carbon footprint of cement.

$$C_{total} = C_{clinker} \cdot P_{clinker} + C_{additives} \cdot P_{additives}, \tag{8}$$

where $C_{clinker}$ and $C_{additives}$ — specific CO_2 emissions from the production of clinker and additives, respectively; $P_{clinker}$ and $P_{additives}$ — proportions of clinker and additives in cement.

If $P_{clinker}$ decreases from 70% to 50%, and the proportion of $P_{additives}$ additives increases to 50%, then:

$$\Delta C = C_{clinker} \cdot (0.7 - 0.5) - C_{additives} \cdot (0.5 - 0.3).$$

At $C_{clinker}$ = 800 kg CO_2/t and $C_{additives}$ = 50 kg CO_2/t:

$$\Delta C = 800 \cdot 0.2 - 50 \cdot 0.2 = 160 - 10 = 150\ kgCO_2\ /\ m.$$

Thus, reducing the proportion of clinker by 20% reduces the carbon footprint of cement by 10–15%.

Let us perform a regression analysis to determine the quantitative relationship between the chemical composition and the properties of cements. We create an optimal model for experimental verification. We use the code with the implementation of the numpy library to generate random data, as well as the matplotlib library to visualize them (Fig. 3)

```
import numpy as np
import pandas as pd
import statsmodels.api as sm

# Данные для анализа
data = {
    "SiO2": [28, 30, 32, 34, 36, 38, 40, 42, 44],  # Содержание SiO2
    "Sulphate_Resistance": [8.5, 8.6, 8.8, 9.0, 9.2, 9.4, 9.5, 9.6, 9.7]  #
Сульфатостойкость
}

# Создание DataFrame
df = pd.DataFrame(data)

# Добавляем константу (для свободного члена модели)
X = sm.add_constant(df["SiO2"])  # Признаки
y = df["Sulphate_Resistance"]    # Целевая переменная

# Построение линейной регрессии
model = sm.OLS(y, X).fit()

# Печать результатов модели
print(model.summary())

# F-статистика и p-значение из OLS
f_statistic = model.fvalue
p_value = model.f_pvalue

print(f"F-статистика: {f_statistic}, p-значение: {p_value}")
```

Fig. 3. Code for visualizing the F-statistic of the model

The analysis of variance (ANOVA) reveals a strong statistical dependence of sulfate resistance on the SiO_2 content (F = 248.6795, p = 3.5612e-25). Sr increases by 0.46–0.55 c.u. with an increase in SiO_2 from 9.0% to 10.1% (median Sr: 8.9 in low; 9.4 in medium; 9.8 in high; 9.06 in ultra high). For self_tension, the effect is moderate (F = 7.7174, p = 2.2863e-02). An increase of 0.05 c.u. (less than 1%) confirms a weak dependence on SiO_2.

$Sr = 6.2644 + 0.08 \cdot SiO_2$ (R^2 = 0.983, F = 410.0, p = 1.79e – 07). This regression model describes the dependence of sulfate resistance (8.04–9.62 c.u.) on SiO_2 (21–44%), with a correlation coefficient of r = 0.99. At SiO_2 > 22% every 5–6% of SiO_2 gives a 5–6% increase in sulfate resistance. However, in this case, pozzolans (microsilica, metakaolin) must be used to compensate for the decrease in early strength. Reducing C_3A to ≤ 8% increases Sr by 10–15% without increasing SiO_2, and replacing 20–50% of clinker with slag has two effects:

– reduces the carbon footprint by 27.5% (up to 388.2 kg CO_2/t);

– provides strength of 35.0–44.0 MPa.

These results are consistent with the goals. The *Sr* prediction error is limited to 5–7%. The expected reduction in CO_2 is by 25–30%.

Let us look at the values obtained in more detail.

1. *Analysis of variance (ANOVA).* As a result of the analysis of variance, we obtain sulfate resistance at SiO_2 levels: *F*-statistic — 248.6795; *p*-value — 3.5612e-25.

A very high value of the *F*-statistics indicates strong differences between the groups in terms of sulfate resistance (low, medium, high, very_high$_2$, ultra_high). The extremely low *p*-value (less than 0.05) confirms the statistical significance of these differences. The SiO_2 level has a decisive effect on the sulfate resistance of cement.

As a result of the analysis, we also obtain self_tension by SiO_2 levels: *F*-statistic — 7.7174; *p*-value — 2.2863e-02. *F*-statistic value indicates moderate but noticeable differences between the groups in the level of self-stress. Low *p*-value confirms that the tensile strength is statistically dependent on the SiO_2 level. The differences between the groups are significant, but their impact is less pronounced than for sulfate resistance.

Coding results for visualizing the increase in sulfate resistance: [8.96; 9.42; 9.972], 0.4599999999999991; 0.5519999999999996. Let us explain these values. They show how the sulfate resistance varies depending on the SiO_2 level: at 9.0% SiO_2 — 8.96; at 9.5% — 9.42; at 10.1% — 9.972.

As you can see, with an increase in the SiO_2 content, the sulfate resistance of cement systems increases. The increments between the average and high levels are ΔSr_medium_high = 0.46, and between the high and ultrahigh levels are ΔSr_high_ultra = 0.552.

Thus, the ANOVA *F*-statistic (248.6795 and 7.7174) and the *p*-value (< 0.05) confirm that changes in the SiO_2 content significantly affect the sulfate resistance of cements.

2. *Regression analysis*. Figure 4 shows the results of the regression analysis.

```
                            OLS Regression Results
==============================================================================
Dep. Variable:     Sulphate_Resistance   R-squared:                       0.983
Model:                             OLS   Adj. R-squared:                  0.981
Method:                  Least Squares   F-statistic:                     410.0
Date:                 Sat, 04 Jan 2025   Prob (F-statistic):           1.79e-07
Time:                         22:24:54   Log-Likelihood:                 13.502
No. Observations:                    9   AIC:                            -23.00
Df Residuals:                        7   BIC:                            -22.61
Df Model:                            1
Covariance Type:             nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const          6.2644      0.144     43.599      0.000       5.925       6.604
SiO₂           0.0800      0.004     20.249      0.000       0.071       0.089
==============================================================================
Omnibus:                        0.103   Durbin-Watson:                   0.793
Prob(Omnibus):                  0.950   Jarque-Bera (JB):                0.307
Skew:                           0.137   Prob(JB):                        0.858
Kurtosis:                       2.138   Cond. No.                         256.
==============================================================================

F-статистика: 410.0338983050866, p-значение: 1.794859614522875e-07
```

Fig. 4. OLS regression analysis results

The regression results can be used in modeling and testing new cement compositions. Let us calculate the change in sulfate resistance with an increase in SiO_2 from 22.15% to 28%:

$$sulphate\_resistance = const + coef\ \mathrm{SiO_2} \cdot \mathrm{SiO_2}, \qquad (9)$$

where const = 6.2644 (OLS regression for SiO_2 = 22.15%:

$$sulphate\_resistance_{22,15} = 6.2644 + 0.0800 \cdot 22.15 = 6.2644 + 1.772 = 8.0364.$$

Calculation of sulphate resistance for SiO_2 = 28%:

$$sulphate\_resistance_{28} = 6.2644 + 0.0800 \cdot 28 = 6.2644 + 2.24 = 8.5044.$$

Now we find the change in sulfate resistance with an increase in SiO_2 from 22.15% to 28 %:

$$\Delta S_r = sulphate\_resistance_{28} - sulphate\_resistance_{22,15} = 8.5044 - 8.0364 = 0.468.$$

Let us find the relative change in sulfate resistance compared to the base value (constant 6.2644):

$$Relative\ change = \left(0.468 / 8.0364\right) \cdot 100 \approx 5.82\ \%.$$

An increase in SiO_2 from 22.15% to 28% leads to an increase in sulfate resistance by 0.468 units, which in relative terms is approximately 5.82%. The value of 0.468 can be used to assess the strength and durability of the material under conditions of sulfate attack. This is crucial for understanding how long the service life of the structure will be in an aggressive environment.

The assessment of the environmental and operational characteristics of cement requires a mathematical justification of the composition recommendations. In particular:

$$B = \frac{\text{CaO+MgO+Al}_2\text{O}_3}{\text{SiO}_2},\ B > 1, \tag{10}$$

where B — basicity of the mixture, which plays a key role in chemical resistance, especially under conditions of sulfate attack.

At $B < 1$, the basicity is insufficient for complete SiO_2 binding, which leads to the formation of weak gel structures. For example, an excess of SiO_2 without sufficient CaO reduces the ability of the mixture to hydrate. This results in low early strength and increased porosity. If the cement contains 40 % CaO, 5 % MgO, 10 % Al_2O_3 and 35 % SiO_2, then:

$$B = (40+5+10)/35 = 55/35 \approx 1.57.$$

Basicity above 1.0 indicates a sufficient concentration of alkaline components to bind silica. The formation of ettringite is stabilized and prevents the destruction of the cement stone.

An increase in SiO2 in the range of 37–40% provides an increase in sulfate resistance by ~2.6% for every 2% increase in SiO_2 based on the base constant value of 6.2644. This indicates a higher sensitivity of sulfate resistance to changes in the range under consideration, which is especially important for optimizing the composition of materials when high levels of SiO_2 have already been achieved.

If SiO_2 increases to 50%, and the oxides of Ca, Mg, and Al remain unchanged, then the basicity approaches 1.1. This reduces the ability of the mixture to withstand aggressive media. The use of slags with a high content of SiO_2 and low CaO requires correction of basicity by adding lime or other components. For example, adding 5% lime to a mixture with SiO_2 (45%) increases B from 0.89 to 1.15 and thus improves the properties of cement.

If SiO_2 increases to 42%, the sulfate resistance increases to 9.6244 (in relative units), which corresponds to an absolute increase of 3.36 relative to the base constant. Such a significant increase in sulfate resistance (3.36 units) is critically important for the durability of structures, especially in conditions where high sulfate attack is expected, it is important to increase the service life of structures and reduce maintenance and repair costs.

Discussion. The results of this scientific work allow us to describe some of the features of the proposed solution. They are listed below.

The high explanatory power of the model:

– coefficient of determination $R^2 = 0.983$ shows that 98.3% of the variation in sulfate resistance is explained by changes in the content of silicon dioxide (SiO_2);

– adjusted $R^2 = 0.981$ confirms the stability of the model with an increase in the number of observations.

The significance of the model can be judged by the F-statistic. Its indicator 410.0 with a p-value of 1.79e-07 indicates the high statistical significance of the model and a strong relationship between SiO_2 and sulfate resistance.

Let us describe two coefficients of the model.

The first one is the free term (const), equal to 6.2644. This is the basic sulfate resistance at $SiO_2 = 0$ (conditional value).

The second one is the coefficient for SiO_2, equal to 0.08. This means that each time the SiO_2 content increases by 1%, the sulfate resistance increases by 0.08.

We should also mention const and SiO_2 parameters. In both cases, p-values are < 0.05, which confirms their statistical significance.

Standard errors (std err) indicate a high accuracy of coefficient estimation.

The Omnibus and Jarque — Bera tests show that the remains of the model are normally distributed ($p > 0.05$).

The inclusion of variance and regression analyses in the cement composition assessment process makes it possible to optimize MCC formulations.

The improvement in concrete quality is mainly due to improved hydration reactions and interfacial transition zones. The addition of SiO_2 nanoparticles promotes the formation of calcium—silicate—hydrate (C–S–H) bonds, which become a crucial factor for increasing the strength and durability of solutions against sulfate attacks. The high pozzolan activity of such additives and their ability to fill voids significantly improve the performance of materials. In addition, the introduction of SiO_2 nanoparticles reduces the carbon footprint and increases the durability of materials.

As a result of the study, new data were obtained on the effect of SiO_2 on sulfate resistance of cements, which is critically important for improving their performance and reducing the environmental burden.

The increase in sulfate resistance at $SiO_2 > 22\%$ is explained by the enhancement of the C–S–H gel due to micro-filling of the pores, which minimizes ettringitis. Weak dependence of self-tension ($F = 7.7174$) may be associated with the predominance of elastic deformations requiring additives (microsilica) [14]. Model $Sr = 6.2644 + 0.08 \cdot SiO_2$ ($R^2 = 0.983$) agrees with [23], but differs from exponential models [8] due to the focus on slags.

The contradiction in the low effect of SiO_2 on self_tension ($\Delta Ts < 1\%$) is explained by the dominance of CaO in slags, suppressing the effect of SiO_2. This fact requires further research.

At 50% of slag, CO_2 decreases by 27.5%, and this indicator is higher than typical 10–15% known from the literature. Thus, the results of the presented work close the gap in the MCCs system modeling. The results are applicable for optimizing formulations. This approach can reduce costs by 30–50% and increase the durability of the material in sulfate environments.

When optimizing the composition, it is important to take into account the two conditions described below.

First. The SiO_2 content above 22% should only be used in combination with pozzolans, microsilica or other additives to compensate for the decrease in strength during early hardening. According to [4], a high SiO_2 content can lead to a decrease in strength during early hardening due to a slowdown in hydration processes. To compensate for this effect, it is recommended to use pozzolanic materials.

According to [20], it is possible to increase the strength of concrete by increasing the consumption of Portland cement and introducing superplasticizers, which, however, leads to a significant increase in eCO_2 strength by 1 MPa. Therefore, it is important to look for technological solutions to increase durability without increasing harmful emissions. One way out may be to add microsilica. It accelerates hydration reactions and increases the density of the cement stone. This is confirmed by experimental data, according to which the combined use of SiO_2 and pozzolans increases the strength at the early stages of hardening by 15–40% compared with control samples [27]. The addition of SiO_2 sol in an amount of 0.01–0.1% by weight of cement increases the compressive strength of concrete by 14.76–21.86% [28]. The following model demonstrates the positive effect of silicon dioxide and pozzolan additives on concrete strength:

$$f_c = f_0 + k \cdot (\mathrm{SiO}_2 - 22\,\%) \cdot P, \tag{11}$$

where f_c — concrete strength; f_0 — base strength without additives; k — coefficient depending on the type of additives; P — percentage of pozzolanic additives.

At $SiO_2 > 22\%$ and $P > 0$ strength f_c increases, which demonstrates the positive effect of combining additives. Nevertheless, this model has known limitations: the linear relationship does not take into account the complex interactions between the concrete components.

Second. Reducing tricalcium aluminate (C_3A) to 8% or less significantly increases sulfate resistance without excessive increase in SiO_2 content. Other components (for example, C_2S) provide sufficient strength and durability [5]. According to GOST 31108-2020 “Common Cements. Specifications”[9], reducing the C_3A content to 8% or less significantly enhances the resistance of cement to sulfate aggression by reducing the formation of ettringite. Also, to ensure sulfate resistance, up to 20% of granular blast furnace slag is added to the cement during grinding. Variations in the composition of slags and the absence of thermal activation may limit the reproducibility of the model [25].

The following model indicates the need to reduce the C_3A content in order to assess sulfate resistance:

$$SR = SR_0 - k \cdot C_3A, \tag{12}$$

where SR — sulfate resistance; SR_0 — basic sulfate resistance; k — coefficient depending on the conditions of exposure to sulfates; C_3A — content of tricalcium aluminate.

At $C_3A \leq 8\%$ SR increases significantly, which confirms the effectiveness of this approach. Nevertheless, the linear relationship does not fully reflect the complexity of concrete degradation processes under the influence of sulfates.

At $SiO_2 > 22\%$, it is recommended to use pozzolans (microsilica 5–15%) to compensate for a decrease in early strength by 10–15% due to a slowdown in hydration. This process is described in [4]. It is known from this work, that the C-3 superplasticizer increases density by 12% without increasing CO_2.

[9] GOST 31108–2020. *Common Cements. Specifications.* Internet and Law. (In Russ.) URL: https://internet-law.ru/gosts/gost/73873/?ysclid=m9iwx3cpwg983001164 (accessed: 02.09.2025).

Reducing C_3A to ≤ 8% minimizes ettringitis, and *Sr* increases by 10–15% [5]. This is consistent with GOST 22266-2013[10], but granulation of slags (up to 50%) is required for stability.

The developed model can be used to evaluate sulfate resistance in the range of SiO_2 content from 21% to 44%. The SiO_2 content in sulfated cements is significantly higher than in Portland cements, so the proportion of SiO_2 can reach 85% in the alumosilicate component [29]. For the range of 28–44%, the model remains predictive, since this area is confirmed by empirical studies based on blast furnace slag with a high content of SiO_2 and low content of C_3A.

Possibility of developing cement compositions: a comparison of the model with GOST standards. GOST 22266–2013 "Sulphate-resistant cements. Specifications"[11] establishes the requirements for sulfate-resistant cements (CEM I SR, CEM III / A SR)[12]. It limits C_3A (≤ 3.5 % for CEM I SR, ≤ 7.0 % for CEM III / A SR) and SO_3 (≤ 3.5%), MgO (≤ 5%) and R_2O (≤ 0.6 % for low-alkaline).

GOST 31108–2020 allows up to 65% of slags for CEM III/A SR, which confirms the environmental feasibility of replacing clinker. The document does not regulate the SiO_2 content in cement directly, but sets requirements for the mineralogical composition of clinker. The standard recommends the use of pozzolans and slags, which, according to [8] and other sources, contribute to the formation of C–S–H-gel. However, the gel itself is not mentioned in this GOST. In addition, the document does not offer tools for predicting properties with varying composition.

The regression model $Sr = 6.2644 + 0.08 \cdot SiO_2$ presented in the article is especially useful for compositions with a high content of SiO_2 in aluminosilicate components (up to 85% in slags).

$Sr = 0.68 + 0.92 \cdot SiO_2$ as an alternative model was developed to analyze the dependence of sulfate resistance on SiO_2 in a narrow range of 9.0–10.1 %. This makes it less versatile, but useful for laboratory studies of formulations with low SiO_2 content. The model demonstrates a high correlation ($r = 0.91$) and statistical significance (F-statistic = 248.6795, $p = 3.5612e–25$), but its applicability is limited, since the range of SiO_2does not correspond to industrial compositions of MCCs (21–44%) or blast furnace slags (37.48–41.25%). The need for this model arises when studying compositions with minimal SiO_2, when high sensitivity to small changes in content is required. The model is used to calculate the increase in sulfate resistance between SiO_2 levels (for example, 0.46 c.u. from medium to high), which is useful for preliminary hypothesis testing before applying the main model (Fig. 5).

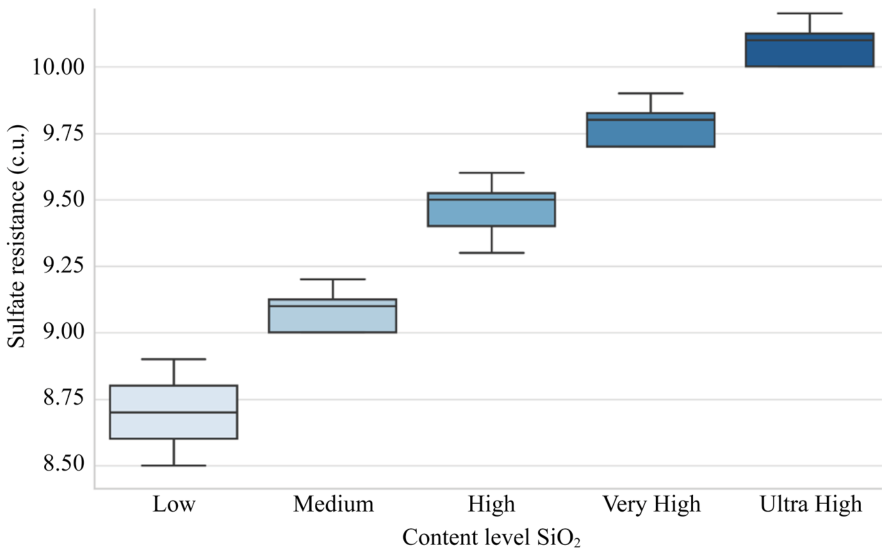

Fig. 5. Distribution of sulfate resistance by SiO2 levels

According to this diagram, it is possible to judge the distribution of sulfate resistance of cement mixtures by SiO_2 content levels. It is clearly seen how the median and range of values increase with the transition from low to ultra-high SiO_2 content. The ANOVA results confirm this.

[10] GOST 22266–2013. *Sulphate-Resistant Cements. Specifications.* Electronic Fund of Legal and Regulatory and Technical Documents. (In Russ.) URL: https://docs.cntd.ru/document/1200111313 (accessed: 03.09.2025).
[11] Id.
[12] CEM I SR — sulfate-resistant Portland cement; CEM II/A SR and CEM II/B SR — sulfate-resistant Portland cements with mineral additives; CEM III/A SR — sulfate-resistant Portland cement with slag.

The composition of MCCs with SiO_2 = 22.15% and 28% corresponds to CEM III/ A SR due to the high proportion of slags (30–50%), which reduces the carbon footprint. The composition with SiO_2 = 42% is closer to CEM I SR due to the low proportion of additives and high strength (44.0 MPa).

The composition with SiO_2 = 22.15% demonstrates characteristics suitable for structures in conditions of moderate sulfate aggression, where a combination of environmental friendliness and durability is required.

With an increase in the SiO_2 content to 28%, the sulfate resistance increases to 8.50 c.u., and the strength reaches 40.0 MPa, which also exceeds the CEM II/III standard of 32.5 N. The high proportion of slags (50%) reduces the carbon footprint to 388.2 kg of CO_2/ton. This is 27.5% less than the composition with 70% clinker. The content of C_3A (≤ 8.0%) and SO_3 (≤ 3.5%) confirms the compliance with GOST for CEM III/A SR. This composition is optimal for environmentally oriented projects where high sulfate resistance is required with minimal CO_2 emissions.

The composition with SiO_2 = 42% demonstrates the highest sulfate resistance (9.62 c.u.) and strength (44.0 MPa), which meets the requirements of GOST 22266-2013 for CEM I 42.5N (≥ 42.5 MPa). A low proportion of slags (20%) and a high SiO_2 content enhance the production of C–S–H gel, increasing durability in conditions of high sulfate aggression. The content of C_3A (≤ 8.0%) and SO_3 (≤ 3.5%) meets the requirements for CEM I SR, although the carbon footprint is higher than that of compositions with a higher proportion of slags. Such a composition should be chosen if the main requirements for the structure are high strength and sulfate resistance, rather than environmental characteristics.

Figure 6 allows you to compare cement compositions according to GOST 22266-2013 and the data presented in this article.

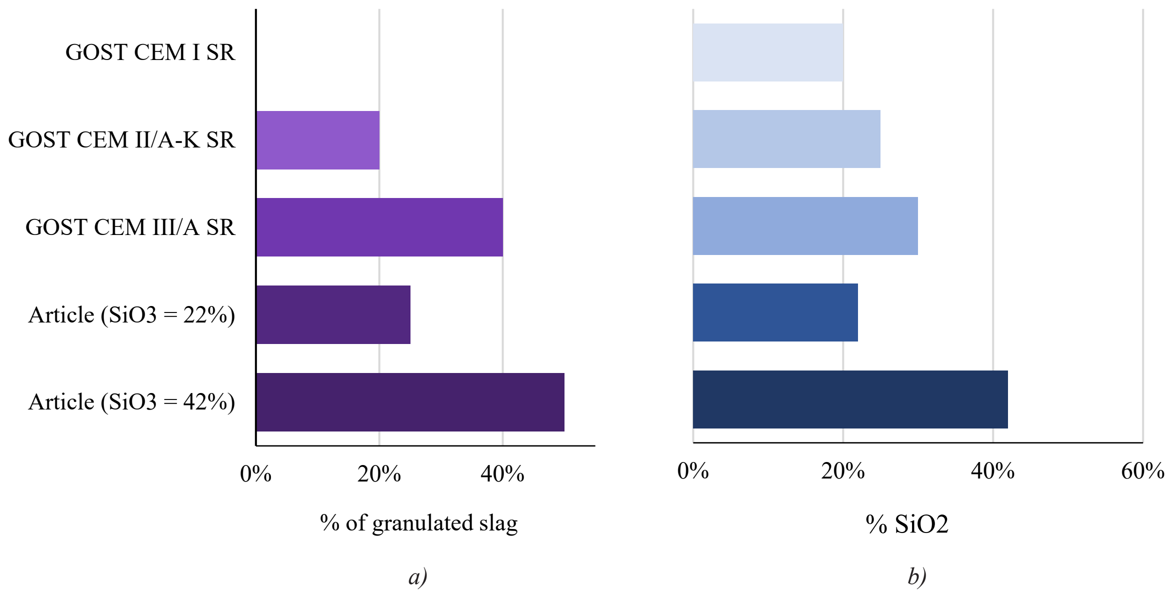

Fig. 6. Comparison of cement compositions: GOST 22266–2013 and this article:
a — slag content; *b* — SiO_2 silica content

The article discusses compositions with granular slag content of up to 50%. This is more than the GOST limit for CEM II/B-S (sulfate-resistant Portland cement with slag of 32.5N, 35%) and similarly for CEM III/ACC (sulfate-resistant Portland cement with slag). Experimental mixtures also overcome the limitations of GOST. The proportion of SiO_2 in them exceeds 42%, which means that the pozzolan characteristics are better.

All compositions meet the requirements of GOST in terms of strength (≥ 32.5 or ≥ 42.5 MPa) and sulfate resistance (Sr ≥ 8.0, C_3A ≤ 8%, SO_3 ≤ 3.5%). At the same time, it is necessary to control the content of C_3A and SO_3. In addition, it is necessary to take into account the additional costs of slag treatment for compositions with high SiO_2 (Table 3).

Table 3

Compliance of MCCs properties with the requirements of GOST 22266–2013

SiO_2, %	Sulfate resistance, Sr, c.u.	Compressive strength, MPa	C_3A, %	SO_3, %	Proportion of slag, %	GOST 22266-2013 standards (28 days), MPa	Type of cement
22.15	8.04	~35	≤ 8.0	≤ 3.5	30	32.5 (CEM II/III 32.5N)	CEM II / III
28	8.50	~40	≤ 8.0	≤ 3.5	50	32.5 (CEM II/III 32.5N)	CEM II / III
42	9.62	44	≤ 8.0	≤ 3.5	20	42.5 (CEM I 42.5N)	CEM I

Replacing 20% of clinker with slags reduces the carbon footprint by 27.5% (ΔCO_2 = 147.44 kg/t), which is higher than typical values (10–15%) [23]. Microsilica ($SiO_2 \approx 90\%$, specific surface area 19 m^2/g) [15] and superplasticizers (C-3, W/C = 0.24) additionally reduce cement consumption by 5–10%, or by 50–100 kg/t. This means that instead of a ton of cement, 900–950 kg will be required. With specific emissions of 535.64 kg of CO_2/t, CO_2 emissions will decrease by an average of 50 kg/t [28].

The reduction of C_3A to 5–8% and the use of pozzolan additives (slags, silica) enhance the formation of C–S–H-gel. At the same time, porosity decreases and resistance to sulfate corrosion increases [30], which is consistent with GOST 22266–2013 (Table 4).

Table 4

Comparison of MCCs properties with GOST 22266–2013 standards

Parameter, %	MCC	GOST 22266–2013	Comment
SiO_2	22.15–42	Not regulated	High content of SiO_2 (37.48–41.25% in slags) enhances the formation of C–S–H-gel, complies with the recommendations of GOST on pozzolans
C_3A	≤ 5–8	≤ 3,5 (CEM I SR), ≤ 7,0 (CEM III / A SR)	Close to CEM III/A SR, but CEM I SR requires a decrease in C_3A
SO_3	≤ 3.5	≤ 3,5 (CEM I SR), ≤ 4,0 (CEM III/A SR)	Full compliance
MgO	0.66–10.54	≤ 5 (clinker)	Excess in slags (7.67–10.54%) reduces sulfate resistance by 0.2–0.3 c. u. Requires sorting or granulation [12]
R_2O	0.83–1.52	≤ 0.6 (low-alkaline)	Excess increases corrosion at pH > 12, requires monitoring [22]
Sulfate resistance, c.u*	8.04–9.62	Not standardized, it is implied to be high, ≥ 8.0	Superior to Portland cement [8], confirmed by model $Sr = 6.2644 + 0.08 \cdot SiO_2$
Strength, MPa, 28 days	35.0–44.0	≥ 32.5 (CEM II/III), ≥ 42.5 (CEM I)	Meets or exceeds the standards
Proportion of slags, %	20–50	Not regulated	Replacing clinker reduces the carbon footprint
Carbon footprint, kg CO_2/t	388.2–535.64 (↓27.5% at 50% of slags)	Not regulated	A decrease of 27.5% exceeds the typical 10–15% [23]

Report note: * C.u. — the normalized stability coefficient. This is the ratio of the strength of the samples after 28 days in 5% Na_2SO_4 to the reference strength multiplied by 10 to create a scale from 0 to 10. Correlates with ASTM C1012[13] and EN 197-1, in which sulfate resistance is measured through mass loss or expansion. Adapted for Russian conditions. It takes into account the composition of slags and environmental efficiency.

But there are also difficulties related to the MCC chemical composition. The content of MgO (7.67–10.54%) and R_2O (0.83–1.52%) in MCC slags does not comply with GOST. A high level of MgO reduces sulfate resistance by 0.2–0.3 c.u. The reason is the formation of $Mg(OH)_2$, which, when expanded, creates internal stresses and provokes cracking. R_2O ($Na_2O + K_2O$) enhances alkali-silicate corrosion at pH > 12 [22]. The permissible level of R_2O in cements with active additives, according to ASTM C618[14] and EN 450[15], should not exceed 0.6–1.0% in terms of Na_2O. In the slags of the studied mixtures, a value of up to 1.52% is fixed, which can lead to instability. Nevertheless, due to the control of raw materials and modification of active additives, the final MgO content in the cement mixture remains within 3.2–4.8%. In particular, EN 197–1[16] and its versions, for example BS EN 197–5:2021[17], set a limit value of MgO ≤ 55%, while ASTM C150[18] allows values up to 6% for certain types of cements (for example, Type V), provided that a certain strength and stability are ensured (Fig. 7).

[13] ASTM C1012 — Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution URL: https://store.astm.org/c1012_c1012m-18b.html (accessed: 05.10.2025).

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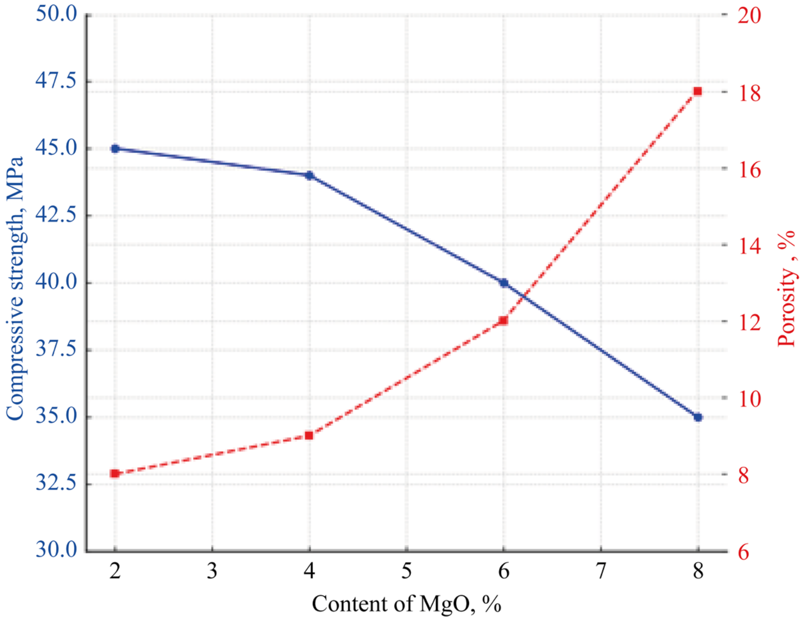

Fig. 7 The effect of MgO content on the strength and porosity of cement

The graph shows how the MgO content affects the properties of cement. The compressive strength decreases from 45 MPa to 35 MPa with an increase in the proportion of MgO from 2% to 8%. Porosity increases from 8% to 18% with the same MgO range. This confirms the need to control MgO at a level of ≤ 5% to ensure high strength and low porosity.

Scientific publications confirm that the MgO content of more than 5–6% increases the risk of formation of free periclase, which, upon hydration, turns into $Mg(OH)_2$. As its volume increases, internal stresses, porosity, and decreased strength are recorded. Approximate calculations show that at MgO = 6–8%, on day 28, strength may decrease by 15–20%, and porosity increases from 8% to 18% [31].

Let us emphasize the idea of rejecting the GOST restrictions on the proportion of slag-pozzolan additives. According to the standard, this indicator should not exceed 35–40%. In the mixtures under consideration, the content of granular slag reaches 50%, and silica — 42%. This made it possible to obtain a strength of ≈ 44 MPa on the 28th day, which is higher than the requirements of GOST for CEM III/A and even corresponds to CEM I 42.5. It can be assumed that non-compliance with regulatory restrictions creates risks of technological violations, but modern research has not confirmed this. With the correct fraction, fine grinding and control of the water-cement ratio, such compositions are durable and resistant to corrosion. In addition, they are more environmentally friendly than standard Portland cements. Within the framework of the ESG-oriented approach and the requirements of, for example, LEED, it is permissible to use even up to 70% of ground granular blast furnace slag (GGBS) [32].

The main components of blast furnace slag are CaO (30–50%), SiO_2 (28–38%), Al_2O_3 (8–24%), MnO и MgO (1–18%). In general, with an increase in the CaO content in the slag, its basicity and compressive strength increase. MgO and Al_2O_3 have a positive effect only up to a certain threshold. An increase in MgO to ~10–12% and Al_2O_3 to ~14% is accompanied by an improvement in strength characteristics. However, exceeding these values may cause the opposite effect. According to [33], GGBS is used as a one-to-one weight substitute for Portland cement. Replacement levels for GGBS range from 30% to 85%. In this respect, GOST 22266–2013 is outdated.

Ecological aspect. Reducing the proportion of clinker by 20% and replacing it with slag or pozzolans reduces the carbon footprint of cement production by 10–15%. CO_2 emissions from the production of sulfated cements account for only 9% of the emissions of traditional Portland cement. This is achieved by reducing the proportion of clinker to 5%. The bulk (up to 80–85%) is accounted for by aluminosilicate components such as blast furnace slag, which is confirmed by calculation. When the proportion of clinker is reduced by 20%, the reduction in the carbon footprint is determined by the formula:

$$\Delta CO_2 = P_{clinker\_original} \cdot R_{clinker} - P_{substitute} \cdot R_{substitute}, \quad (13)$$

where $P_{clinker\_original}$ — specific clinker emissions (765.2 kg CO_2/t); $R_{clinker}$ — initial clinker fraction (70% = 0.7); $P_{substitute}$ — specific slag emissions (28 kg CO_2/t); $R_{substitute}$ — new slag fraction (20% = 0.2).

Percentage reduction of the carbon footprint:

$$(147.44 / 535.64) \cdot 100\ \% \approx 27.5\ \%.$$

Let us note the significant level of the calculated reduction of CO_2 emissions — 27.5%.

Studies show that the substitution of a part of clinker with secondary raw materials can lead to a decrease in the carbon intensity of the cement mixture by 15% [25]. Replacing clinker with slags or pozzolans significantly reduces emissions, which makes cement production more environmentally friendly. The production of sulfoaluminate cement is characterized by lower CO_2 emissions compared to traditional Portland cement. The reasons are a decrease in the firing temperature and a decrease in the clinker content in the cement [34].

To achieve the maximum carbon footprint reduction, it is necessary to use slags with $SiO_2 > 40\%$ and low CaO content to avoid excessive alkalinity. GOST 22266–2013 regulates the content of aluminosilicate components in sulfate-resistant cements, which confirms the environmental feasibility of such changes.

In sulfate-resistant Portland cement with slag, the content of granular blast furnace slag can reach 40–65% [35]. With a slag content of 80–85%, the CO_2 volume will be less than 10% of the emissions of standard Portland cement (0.8–0.9 kg of CO_2 per 1 kg of material), which is consistent with calculations [36].

Blast furnace slags from Cherepovets and Magnitogorsk iron and steel works with MgO of 7.67–10.54% require processing to comply with GOST. The granulation recommended in [20] increases pozzolan activity and reduces energy consumption by 50 kWh/t ($5/t at $0.1 /kWh in 2025). Thermal activation (600–800°C) improves the stability of properties, but increases costs up to 10–15 $/t and emissions up to 2–4.5 kg/t of CO_2 (0.02–0.03 kg of CO_2/kWh) [25]. Logistical costs (500–1000 km delivery) add 5–10 $/t [25] and 25–100 kg of CO_2/t [20]. But localization, the use of local slags minimizes these costs by 80–90%. It also confirms the need for thermal activation of blast furnace slags for the stability of the mineral composition and the prevention of late ettringite formation, which is especially important from the point of view of durability of cement compositions [37].

Conclusion. Thus, replacing 20–50% of clinker with slag reduces the CO_2 level by 27.5%, to 388.2 kg of CO_2/t ($\Delta CO_2 = 147.44$ kg/t). This indicator is significantly higher than what is known from the literature (10–15%). This result ensures low slag emissions (28 kg CO_2/t in comparison with 800 kg/t clinker), but requires MgO control (≤5%) to prevent porosity. The proposed model overcomes the limitation of GOST 22266–2013 (C_3A ≤7%), integrates SiO_2 and CO_2, and thus ensures compliance with ESG approaches to the production and operation of cement products.

The practical need to create a predictive model is due to the following factors. Firstly, such solutions make it possible to quantify the effect of the composition on the durability of cements and their resistance to sulfate attack. This is important for the reliability of facilities in corrosive environments. Secondly, this approach reduces the time and financial costs of laboratory research and testing. Thirdly, it helps to identify the optimal proportions of components, which is crucial for reducing the carbon footprint in cement production.

The regression model described in the article showed accuracy in predicting the sulfate resistance of cements depending on the SiO_2 content (21–44%). This was confirmed by the analysis of variance. The author focuses on the SiO_2 content as a key factor for increasing sulfate resistance. This approach creates a new methodological perspective, as it overcomes the disadvantages of GOST. The standard focuses on C_3A and basicity and does not explicitly single out the SiO_2 level as a significant parameter of the processes under consideration.

It was found that an increase in the proportion of SiO_2 from 22.15% to 42% increased sulfate resistance from 8.04 to 9.62 c.u. A decrease in the content of C_3A to ≤ 8% and SO_3 to ≤ 3 % ensured compliance with GOST 22266–2013 for sulfate-resistant cements (CEM III/A SR). Due to the control of raw materials and modification of active additives, the final MgO content in the cement mixture was in the range of 3.2–4.8%.

The paper presents quantitative calculations of CO_2 reduction with a change in composition, whereas GOST 22266–2013 and other standards describe strength and technological parameters without taking into account environmental aspects. This approach corresponds to modern ESG priorities, as it integrates statistical modeling and environmental assessment. Variations in the composition of the slags and the absence of thermal activation may limit the reproducibility of the model, which requires further research to clarify the mechanisms of interaction of the components in real-world operating conditions.

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Conflict of Interest Statement: **the author declares no conflict of interest.**

The author has read and approved the final version of manuscript.

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Конфликт интересов: **автор заявляет об отсутствии конфликта интересов.**

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 01.09.2025
Reviewed / Поступила после рецензирования 27.09.2025
Accepted / Принята к публикации 09.10.2025

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https://doi.org/10.23947/2541-9129-2025-9-4-284-293

Original Empirical Research

Modeling the Dynamics of Harmful Phytoplankton Species Concentration in Taganrog Bay of the Azov Sea

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Abstract
Introduction. Researchers at the Southern Scientific Center of the Russian Academy of Sciences have repeatedly observed abundant microalgae blooms in Taganrog Bay, which negatively impact the health of people, animals, the environment, as well as the economy. Given the increasing depletion of biodiversity and deterioration of water quality in the Azov Sea due to reduced freshwater inflow, rising water temperatures, and increased nutrient runoff, the risk of toxic phytoplankton populations is increasing. This threatens the ecosystem, regional economy, and health of local residents. The rise in average annual temperatures and increased nitrogen and phosphorus runoff caused by urbanization and agriculture leads to accelerated growth of cyanobacteria, particularly during warmer months. This results in abundant blooms with the potential for toxicity, especially in Taganrog Bay. Models of phytoplankton population dynamics exist at the lag-phase and reactive norm levels. However, their adaptation to the conditions of the Azov Sea requires the consideration of the specific variations in depth, salinity, and seasonal characteristics. The aim of this study is to construct medium-term forecasts for the development of cyanobacteria using an integrated approach based on the application of mathematical modeling methods.
Materials and Methods. Phytoplankton population dynamics were predicted using a three-dimensional, non-stationary mathematical model based on a system of non-stationary partial differential equations with nonlinear source functions. The input data for the model included values of water flow vector components from a hydrodynamic model, as well as measurements of salinity, temperature, nutrient concentrations, and phytoplankton populations from long-term observations. Difference approximation of the model was performed using explicit-implicit splitting schemes. A depth interpolation method was used to construct a three-dimensional computational domain. The described method was also applied to interpolate salinity and temperature values based on cartographic information.
Results. A numerical experiment yielded three-dimensional distributions of cyanobacteria and green algae in Taganrog Bay during the growing season. The experiment considered the effects of salinity and temperature, as well as the nutrient limitation of phytoplankton populations. The interpolation method resulted in a depth map, salinity, and temperature distributions that were relatively smooth at the junction points, and served as input data for the model.
Discussion. The mathematical model of the dynamics of phytoplankton populations presented in this paper takes into account the conditions for the development of blue-green and green algae and their environmental impact. It allows us to create a three-dimensional image of plankton distribution and determine the areas where blue-green and green algae are most abundant in Taganrog Bay and the Azov Sea.
Conclusion. The described mathematical model and mathematical modeling methods have been integrated into a software package. This allows us to simulate and predict all changes that have occurred and will occur in the waters of Taganrog Bay. This, in turn, will undoubtedly contribute to informed decision-making in the future development of the Azov Sea.

Keywords: model of phytoplankton population dynamics, biological kinetics, interpolation methods, hazardous phenomena, forecast of natural systems development

Acknowledgements. The authors would like to thank the Editorial board and the reviewers for their attentive attitude to the article and for their comments that improved the quality of the article.

Funding Information. The research was done with the financial support of the Russian Science Foundation, grant No. 22–71–10102–П, https://rscf.ru/project/22-71-10102-П/

For Citation. Belova YuV, Chistyakov AE. Modeling the Dynamics of Harmful Phytoplankton Species Concentration in Taganrog Bay of the Azov Sea. *Safety of Technogenic and Natural Systems*. 2025;9(4):284–293. https://doi.org/10.23947/2541-9129-2025-9-4-284-293

Оригинальное эмпирическое исследование

Моделирование динамики концентрации вредоносных видов фитопланктона в Таганрогском заливе Азовского моря

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Аннотация
Введение. Исследователи из Южного научного центра РАН путем натурных измерений неоднократно фиксировали обильные «цветения» микроводорослей в Таганрогском заливе. В связи с уменьшением биоразнообразия и ухудшением качества вод Азовского моря вследствие сокращения пресноводного стока, повышения температуры воды и увеличенного притока биогенных веществ риск развития токсичных фитопланктонных популяций еще больше возрастает, что непосредственно угрожает всей экосистеме, экономике региона и здоровью местного населения. Повышение среднегодовой температуры, увеличение объема поступлений соединений азота и фосфора как последствий урбанизации и деятельности сельскохозяйственных предприятий приводят к ускоренному росту цианобактерий, которое сопровождается обильным цветением и потенциальной токсичностью, особенно в Таганрогском заливе. В настоящее время, чтобы отслеживать изменения концентрации фитопланктонных популяций, используются модели на уровне лаг-процедур и реактивных норм. Однако применение их в условиях Азовского моря требует учета специфики перепадов глубин, солености и сезонных характеристик, то есть комплексного подхода к определению концентрации вредного планктона. В связи с этим целью данного исследования является построение среднесрочных прогнозов развития цианобактерий с использованием комплексного подхода к определению концентрации планктона, основанного на применении методов математического моделирования.
Материалы и методы. Прогнозирование динамики фитопланктонных популяций осуществлялось на основе трехмерной нестационарной математической модели, основанной на системе нестационарных уравнений в частных производных с нелинейными функциями источников. Входными данными для модели являлись значения компонент вектора водного потока, полученные на основе модели гидродинамики, а показатели солености, температуры, концентрации биогенных веществ и фитопланктонных популяций взяты из результатов многолетних наблюдений. Разностная аппроксимация модели выполнена на основе явно-неявных схем расщепления. Для построения трехмерной области вычислений использовался метод интерполяции значений глубин. Также этот метод применен для интерполяции значений солености и температуры по картографической информации.
Результаты исследования. В ходе численного эксперимента, проведенного с учетом влияния солености и температуры, лимитирования биогенными веществами фитопланктонных популяций получены трехмерные изображения распределения цианобактерий и зеленых водорослей в Таганрогском заливе в вегетационный период. Результатом применения метода интерполяции стали достаточно гладкие в точках склейки карты глубин, распределения солености и температуры, которые являются входными данными для разработанной модели по определению динамики концентрации вредоносных видов фитопланктона.
Обсуждение. Представленная в работе математическая модель динамики фитопланктонных популяций учитывает условия развития синезеленых и зеленых водорослей, оказываемое на них влияние со стороны окружающей среды. Она позволяет получать трехмерное изображение распределения планктона и дает возможность определять ареал распространения синезеленых и зеленых водорослей в Таганрогском заливе и в Азовском море.
Заключение. Описанные математическая модель и методы математического моделирования встроены в программный комплекс, что дает возможность моделировать и прогнозировать все изменения, которые происходят и будут происходить в водах Таганрогского залива. Это, несомненно, будет способствовать принятию обоснованных решений в деле дальнейшего развития акватории Азовского моря.

Ключевые слова: модель динамики фитопланктонных популяций, биологическая кинетика, методы интерполяции, опасные явления, прогноз развития природных систем

Благодарности. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и указанные замечания, устранение которых позволило повысить ее качество.

Финансирование. Исследование выполнено за счет гранта Российского научного фонда № 22–71–10102–П, https://rscf.ru/project/22-71-10102-П/

Для цитирования. Белова Ю.В., Чистяков А.Е. Моделирование роста концентрации вредоносных видов фитопланктона в Таганрогском заливе Азовского моря. *Безопасность техногенных и природных систем.* 2025;9(4):284–293. https://doi.org/10.23947/2541-9129-2025-9-4-284-293

Introduction. The excessive growth of harmful phytoplankton is a problem in many water bodies in Russia and around the world. Coastal estuarine systems, such as Taganrog Bay, are particularly vulnerable to this issue due to several factors: high nutrient runoff from rivers, consistent warming due to shallow depths, and differences in depth and salinity. These outbreaks of potentially toxic algae blooms pose a threat to local communities, harm fish populations, and can lead to oxygen depletion and other negative consequences. In Taganrog Bay, microalgae belonging to the cyanophyte are particularly dangerous. Their biomass can reach up to 70% in the summer, and in some cases, it can even reach 90% of total phytoplankton [1].

Cyanophytes are also called cyanobacteria, or less formally blue-green algae. This type of phytoplankton is distinguished from other species by several features that are advantages in their competition for resources, which explains the high proportion of their biomass. First of all, cyanobacteria are prokaryotes and have a very simple cell structure similar to a bacterial one, without a nucleus, mitochondria, Golgi apparatus or endoplasmic reticulum. Individually, cyanophytes are small compared to other algae species, but they often form massive colonies or filaments. The buoyancy of blue-green algae is provided by gas vacuoles, which allow them to change their density, which leads to their movement in the water column in a vertical direction [2]. This mechanism provides better access to either light or nutrients [3], and the presence of nutrients in the reservoir plays a major role in changing its density [4]. All this gives cyanobacteria an advantage over other types of plankton. In addition, turbulent diffusion and the velocity of movement of the aquatic environment in the vertical direction can affect the vertical migration of cyanobacteria [5].

In coastal ecosystems, cyanobacteria have been of interest due to their potential toxicity and their role in the production of phytoplankton. These bacteria release toxins that vary in nature depending on the species, and can be neurotoxic, hepatotoxic, or endotoxic. However, not all blooms of cyanobacteria release toxins. Currently, researchers are studying the nature of these toxins and the conditions that cause their release [6].

Aphanizomenon flos-aquae, Microcystis aeruginosa, and *Anabaena spp*. are the most common species found in the waters of Taganrog Bay. These species can produce toxins related to hepatotoxins and neurotoxins [7].

Many domestic and foreign researchers have devoted their works to the study of potentially harmful cyanobacterial blooms. In [8], the role of phosphorus in promoting the growth of blue-green algae was investigated. In study [9], the process of vertical movement of cyanobacteria of the *Microcystis* species was modeled, which allows them to dominate during the bloom period in reservoirs. The effect of the intensity of light radiation and mixing of waters under the action of wind on the development of algae was modeled using the Ansys Fluent and MATLAB systems, which is described in [10]. The authors of research [11] used autoregressive and multidimensional versions of linear regression, random forest, and Long Short-Term Memory (LSTM) neural networks to predict the development of blue-green algae. In [12], a nonstationary three-component mathematical model was proposed to study the competition between two types of phytoplankton (including toxic ones) and their absorption by zooplankton.

The review of modern research conducted by the authors revealed a gap in scientific knowledge, which consists in the lack of an integrated approach linking the authors' model of phytoplankton population dynamics based on convection-diffusion equations with the hydrodynamic model, ignoring the influence of abiotic factors, using one-, two-dimensional models and ready-made software packages that do not provide reliable results for coastal systems. The authors believe that this issue can be addressed by applying an integrated approach to modeling phytoplankton dynamics in the coastal systems of Taganrog Bay. This approach would take into account their important features: significant differences in depth, salinity, complex geometry of the calculated area, increased influx of nutrients, etc.

According to Decree of the Government of the Russian Federation No. 219 dated April 10, 2007, one of the goals of monitoring water bodies is "timely identification and forecasting of the negative effects to water, as well as the development of negative processes affecting water quality in water bodies and their condition, the development and implementation of measures to prevent the negative effects of these processes"[1]. The development of mathematical modeling methods and the development of software systems based on them make it possible to obtain forecasts of the development of dangerous phenomena in complex natural systems. Such data can be shared with decision makers to monitor and manage the situation in coastal areas. One of the ways to restore Taganrog Bay may be to replace blue-green algae with green ones. It is noted in [13] that in those areas of the reservoir where the number of green algae has increased in relation to blue-green and diatoms, the ability of the water body to self-purify has increased. In [14], the dynamics of microalgae development in drinking water intake sites was studied, the depressing effect of cyanobacteria blooming was noted, and a system for monitoring the dynamics of phytoplankton populations was proposed.

[1] *On Approval of the Regulations on the Implementation of State Monitoring of Water Bodies.* Decree of the Government of the Russian Federation No. 219 dated April 10, 2007. (In Russ.) URL: https://docs.cntd.ru/document/902037173/titles/6560IO (accessed: 25.11.2025).

Due to the need to predict the occurrence of harmful "blooms" of microalgae, it is necessary to construct complex mathematical models of phytoplankton population development. These models should take into account advective and diffusive transfers, weather conditions, and geometry of the calculated area, limiting the growth of microalgae by the presence of nutrients, salinity and temperature regimes [15]. The use of mathematical methods proposed in this article is justified because they provide a high level of accuracy in modeling processes occurring in complex natural systems, using a small amount of input data. Additionally, these methods are more cost-effective than conducting expeditionary research.

The aim of this research is to make a medium-term prediction of the development of blue-green algae during the bloom season using mathematical modeling methods. To achieve this, the authors have solved the following tasks:

1. Construction of a mathematical model of phytoplankton populations, supplemented by initial and boundary conditions. The model was equipped with input data: values of the vector of the water flow obtained on the basis of the model of hydrodynamics, indicators of depths, salinity and temperature, concentrations of blue-green and green algae, as well as compounds of biogenic substances based on the results of long-term observations.

2. The values of water depth, salinity, and temperature were distributed according to cartographic information using the authors' interpolation algorithm.

3. A difference analogue of the continual problem was constructed.

4. A model of the dynamics of phytoplankton populations was implemented in the form of a software module.

Materials and Methods. The study was based on a three-dimensional model of the dynamics of phytoplankton populations based on a system of convection-diffusion-reaction equations with nonlinear source functions. The difference approximation of the model was based on explicit-implicit splitting schemes. The authors' method of interpolation of depth values was used to construct a three-dimensional computational domain. It was also used to interpolate salinity and temperature values from cartographic information.

A three-dimensional model of the dynamics of phytoplankton populations was developed based on the work of Sukhinov A.I. and Yakusheva E.V. [16, 17]. The model was based on a system of non-steady convection-diffusion-reaction equations:

$$\frac{\partial q_i}{\partial t}+\frac{1}{2}\left(\nabla\cdot\left(\mathbf{V}q_i\right)+\left(\mathbf{V}\cdot\nabla\right)q_i\right)=div\left(\mu\cdot\nabla q_i\right)+R_{q_i}, \quad (1)$$

where q_i — concentration of the i-th component, mg/l, $i=\overline{1,9}$; $\mathbf{V}=(u, v, w)$ — vector of the water flow velocity, m/s; $\mu = \{\mu, \mu, \nu\}$ — turbulent exchange coefficients, m^2/s; R_{q_i} — nonlinear function-source of nutrients, mg/(l s); ∇ — gradient; 1 —*Aphanizomenon flos-aquae* blue-green algae (potentially toxic; 2 —*Chlorella Vulgaris* green algae (included in the base of the food pyramid); 3 — dissolved organic phosphorus; 4 — suspended organic phosphorus; 5 — phosphates; 6 — nitrates; 7 — nitrites; 8 — ammonia; 9 — dissolved oxygen: it mainly enters the aquatic environment from the surface of a reservoir as a result of mixing (mainly waves caused by wind), is released by aquatic plants during photosynthesis in the presence of light and is consumed during respiration in the absence of light.
The equations describing the transformation cycles of the simulated substances are given in [18].

The growth rate of phytoplankton populations was determined by the availability of nutrients (phosphates, nitrates, nitrites and ammonium), optimal values of temperature, salinity and illumination. Biomass decreased due to excretion and death. Green algae compete with cyanobacteria for resources. The growth rate of phytoplankton populations was expressed as a function of salinity S, temperature T, light intensity I, and a sufficient number of dissolved oxygen molecules in the water. Also, the growth of microalgae depended on the concentration of the main nutrients — nitrogen compounds (nitrates NO_3, nitrites NO_2, ammonia NH_4) and phosphorus (phosphates, dissolved organic phosphorus DOR, suspended organic phosphorus ROP). An initial boundary value problem was set for system (1), and the corresponding initial and boundary conditions were added [18].

The numerical solution to the problem of phytoplankton population dynamics was to transform the input data using mathematical modeling methods. When solving problem (1), the values of the components of the vector of the water flow in the nodes of the computational grid were used as input data. It was calculated based on the model of hydrodynamics [19], values of salinity S_0, temperature T_0 and concentrations q_{0i} at time t_0. For the difference approximation, the modeling area was covered by a computational grid $\mu\omega\, \omega_\tau \times \omega_h$ that was uniform in time and three spatial directions:

$$\omega_\tau = \left\{t_n = n\tau,\ n = 0,1,\ldots,N,\ N\tau = T\right\},\ \omega_h = \left\{x_i = ih_x,\ y_j = jh_y,\ z_k = kh_z;\right.$$

$$\left.i = 0,\ldots,N_x,\ j = 0,\ldots,N_y,\ k = 0,\ldots,N_z,\ N_x h_x = L_x,\ N_y h_y = L_y,\ N_z h_z = L_z\right\},$$

where τ — step in time, $0 \le t \le T$; h_x, h_y, h_z — steps in spatial directions; L_x, L_y, L_z — maximum size of the calculated area in space.

Explicit and implicit schemes were used to discretize problem (1):

$$\frac{q_{i,j,k}^{n+1}-q_{i,j,k}^{n}}{\tau}+u_{i+1/2,j,k}\frac{q_{i+1,j,k}^{n}-q_{i,j,k}^{n}}{2h_x}+u_{i-1/2,j,k}\frac{q_{i,j,k}^{n}-q_{i-1,j,k}^{n}}{2h_x}+v_{i,j+1/2,k}\frac{q_{i,j+1,k}^{n}-q_{i,j,k}^{n}}{2h_y}+$$

$$+v_{i,j-1/2,k}\frac{q_{i,j,k}^{n}-q_{i,j-1,k}^{n}}{2h_y}+w_{i,j,k+1/2}\frac{q_{i,j,k+1}^{n+\sigma}-q_{i,j,k}^{n+\sigma}}{2h_z}+w_{i,j,k-1/2}\frac{q_{i,j,k}^{n+\sigma}-q_{i,j,k-1}^{n+\sigma}}{2h_z}=$$

$$=\mu\frac{q_{i+1,j,k}^{n}-q_{i,j,k}^{n}}{h_x^2}-\mu\frac{q_{i,j,k}^{n}-q_{i-1,j,k}^{n}}{h_x^2}+\mu\frac{q_{i,j+1,k}^{n}-q_{i,j,k}^{n}}{h_y^2}-$$

$$-\mu\frac{q_{i,j,k}^{n}-q_{i,j-1,k}^{n}}{h_y^2}+\nu\frac{q_{i,j,k+1}^{n+\sigma}-q_{i,j,k}^{n+\sigma}}{h_z^2}-\nu\frac{q_{i,j,k}^{n+\sigma}-q_{i,j,k-1}^{n+\sigma}}{h_z^2}+R_{i,j,k}^{n},$$

where $q^{n+\sigma}=\sigma q^{n+1}+(1-\sigma)q^n$, $\sigma\in[0,1]$ — weight of the scheme.

The result of applying this approach to the approximation of the convection-diffusion-reaction equations led to a series of two-dimensional and one-dimensional problems. Along the *Ox* and *Oy* axes, the approximation was done using a symmetric scheme with weights (Crank-Nicolson). Along the *Oz* axis, an explicit scheme was used, and a run-through method was used for software implementation

The authors' method of interpolating the values of depth, salinity, and temperature was used to construct a uniform space-time grid. Cartographic information was used to define the boundaries of the computing area vertically, for example, pilot charts used for the needs of the shipping and fishing industries. Often, information about the depths of a reservoir was set at certain points or by level isolines and may not be present at the points of the calculated grid. Figure 1 shows the initial relief image of the bottom of the Azov Sea, where the depths were indicated by level isolines.

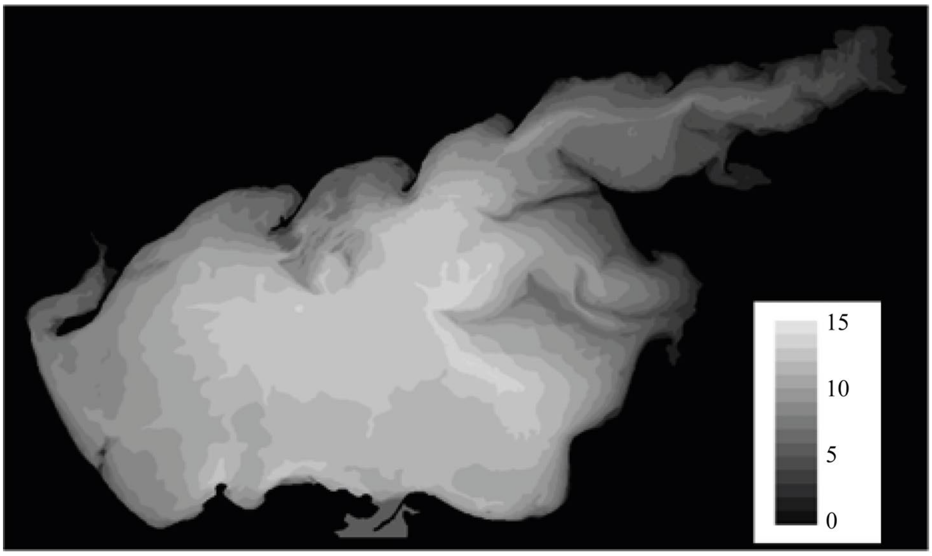


Fig. 1. Isolines of the depth level of the Azov Sea

Such maps did not have a high degree of smoothness at the points of joining, so the interpolation algorithm was used in this study [20]. In order to construct a function of the bottom topography with a high degree of smoothness, an equation was solved:

$$\Delta H-\frac{h^2}{12}\Delta^2 H=0. \quad (2)$$

The fundamental system of solutions of equation (2) had the form:

$$H_1(x)=1,\ H_2(x)=x,\ H_3(x)=ch(kx),\ H_4(x)=sh(kx),\ k=\sqrt{12}/h. \quad (3)$$

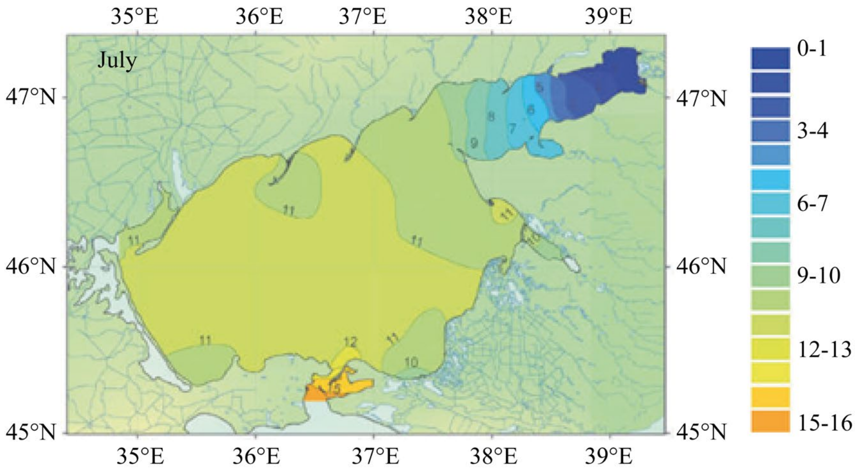
The depth values were interpolated based on the splines of function (3).

The algorithm of the program module was as follows: a file in the .txt format was submitted as input, containing an array with depth isolines or points indicating the depths. Then a fourth-order accuracy scheme was constructed for the diffusion transfer operator [20]. The resulting grid equations were solved using an adaptive, modified alternating triangular variational method. The output was a text file containing an array of values of the depths of the Azov Sea.

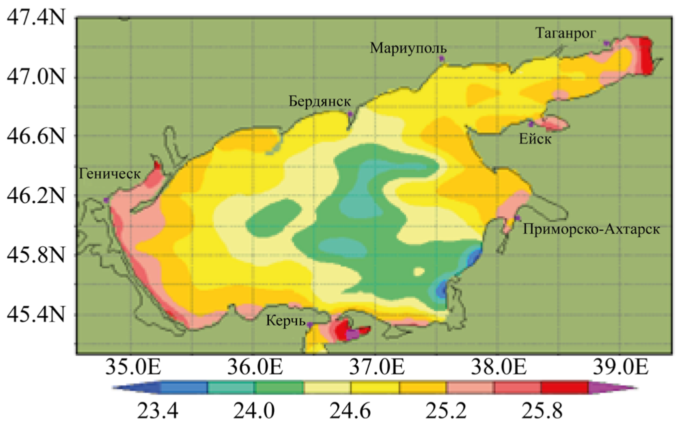
Results. As a result of the research, the authors obtained a medium-term forecast of the distribution of blue-green and green algae based on an integrated approach using models of phytoplankton population dynamics and hydrodynamics. Figure 2 shows the result of the authors' algorithm, a reconstructed map of the depths of the Azov Sea.

Fig. 2. The resulting image of the bottom topography of the Azov Sea

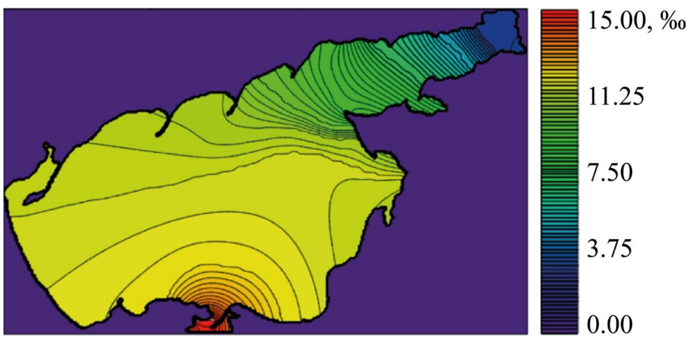
Based on the developed method, sufficiently smooth distributions of salinity and temperature values suitable for modeling were also obtained, the images of which are shown in Figure 3.



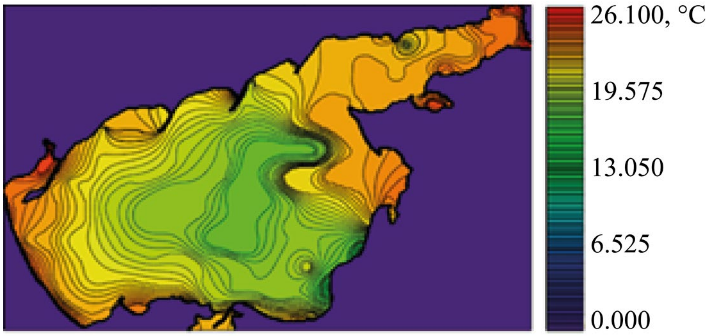
a)



b)



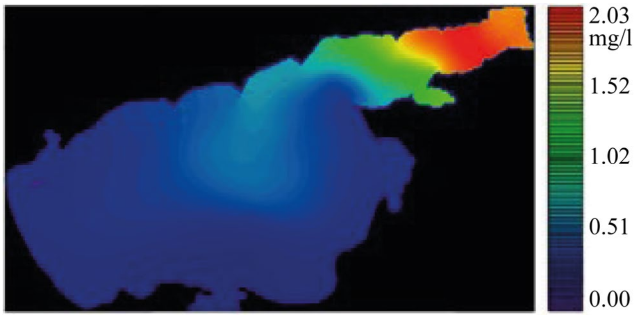
c)



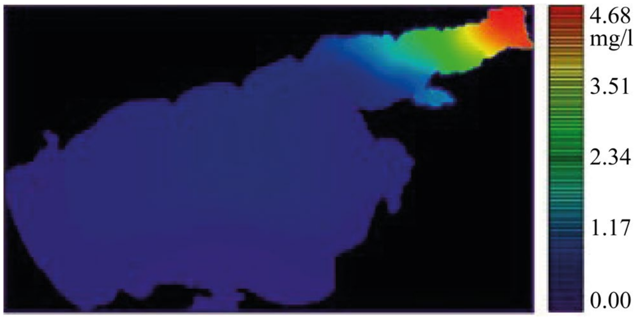
d)

Fig. 3. Application of the interpolation method: *a* — initial image of isohaline [21]; *b* — initial image of isotherms[2]; *c* — resulting image of salinity distribution *S*, ‰; *d* — resulting image of temperature distribution *T*, °C

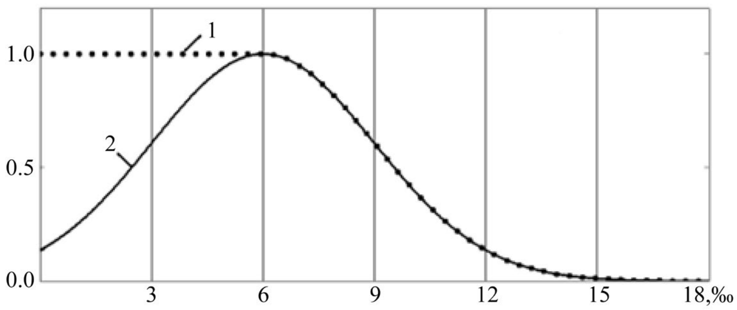
The obtained distributions of depths, salinity, and temperature were used as input data for solving problem (1). Figure 4 shows the concentrations of two phytoplankton populations obtained as a result of the computational experiment. Uniform distributions of the simulated substances were input data for the software module, with a time interval of 30 days.



a)



b)



c)

Fig. 4. Results of solving the problem of dynamics of phytoplankton populations: *a* — distribution of concentrations of blue-green algae q_1, mg/l; *b* — distribution of concentrations of green algae q_2, mg/l; *c* — graph of the dependence of the growth coefficient of phytoplankton populations on salinity *S*: 1 — green algae; 2 — blue-green algae

[2] *The ESIMO Operational Module. Water Surface Temperature in the Azov Sea.* The Unified State Information System on the Situation in the World Ocean. (In Russ.) URL: http://hmc.meteorf.ru/sea/azov/sst/sst_azov.html (accessed: 25.11.2025).

Discussion. The interpolations of the distributions of depths, salinity, and temperature, obtained using the algorithm presented in this paper, have a sufficient degree of smoothness at the points where they are joined. A computational experiment has shown that the range of blue-green algae is wider than that of green algae — they are distributed throughout Taganrog Bay and carried by currents into the main part of the Azov Sea.

The mathematical model of phytoplankton population dynamics takes into account several factors, including the limitation of microalgae growth by nutrients, the influence of the hydrological regime on the growth coefficient, geographical dynamics under the influence of convection and diffusion processes, and the oxygen regime. By combining this model with a hydrodynamic model, it is possible to create three-dimensional images of the distribution of substances being modeled. This allows for the consideration of not only the biological aspects of phytoplankton growth but also the spatio-temporal dynamics of biomass and the shape of the computational area.

Conclusion. The described mathematical model and the proposed methods have been integrated into the Azov3D software package. This allows us to predict the development of hazardous blooms of phytoplankton (eutrophication) under different weather conditions, taking into account changes in salinity, temperature, current patterns, nutrient availability, and oxygen regime. The forecasts generated can be used to develop a strategy for the sustainable management of Taganrog Bay, an important natural area. Various strategies for managing this aquatic ecosystem are currently being developed, as well as safety mechanisms to prevent suffocation and eutrophication events. Mathematical modeling techniques, the development of which is discussed in this article, provide inexpensive and efficient tools for monitoring and predicting the state of aquatic systems.

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Conflict of Interest Statement: **the authors declare no conflict of interest.**

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Заявленный вклад авторов:

А.Е. Чистяков: разработка концепции, научное руководство.

Ю.В. Белова: написание черновика рукописи, визуализация.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 12.09.2025
Reviewed / Поступила после рецензирования 08.10.2025
Accepted / Принята к публикации 16.10.2025

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https://doi.org/10.23947/2541-9129-2025-9-4-294-304

Scoping Review

EDN: RPBVLG

Research on the Activities of Voluntary Firefighting Societies (Using the Example of the Udmurt Republic)

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Abstract

Introduction. In today's world, fire safety has become a top priority for public administration in every country. The challenges of providing professional fire protection are addressed, among other measures, through the institution of volunteer firefighting both in Russia and abroad. Problems in ensuring the activities of volunteer firefighters are generally quite typical, regardless of the level of socio-economic development of the territory. Thus, in modern conditions in the Russian Federation, there are quite noticeable imbalances in the level of fire safety. These issues are particularly acute for small, remote settlements, where it is quite resource-intensive to maintain professional fire protection. Nevertheless, the principle of equal access and quality of public services is a key component of state policy and regional administration. The activities of volunteer fire brigades play an essential role in the fire safety system in Russia and abroad. However, as practice shows, there is a significant problem of ignorance and, in general, unwillingness of citizens to participate in voluntary fire protection and to assist in the development of this institution. In this regard, this study aims to investigate the role of volunteer firefighting societies (hereinafter referred to as VFFS) and analyze the specifics of their activities abroad in order to identify common practices and assess the perception of this institution by the population.

Materials and Methods. The research plan consisted of two interconnected parts. First, we planned to study the sources devoted to evaluating the role of volunteer firefighters in other countries and analyze the activities of volunteer firefighting organizations in the Russian Federation. Then, we conducted a sociological survey and processed the results. The processing of responses involved summarizing the collected data and identifying the reasons and motives behind the responses received. For the regional part of the study, statistical data on the activities of voluntary firefighting societies and the dynamics of the number of volunteers were analyzed in order to assess the contribution of voluntary firefighting societies to the fire safety system.

Results. It has been revealed that the institute of volunteer firefighters is widespread in the fire extinguishing system both in Russia and abroad. It has been found that approaches to the organization, financing and financial incentives of volunteer firefighters from different countries have both similarities and some differences, including the subjective perception of this institution by the population. It was found that the number of VFFS branches and the participation of VFFS units in extinguishing fires in the Russian Federation have increased significantly in the Russian Federation. This indicates the relevance and effectiveness of their work. An analysis of the distribution of the number of fires by fire extinguishing participants showed that the proportion of volunteer fire brigades participating in firefighting has been growing annually. However, the analysis has also showed a decrease in the overall number of volunteer firefighters in the Udmurt Republic. According to the sociological survey conducted, the vast majority of respondents were generally not ready to participate in voluntary fire protection and assist in the development of this institution.

Discussion. This work has shown that the institution of volunteer firefighters is a highly sought-after and socially significant phenomenon both in Russia and abroad. However, there are clear problems at both the national and regional levels with the organization of the VFFS system itself. Generally, the population is not very willing to join volunteer firefighting groups, and the reasons why people do not join these groups have been identified. The analysis revealed the motivations and conditions under which respondents were willing to participate in volunteer firefighting activities. The results show the need for a comprehensive approach to developing measures to improve the status of volunteers. It is also necessary to develop a set of measures to increase the appeal of the image of a volunteer firefighter to attract young people into this field.

Conclusions. The research confirms the important role of volunteer firefighters in ensuring fire safety in the subject area under study, both in Russia and abroad. The review showed that the key problems in organizing the work of voluntary firefighting services are identical for most countries. These conclusions are supported by the results of the analysis. The main results of the study include data on the dynamics of the number of volunteers in the region as well as factors that determine the motivation of the population to participate in volunteer firefighting activities. The practical significance of the research lies in its application in predicting additional measures to attract more volunteers to volunteer firefighting organizations. Further research will aim to develop mechanisms to promote volunteer firefighting activities.

Keywords: voluntary firefighting societies, volunteer firefighter, regional management, survey, VFFS financing, fire safety

Acknowledgements. The authors would like to express their gratitude to the reviewers and the Editorial team for their attention to the article and their assistance in improving its quality.

For Citation. Shirobokov SV, Kasatkina EA. Research on the Activities of Voluntary Firefighting Societies (Using the Example of the Udmurt Republic). *Safety of Technogenic and Natural Systems*. 2025;9(4):294–304. https://doi.org/10.23947/2541-9129-2025-9-4-294-304

Обзор предметного поля

Исследование деятельности добровольных пожарных обществ (на примере Удмуртской Республики)

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Аннотация
Введение. В современных условиях обеспечение пожарной безопасности — одна из приоритетных задач государственного управления во многих странах. Проблемы организации профессиональной пожарной охраны частично решаются за счёт института добровольных пожарных как в России, так и за рубежом. Трудности функционирования добровольных пожарных обществ во многом сходны, независимо от уровня социально-экономического развития территории. В Российской Федерации сохраняются заметные диспропорции в обеспечении пожарной безопасности, особенно в небольших и удалённых населённых пунктах, где содержание профессиональной пожарной охраны экономически затратно. Между тем принцип равной доступности и равного качества социальных услуг остаётся ключевым в государственной и региональной политике. Значительная роль в системе пожарной безопасности отводится добровольным пожарным формированиям. На практике одной из серьёзных проблем является недостаток информированности и низкая мотивация граждан к участию в добровольной пожарной охране и поддержке развития этого института. Цель исследования — изучить роль добровольных пожарных обществ (далее ДПО), проанализировать особенности их деятельности за рубежом с целью выявления общих практик и оценить восприятие данного института населением.
Материалы и методы. Исследование включало две взаимосвязанные части. Сначала проведён обзор источников, посвящённых роли добровольных пожарных в зарубежных странах, и анализ функционирования добровольных пожарных обществ в Российской Федерации. Во второй части выполнено социологическое обследование с последующей обработкой полученных данных. Обработка ответов предполагала агрегирование материалов и выявление причинно-мотивирующих факторов, формирующих позиции респондентов. Для региональной части исследования проанализированы статистические данные о деятельности добровольных пожарных обществ и динамике численности добровольцев с целью оценки вклада добровольных пожарных обществ в систему обеспечения пожарной безопасности.
Результаты исследования. Установлено, что институт добровольных пожарных широко распространён в системе пожаротушения как в России, так и за рубежом. Подходы к организации, финансированию и материальному стимулированию добровольцев в разных странах содержат как общие черты, так и специфические различия, в том числе в восприятии института населением. Зафиксирован рост числа филиалов ВДПО и увеличившееся участие подразделений ДПО в тушении пожаров в России, что свидетельствует об актуальности и эффективности их деятельности. Анализ распределения числа пожаров по участвующим в тушении субъектам показал ежегодное увеличение доли добровольных пожарных. Вместе с тем в Удмуртской Республике наблюдается сокращение общей численности добровольцев. По данным социологического опроса, подавляющее большинство респондентов не готовы вступать в добровольную пожарную охрану или активно содействовать развитию института.

Обсуждение. Работа подтверждает востребованность и социальную значимость добровольных пожарных как в России, так и за рубежом. Одновременно выявлены системные проблемы как на национальном, так и на региональном уровнях в организации деятельности ДПО. Наблюдается невысокая готовность населения вступать в ряды добровольцев; определены основные барьеры, препятствующие участию. Анализ позволил выделить мотивы и условия, при которых респонденты готовы принимать участие в деятельности ДПО. Полученные результаты указывают на необходимость комплексного подхода к повышению статуса добровольного пожарного и разработки мер, повышающих привлекательность этой деятельности для молодёжи.
Заключение. Исследование подтверждают важную роль добровольных пожарных в обеспечении пожарной безопасности в исследуемой предметной области как в России, так и за рубежом. Обзор показал, что ключевые проблемы организации ДПО являются сопоставимыми для большинства государств; эти выводы поддерживаются результатами анализа. В числе основных результатов — данные о динамике численности добровольных пожарных в регионе и факторы, определяющие мотивацию населения к участию в деятельности ДПО. Практическая значимость работы заключается в возможности использования её результатов для прогнозирования и разработки мероприятий по привлечению добровольцев. Дальнейшие исследования будут направлены на разработку механизмов популяризации и повышения привлекательности деятельности добровольных пожарных.

Ключевые слова: добровольные пожарные общества, добровольный пожарный, региональное управление, опрос, финансирование ДПО, пожарная безопасность

Благодарности. Авторы выражают благодарность рецензентам и сотрудникам редакции за внимательное отношение к статье и помощь в повышении её качества.

Для цитирования. Широбоков С.В., Касаткина Е.А. Исследование деятельности добровольных пожарных обществ (на примере Удмуртской Республики). *Безопасность техногенных и природных систем.* 2025;9(4):294–304. https://doi.org/10.23947/2541-9129-2025-9-4-294-304

Introduction. In modern conditions, the Russian Federation, due to objective factors, is characterized by significant regional imbalances and differentiated conditions for the development of many spheres of public life. At the same time, the principle of equal accessibility and equal quality of social services remains crucial in the state policy and regional governance. In particular, this applies to fire safety guarantees. As the authors note, "ensuring the required level of fire safety is one of the most important components of the country's national security" [1]. Therefore, in modern Russia with its diversity, the activities of volunteer fire departments play a crucial role in the fire safety system [2]. In this context, studies of the factors determining the expediency of creating voluntary fire protection units in populated areas are relevant [3]. Let us agree that "the regulation of legal relations between state authorities, local governments, organizations and citizens in the field of voluntary fire protection is an essential part of the development and modernization of the regulatory frameworks" [4]. This process has been facilitated by the establishment of a modern legal basis for public administration [5].

The practice of interacting with representatives from various fields allows us to assume that a significant problem today is the lack of knowledge and, in general, the reluctance of citizens to participate in volunteer fire protection and contribute to the development of this institution. A similar trend is also reflected in the experience of volunteer firefighters in several foreign countries.

The aim of this research is to examine the activities of voluntary firefighting societies (VFFSs) and to consider their specific functioning in other countries in order to gain a comprehensive understanding of their role in improving fire protection for the population. More specifically, the study focuses on analyzing the role of VFFSs and how they are perceived by different social groups.

Materials and Methods. The study analyzed sources on the role of volunteer firefighters in foreign countries [1–3]. The study of the specific features of VFFS functioning in a particular region was based on the analysis of data on the activities of voluntary firefighting societies, with the identification of trends in the number of volunteers [4, 5]. A sociological survey was conducted to assess the attitudes of the population towards the institution of volunteer firefighters, the level of awareness about their activities, and their perception of the practice of VFFS financing [6]. The work employed the method of content analysis, statistical methods, and methods of sociological survey, with subsequent processing of the obtained results [7, 8]. Processing of responses involved generalizing data, interpreting the identified patterns, and establishing causally motivated factors that determined the respondents' positions [9].

Content analysis of publications covered the materials on the role of volunteer firefighters and the specifics of organizing their activities in foreign countries. The sample included works that contained information on the state, specific features and problems of organizing volunteer firefighting activities. The mechanism for attracting volunteers is widespread in firefighting systems both in Russia and abroad. The institution of volunteer fire protection has been historically present in almost all countries, and publications on this topic are widely represented in scientific literature. An overview of the subject area reflecting the special role of volunteer firefighting units in the firefighting system was presented in [6–10].

A comprehensive overview of the organization of volunteer firefighters in foreign countries, such as the USA, France, Germany, Italy, Hungary, was presented in [11, 12]. At the same time, most of the review publications were focused on studying the experience of Western European countries, while the activities of volunteer firefighters in the Asian region remained without detailed consideration. Meanwhile, the available reviews of scientific articles revealed the specific organization of voluntary fire protection in these states. Thus, the Chinese volunteer fire department system stood out for its high level of public involvement: "everyone knew what to do in an emergency situation, despite the fact that there was no question of any reward or financial reward. The Chinese still had a very strong sense of social duty" [12]. In Japan, volunteer fire brigades were largely formed from the rural population — these were well-trained citizens who were able to professionally cope with their tasks [13].

The analyzed studies emphasized the significant role of volunteer firefighters not only in extinguishing fires, but also in conducting rescue operations in emergency situations.

In the Russian Federation, there has been a growing interest in volunteerism since the end of the 20th century. This was due to the need to address a number of social issues caused by economic factors [14].

According to Clause 2 of Article 10 of Federal Law No. 100 FZ dated May 06, 2011 "On Voluntary Fire Protection", individuals who have reached the age of eighteen and are physically able to perform duties related to participation in fire prevention and (or) fire extinguishing, as well as in emergency rescue operations, can become voluntary firefighters. The state "recognizes the legal status and value of the work of VFFS personnel" [15].

Regional (subject) legislation provides for the development of relevant legal acts, which is due, among other things, to "the need to conduct exercises taking into account the local characteristics of the regions" [16]. The Udmurt Republic has Law of the Udmurt Republic No. 30-RZ[1] dated June 30, 2011 "On Voluntary Fire Protection in the Udmurt Republic" and Decree of the Government of the Udmurt Republic No. 155 dated April 16, 2012 "On Approval of the Regulations on Granting Subsidies to Public Fire Protection Associations"[2].

It should be noted that, in recent years, there have been some difficulties in obtaining digital data due to certain objective reasons. Additionally, the research in this area has been hindered by the lack of a unified database that aggregates information on the activities of organizations involved in emergency prevention and response at various levels. To address this issue, the presented work utilized data from various open sources. The analysis was based on official data from the Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disastes[3], the Ministry of Emergency Situations of Russia in the Udmurt Republic[4], the All-Russian Public Organization "All-Russian Voluntary Fire Organization"[5], the Regional Branch of the All-Russian Public Organization "All-Russian Voluntary Fire Organization"[6].

Results. According to official materials, by the end of 2023, there were 20,834 registered public fire protection associations on the territory of the Russian Federation.

Public fire protection associations include:

– volunteer fire brigades — 25,638 (the same period last year (hereinafter referred to as SPLY) — 27,822, 7% dynamics), the number of volunteers — 268,619 people (SPLY — 296,872, 9% dynamics);

– volunteer fire units — 8,946 (SPLY — 8,866, +1% dynamics), the number of volunteers — 55,351 people (SPLY — 55,156, +3% dynamics).

[1] *On Voluntary Fire Protection in the Udmurt Republic.* Law of the Udmurt Republic No. 30-RZ dated June 30, 2011. GARANT system. (In Russ.) URL: https://base.garant.ru/15745029/ (accessed: 20.10.2025).

[2] *On Approval of the Regulations on Granting Subsidies to Public Fire Protection Associations.* UR Government Resolution No. 155 dated April 04, 2012. GARANT system. (In Russ.) URL: https://base.garant.ru/15751256/ (accessed: 20.10.2025).

[3] Official website of The Ministry of the Russian Federation for Civil Defence, Emergencies and Elimination of Consequences of Natural Disasters. (In Russ.) URL: https://mchs.gov.ru (accessed: 10.06.2025).

[4] Official website of the Main Directorate of the Ministry of Emergency Situations of Russia in the Udmurt Republic. (In Russ.) URL: https://18.mchs.gov.ru (accessed: 20.10.2025).

[5] Official website of the All-Russian Voluntary Fire Organization. (In Russ.) URL: https://vdpo.ru (accessed: 20.10.2025).

[6] Id.

Figure 1 provides the data on the number of fires with the involvement of VFFS units[7].

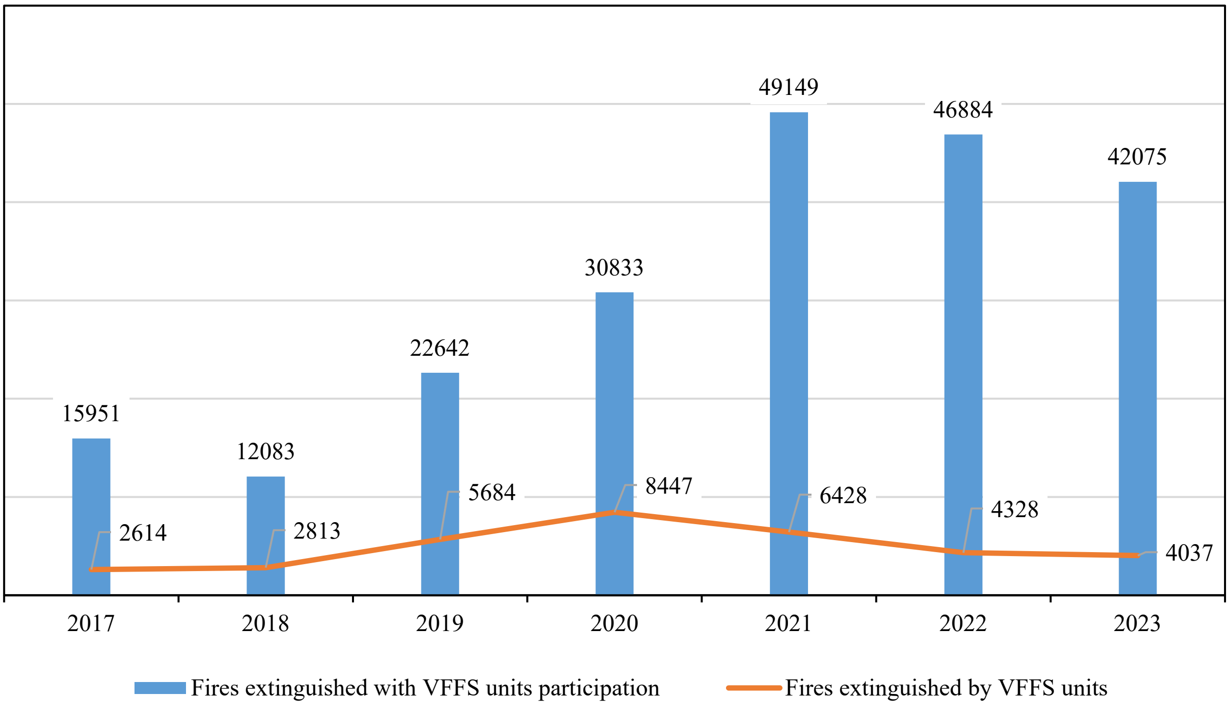

Fig. 1. Participation of VFFS units in extinguishing fires on the territory of the Russian Federation in 2017–2023

Based on the data in Figure 1, we can see that the number of fires extinguished with the assistance of VFFS increased by 33,198 units between 2017 and 2021, or by 208.12%. However, from 2021 to 2023, there was a decrease of 7,074 units, or 14.4%.

The participation of VFFS units in firefighting affected directly the effectiveness in this area as a whole. The more VFFS units there were, the fewer fire losses there were. In the period from 2020 to 2024, the number of VFFS branches increased by 131 or by 23.33%, which indicated the relevance and effectiveness of their activities. The VFFS had its branches in every federal district and almost every region.

State regulation of industry activities was based on the principle of achieving positive results. The effectiveness of fire protection work was assessed based on response time to calls, number of lives saved, and material assets saved [17]. The number of participants in various categories was directly correlated with these indicators. Data analysis showed that the proportion of volunteer firefighters participating in firefighting activities was increasing annually. In 2016, the members of the volunteer firefighting service (VFFS) extinguished 11,594 fires; while in 2022, there were 39,103 (237.3% more) fires. Among all participants in fire extinguishing efforts, the VFFS held the fourth place in terms of proportion. They are inferior only to employees of the territorial divisions of the Federal Fire-Fighting Service of the State Fire Service, as well as employees of the territorial divisions of the Fire-Fighting Service of the subject of the Russian Federation, for whom fire extinguishing was a direct professional field of activity.

According to data for 2024, there were 119 voluntary fire protection public institutions in the Udmurt Republic, which included 436 territorial and facility-based voluntary fire departments with a total number of 4,888 people.

The dynamics of the number of volunteer firefighters in the Udmurt Republic is shown in Table 1.

Table 1

The dynamics of the number of volunteer firefighters in the Udmurt Republic from 2020 to 2024, people

Year	2020	2021	2022	2023	2024
Number, people	5,234	5,457	5,683	5,206	4,888

[7] *Analysis of the Development of Voluntary Fire Protection in the Russian Federation by the End of 2023.* Moscow: 2024. 6 p. (In Russ.) URL: https://mchs.gov.ru/uploads/document/2025-02-04/43e5a62d9d6f39c244d6bd6f7cb1ef41.pdf?ysclid=mha4bes5qv305014601 (accessed: 20.10.2025).

Thus, during the period under review, the number decreased by 346 people, or 6.6%. In accordance with the “Technical Regulations” requirements, 392 settlements of the Udmurt Republic (20%) are covered by volunteer fire departments. At the same time, according to the Ministry of Emergency Situations of Russia in the Udmurt Republic, since the beginning of 2024, volunteers have independently extinguished 13 fires, 435 times participated in extinguishing fires as additional forces and 8 times participated in the elimination of consequences of road accidents[8].

Despite the importance and high status of volunteerism, most studies focused primarily on its motivational component. In particular, it was emphasized that “the participation of volunteers in search and rescue activities, extinguishing fires ... was often associated with a risk to the health and even the lives of volunteers, and therefore issues of compensation for damage suffered by a volunteer while performing relevant work were essential for further development” [18]. Modern reviews showed that financial support played a crucial role in ensuring the stability of volunteer firefighting organizations in foreign countries. However, there were also challenges in financing these organizations [19, 20]. These challenges were not unique to foreign countries but also affected modern Russia and its regions, such as the Udmurt Republic. This was confirmed by our research. The situation was further complicated by the rather strict requirements for volunteer firefighters, as indicated by research [11, 21].

Summing up the results of the analysis, we noted that one of the main problems was the lack of stable positive growth in the number of volunteer firefighters. This decrease in their numbers, despite the high demand for their services, rapid response to fires, and qualified approach to extinguishing fires and saving people and property, was seen as a negative trend that requires close attention. To identify the reasons for this phenomenon and understand the motivational expectations of the population, we conducted a survey as part of this study. We randomly selected a group of respondents from the Udmurt Republic and neighboring regions to participate in the survey.

The results of a social survey on the topic “Voluntary Firefighting Societies in the development of the territory”

Research generally showed the multidimensional nature of the factors affecting the effectiveness of fire protection activities. For example, there have been studies on the influence of the gender factor on professional competencies [22], as well as an increase in the number of women entering professional fields [23]. This article focuses on the subjective aspects that were raised in the survey.

The first set of questions aimed to gather information about the age, gender, and social status of respondents. These results did not need statistical analysis. However, we noticed that the sample included a diverse range of participants (Fig. 3).

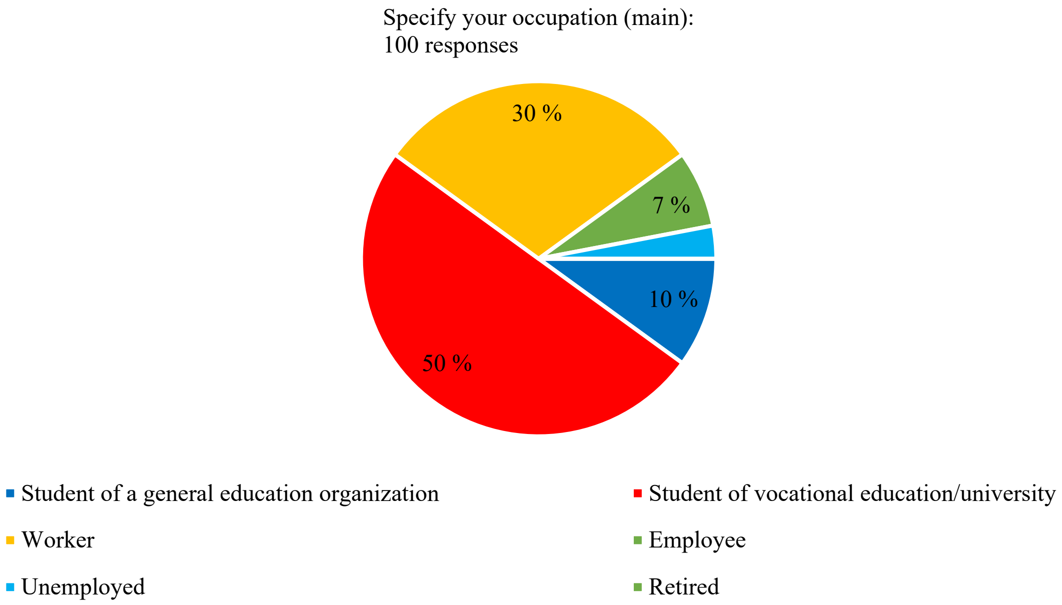

Fig. 2. Distribution of respondents by occupation

[8] *Results of the Development and Activity of Volunteerism in Udmurtia in 2024.* Official website of the Main Directorate of the Ministry of Emergency Situations of Russia in the Udmurt Republic. (In Russ.) URL: https://18.mchs.gov.ru/deyatelnost/press-centr/novosti/5441040 (accessed: 20.10.2025).

It was found out that among 100 respondents, 34% (34 people) were aware of the VFFS existence, and 66% (66 people) were unaware of its existence (Fig. 4).

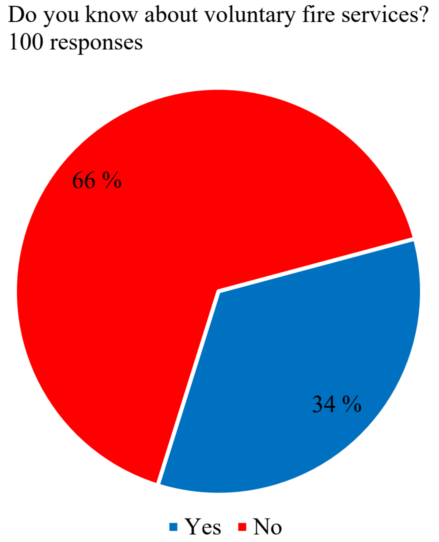

Fig. 3. Data on the number of respondents who have information about the VFFS activities

Ninety people answered positively to the question “Do you think we need a VFFS?”, and ten people answered “No”. Based on this, we could say that most people believe that VFFS was needed (Fig. 5).

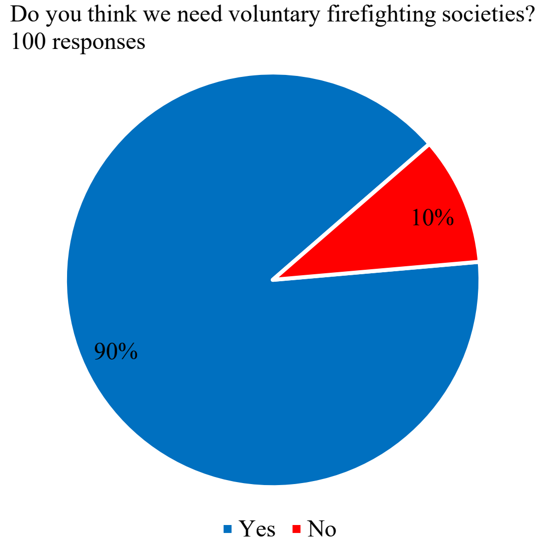

Fig. 4. Distribution of answers to the question about the need for VFFS

Despite the widespread recognition of the importance of volunteer firefighting societies, not all respondents were ready to join their ranks. 86% of respondents (86 people) were not ready to become volunteer firefighters, while only 14% (14 people) expressed their willingness to join.

A key set of questions concerned the respondents' willingness to join VFFSs and the conditions under which they would be willing to do so. Most of the positive responses (27.3% each) suggested joining only if a number of conditions were met — if the organization provided necessary training and equipment, medical protection and compensation for time spent, and if their skills and abilities would contribute to saving lives and property in emergency situations. The remaining answers were within an acceptable margin of error — free of charge, in their free time, at pre-arranged times, friendly team, acceptable conditions while traveling, benefits and incentives, limitation of hours worked per week, provided they did not participate personally in firefighting.

Regarding indirect forms of participation or assistance in the activities of voluntary firefighting societies, it was found that almost half of the respondents (46.7%) were unwilling to help voluntary firefighting societies in any way; almost a third (26.7%) were ready to assist in finding resources and information; only 3.3% were ready to financially support the activities of voluntary firefighting societies.

Obviously, the issue of financing was one of the main topics discussed in the context of the study. Nearly half of the respondents (43.3%) believed that VFFSs should be funded exclusively by the state; a slightly smaller number (26.7%) supported a mixed model, with both the state and the public contributing.

As part of the study, we also attempted to identify the reasons that prevent people from participating in VFFSs. The respondents were able to choose several options for this question or provide their own response. Their answers were distributed as follows:

1. No time due to work or study — 73% (73 people).
2. Frightening/dangerous — 28% (28 people).
3. No financial incentive — 19% (19 people).
4. I consider it pointless — 3% (people).

Other answers that scored less than 5% each: I don't want to; I don't know where to look for a society to join; I don't know the requirements for participating in a voluntary fire society; lack of information about the organization as a whole; health status; I support another charity; I believe that this is primarily a male role; I am in another city; lack of physical fitness.

The final question was an open question: "What changes or improvements would you propose for the development of voluntary firefighting societies?" Constructive proposals were received: to strengthen the advertising campaign to attract volunteers; to give more coverage to the activities of the VFFSs in the media to inform the public; to encourage participants; to provide uniforms, transport and specialized equipment; to discuss this topic from childhood. A small part of the respondents believed that it was impossible to motivate a person without internal motivation.

There is no doubt that professional firefighters and volunteers cannot be compared. As noted in [24], there are situations "that are not within the scope of the systematic activities of civilian volunteers". Perhaps it is reasonable and beneficial from the point of view of involving the public in the opinion that "the training of volunteers to perform tasks not related to emergency rescue operations can be limited to briefings" [25].

The right solution to the tasks is possible with a balance of authority and responsibility. On the one hand, residents "with the organizational and financial support of government agencies can successfully protect their small homeland from fires" [26]. On the other hand, it is necessary to improve "motivational tools that can encourage citizens to become volunteers" [27]. In addition, volunteer actions [28], mentoring as the most important tool for personal and professional growth [29], as well as government support for active citizenship play a special role in attracting people to VFFSs activities.

Discussion. The conducted research has shown that the institution of volunteer firefighters is in demand and socially significant both in Russia and abroad. However, there are challenges at both the national and regional levels in the organization of the VFFS system. The findings indicate the need for an integrated approach to the development of measures to enhance the status of volunteer firefighters. It is also necessary to develop measures to increase the attractiveness of the image of a volunteer firefighter to attract young people. Regarding the region under study, the study demonstrated that, despite the crucial role of VFFSs in the development of territories, there were several areas that needed improvement. The survey revealed that the majority of respondents recognized the importance of vocational training and considered them necessary for the successful socio-economic development of territories, but the level of public engagement remained low.

Conclusion. The survey revealed that the majority of respondents recognized the importance of vocational training and considered them necessary for the successful socio-economic development of territories, but the level of public engagement remained low. The study found that the general public was not inclined to join the ranks of volunteer firefighters. The main reasons for this unwillingness included the lack of free time, insufficient training or age, and weak financial motivation. The analysis also allowed us to identify the motives and circumstances under which respondents were more likely to participate in volunteer firefighting activities. Some of the respondents expressed interest in joining if they received decent pay and had a schedule with weekends at their main job.

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Conflict of Interest Statement: **the authors declare no conflict of interest.**

All the authors have read and approved the final manuscript.

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Заявленный вклад авторов:

С.В. Широбоков: разработка концепции, научное руководство, разработка методологии исследования, формальный анализ.

Е.А. Касаткина: визуализация, проведение исследования, написание черновика, включая его перевод на иностранный язык.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 07.09.2025
Reviewed / Поступила после рецензирования 01.10.2025
Accepted / Принята к публикации 17.10.2025

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https://doi.org/10.23947/2541-9129-2025-9-4-305-318

Original Empirical Research

Study of Artificial Reservoir's Bioproductivity Based on a Graph Model of Natural and Anthropogenic Factor Interaction

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Abstract
Introduction. Ignoring the systemic nature of a reservoir can lead to ineffective and damaging management decisions. However, the study of such objects often focuses on individual factors. The predictive potential of graph models is limited by a lack of expert information and outdated databases of indicators. This work aims to address these issues by evaluating the effectiveness of measures to improve the condition of the Tsimlyansk Reservoir. The solution is based on the author's graph model that takes into account the interaction of anthropogenic and biotic characteristics of the object.
Materials and Methods. The literature sources and information on hydrobiochemistry and species composition of fish were analyzed. A model was created that took into account 20 factors related to the state of the Tsimlyansk Reservoir. A hydrobiological analysis allowed us to create graph $G(V, E, Y)$. V — set of vertices, $v_k \in V$, $k = \overline{1, 20}$. E — set of oriented edges $e_k = (v_i, v_j)$ in the form of ordered pairs of length 2, $i \neq j$. Y — mapping, $Y : V \to V$. A weight matrix was created based on an integral assessment of each factor by experts. The weighting coefficients (±0.5–±1) were calculated using information from hydrobiological and chemical databases.
Results. We investigated how the removal of zebra mussels would affect the facility during a single cleaning (scenario 1) and a three-year cleaning (scenario 2). We visualized the dynamics of pulses for the state of the water (v_{15}) and changes in the concentration of biological substances (v_{18}). In the first scenario, for the first factor, the maximum pulse (0.5) was fixed from the third year of exposure; the minimum (0) was during the first year. For the second factor, the pulse increased from a minimum (–0.5) to a maximum (0.25) over the third year. In the second scenario, both factors did not change in the first year. Then the pulse for v_{15} increased (to 0.75), v_{18} fell in the second year to –0.5, and then increased to –0.25.
Bream reproduction with v_5 feeding was evaluated for a year (scenario 3) and five years (scenario 4). The state of spawning fish v_1, replenishment of juveniles v_2, fishing v_7, and eutrophication v_{14} were taken into account. v_2, v_7, and v_{14} pulses remained zero for two years. Then v_2 and v_7 grew to one, and in the fourth year they fell to zero. The eutrophication pulse dropped to –1, and returned to zero by the end of the fourth year. With a five-year feeding, v_1 pulse dropped to –1 in the first year, v_{14} — in the third, and its value did not change, and v_1 returned to 0 in the fifth year of modeling. The pulse for v_2 and v_7 grew from zero to one in three years.
Discussion. Annual cleaning of a reservoir from zebra mussel was more effective for improving the water condition and less effective for the concentration of nutrients. One-time feeding would increase the number of juveniles and fishing. Eutrophication would decrease, but there would be no sustainable results. Annual feeding would increase the number of juveniles, reduce eutrophication and lead to the development of fishing.
Conclusion. The proposed solution makes it possible to predict potential benefits or harm of anthropogenic activities on the reservoir. The model can be improved by fine-tuning the weighting coefficients, taking into account non-linear and threshold effects as well as other indicators.

Keywords: Tsimlyansk Reservoir, graph model of reservoir condition, anthropogenic impact on the reservoir, cleaning the reservoir from zebra mussels, bream reproduction with feeding

Acknowledgements. The authors would like to thank the Editorial board and the reviewers for their attentive attitude to the article and the comments indicated, which made it possible to improve its quality.

Funding Information. The research was done with the financial support of the Russian Science Foundation, grant No. 25–71–20001, https://rscf.ru/project/25-71-20001/

For Citation. Kuznetsova IYu, Nikitina AV. Study of Artificial Reservoir's Bioproductivity Based on a Graph Model of Natural and Anthropogenic Factor Interaction. *Safety of Technogenic and Natural Systems*. 2025;9(4):305–318. https://doi.org/10.23947/2541-9129-2025-9-4-305-318

Оригинальное эмпирическое исследование

Изучение биопродуктивности искусственного водоема на основе графовой модели взаимодействия природных и антропогенных факторов

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Аннотация

Введение. Игнорирование системной природы водохранилища обусловливает неэффективные и деструктивные управленческие решения. Однако изучение таких объектов часто фокусируются именно на отдельных факторах. Прогнозный потенциал графовых моделей для этих целей ограничивается дефицитом экспертной информации и устаревающей базой индикаторов. Представленная работа призвана восполнить эти пробелы. Цель — оценка эффективности мероприятий по улучшению состояния Цимлянского водохранилища. Основа решения — авторская графовая модель взаимодействия антропогенных и биотических характеристик объекта.

Материалы и методы. Анализировались литературные источники, информация о гидробиохимии и видовом составе рыб. В модели учли 20 факторов состояния Цимлянского водохранилища. Анализ гидробиологии позволил составить граф $G(V, E, Y)$. V — множество вершин, $v_k \in V$, $k = \overline{1, 20}$. E — множество ориентированных ребер $e_k = (v_i, v_j)$ в виде упорядоченных пар длины 2, $i \neq j$. Y — отображение, $Y : V \to V$. Матрицу весов построили по интегральной оценке экспертов для каждого фактора. Весовые коэффициенты (±0,5–±1) рассчитали по информационной базе гидробиологических и химических данных.

Результаты исследования. Выяснили, как повлияет на объект устранение дрейссены при однократной очистке (1-й сценарий) и трехлетней (2-й). Визуализировали динамику импульсов для состояния воды (v_{15}) и изменения концентрации биовеществ (v_{18}). В первом сценарии для первого фактора максимальный импульс (0,5) фиксируется с 3-го года воздействия, минимальный (0) — в течение 1-го. Для второго фактора за 3-й год импульс увеличивается с минимума (–0,5) до максимума (0,25). Во втором сценарии оба фактора не меняются в 1-й год. Затем импульс для v_{15} растет (до 0,75), v_{18} падает во 2-й год до –0,5, а потом увеличивается до –0,25.

Оценили воспроизводство леща при подкорме v_5 в течение года (3-й сценарий) и пяти лет (4-й). Учитывалось состояние нерестовой рыбы v_1, пополнение молоди v_2, промысел v_7, эвтрофикация v_{14}. Два года остаются нулевыми импульсы v_2, v_7 и v_{14}. Затем v_2 и v_7 растут до единицы, в 4-й год падают до нуля. Импульс эвтрофикации падает до –1, к концу 4-го года возвращается к нулю. При пятилетнем подкорме импульс v_1 падает до –1 в 1-й год, v_{14} — в 3-й, и его значение не меняется, а v_1 возвращается к 0 на 5-й год моделирования. Импульс для v_2 и v_7 за три года растет с нуля до единицы.

Обсуждение. Ежегодная очистка водоема от дрейссены более эффективна для улучшения состояния воды и менее — для концентрации биогенных веществ. Единоразовая подкормка повысит поголовье молоди и промысел. Эвтрофикация сократится, однако устойчивых результатов не будет. Ежегодный подкорм увеличит поголовье молоди, сократит эвтрофикацию и обусловит развитие промысла.

Заключение. Предложенное решение позволяет прогнозировать пользу или вред антропогенных воздействий на водохранилище. Модель можно совершенствовать за счет более тонкой настройки весовых коэффициентов, учета нелинейных и пороговых эффектов и других индикаторов.

Ключевые слова: цимлянское водохранилище, графовая модель состояния водоема, антропогенное воздействие на водоем, очистка водоема от дрейссены, воспроизводство леща при подкорме

Благодарности. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и замечания, которые позволили повысить ее качество.

Финансирование. Исследование выполнено за счет гранта Российского научного фонда № 25–71–20001, https://rscf.ru/project/25-71-20001/

Для цитирования. Кузнецова И.Ю., Никитина А.В. Изучение биопродуктивности искусственного водоема на основе графовой модели взаимодействия природных и антропогенных факторов. *Безопасность техногенных и природных систем*. 2025;9(4):305–318. https://doi.org/10.23947/2541-9129-2025-9-4-305-318

Introduction. A hydrobiological study of a reservoir allows us to assess the ecological state of aquatic ecosystems and develop measures for their conservation and restoration. Reservoirs are important environmental facilities. They provide water supply to the population, industry, and agriculture. However, the quality of the aquatic environment is deteriorating due to anthropogenic influence. Urban and agricultural runoff and waste change the temperature of reservoirs, disrupt the natural food supply, and promote the growth of harmful plants and animals [1]. All this leads to a decrease in the bioproductivity of reservoirs, i.e. generates environmental and economic risks.

The Tsimlyansk Reservoir is a source of drinking water for millions of residents of the Rostov and Volgograd Regions. It is important to monitor changes in the hydrobiological indicators of the reservoir and to develop methods for the protection and restoration of the ecosystem [2].

The creation of effective strategies for the conservation and restoration of the ecosystem of a reservoir requires a deep understanding of the mechanisms of interaction between its anthropogenic and biotic characteristics.

Russian and foreign scientists have studied the factors that affect the productivity of artificial reservoirs, but many challenges remain unsolved. Additionally, an integrated approach to addressing environmental quality issues in these reservoirs has not become the standard.

The key anthropogenic factor affecting the biotic health of a reservoir is water level [3]. Success of spawning [4], survival rate of juveniles, availability of feed biotopes, and wintering [5] depends on it. Therefore, drawdown (lowering) of the water level in a reservoir can be dangerous. Due to this, roe of phytophilic fish (carp, bream, crucian carp, roach) die during spawning. However, after spawning, lower water levels provide good warming for shallow waters, thus improving feeding conditions for juveniles.

Both natural and anthropogenic factors can be the causes of eutrophication. On the one hand, it increases the productivity of zooplankton (feed for juveniles), on the other hand, it can cause toxic blooms, as well as hypoxia and benthic death (feed for bottom-dwelling fish) [6].

Source [7] demonstrates the impact of toxic substances on water quality and productivity in reservoirs. Book [8] presents a comprehensive analysis of the impact of fishing, overfishing and the choice of fishing gear on fish populations. In [9], the causes and consequences of the introduction of new species of shellfish and fish into freshwater reservoirs are analyzed. It has been shown that alien species change biogeochemical cycles and the biotic composition of ecosystems. Invasive species can compete with native species or become a new target. Source [10] summarizes the results of long-term research by scientists from the Zoological Institute of the Russian Academy of Sciences, exploring the causes and mechanisms behind species dispersal and biodiversity in terrestrial and aquatic ecosystems, as well as the influence of alien species. Authors [11] evaluate the risks of biological invasions in marine coastal ecosystems through the example of Primorsky Krai. Article [12] explores the biodiversity of the Tsimlyansk Reservoir, identifies new species of zooplankton, and defines the zones of their settlement in the reservoir.

Let us specify the biotic factors essential for the productivity of water areas:

– abundance and availability of food resources (zooplankton, benthos, fish);

– influence of predators, including alien species, on commercial fish populations [13].

So, there is open access literature on certain conditions that affect the productivity of reservoirs. However, the interaction of these factors and their cumulative impact on biodiversity and commercial fish populations have not been sufficiently studied. Ecosystems of reservoirs are characterized by high dynamics of transformations, spatial heterogeneity and nonlinear relationships between various factors [14]. In recent decades, network models have become widespread, allowing for the analysis of dynamic relationships between individual species and environmental parameters.

Graph models allow you to identify key nodes, simulate impact scenarios, and quantify strength and direction of connections. These solutions show the structure of interactions, with nodes representing factors and edges representing connections. One example of using graph models in ecology is the description of trophic networks from several intertwining food chains. This approach is needed to analyze sustainability and identify key species [15]. It is also widely used in modeling habitat connectivity, describing migration processes [16], and modeling the impact of a specific species or factor on an ecosystem [17]. In [18], a graph model of the interaction between anthropogenic and biotic factors allowed researchers to evaluate the effectiveness of artificial population restoration for the Caspian Sea, which had been subjected to excessive commercial fishing.

Thus, the study of the graph model of the interaction between anthropogenic and biotic factors offers the potential for high-quality solutions to practical problems:

– development of sustainable fisheries;

– optimization of fish breeding processes.

In addition, thanks to the proposed approach, it is possible to scientifically justify recommendations for the protection of unique reservoir ecosystems. The graph model clearly reflects the complex structure of cause-and-effect relationships within the ecosystem of the reservoir, making it possible to quantify the strength and direction of influence of various factors and perform a scenario analysis of the consequences of various changes in the ecosystem. The aim of this research is to construct a graph model of the interaction between anthropogenic and biotic factors in the Tsimlyansk Reservoir, as well as evaluate the effectiveness of different measures to improve its ecological state.

Materials and Methods. When determining materials and methods, we considered, in particular, the characteristics of the research object. The Tsimlyansk Reservoir, located on the Don River in the Rostov and Volgograd Regions, is one of the largest and most significant artificial reservoirs in southern Russia.

The Tsimlyansk Reservoir belongs to the type of flat run of the river reservoirs, with a highly developed coastline.

Its characteristics are:

– large mirror area (~2700 km²);

– significant length (~260 km);

– relatively shallow depths (average ~8.8 m, maximum ~35 m in the old Don riverbed).

Significant seasonal and long-term fluctuations in water levels are determined by the operation of water intake facilities, hydroelectric power plants, and climatic conditions such as snowmelt, precipitation, and evaporation. The weak spring flood can be explained by overregulation of the Don upstream the reservoir. In recent years, there has been a significant decrease in water intake[1].

Winter is characterized by stable ice cover, while summer sees clear temperature stratification. Due to this, oxygen deficiency occurs and hypolimnion is formed, especially in deep-water areas.

The Tsimlyansk Reservoir was built in 1952 and completely filled in 1953. The facility is used for fishing, water supply to the population in the Rostov and Volgograd Regions, irrigation of agricultural land and electricity generation. Additionally, the reservoir ensures the operation of the Volga-Don Shipping Channel.

In recent decades, there has been a change in the hydrobiological regime of the reservoir under the influence of natural and anthropogenic factors.

Long-lasting high levels of biogenic elements (nitrogen and phosphorus compounds) with wastewater and agricultural runoff lead to a deterioration of the oxygen regime and the formation of dead zones. In such conditions, toxic species of cyanobacteria develop, phytoplankton grow (“blooming” of water) [19]. Other features of the reservoir:

– active siltation;

– high water turbidity in the dam area due to the accumulation of sediments from the Upper Don[2].

A large mass of vegetation in shallow water negatively affects natural reproduction of commercial fish species [20].

Intensive long-term operations, powerful anthropogenic impacts, and natural aging processes have led to significant transformations in the ecosystem and a deterioration of the hydrobiological conditions of the reservoir.

In addition, the productivity of the reservoir is significantly reduced for at least two reasons:

– overfishing of commercial species (bream, pike perch, Azov roach, carp, pike and silver carp);

– invasion of alien species (for example, *Dreissena polymorpha*, *D. bugensis*, crustaceans).

Monitoring and assessment of the system's condition, identification of key problems and forecasting their development are critically important for developing strategies for sustainable reservoir management[3] and preventing its further degradation [21].

The choice of the graph model and its components is explained below.

The analysis of an artificial reservoir is a complex and time-consuming process. It requires taking into account various factors that influence the condition of the reservoir:

1) complexity of the ecosystem, in which hydrology, climate, pollution, biogens, biota and other factors interact non-linearly;

2) spatial heterogeneity of reservoirs with different conditions (upper section, central stretch, dam zone);

3) lack of high-resolution spatial representative data on all ecosystem components (especially benthos, zooplankton, microbiology, pollutants) for model calibration and validation;

4) uncertainty of input data and model parameters.

[1] *The Tsimlyansk Reservoir and Reservoirs of the Lower Don Basin. Federal Agency for Water Resources.* (In Russ.) URL: https://voda.gov.ru/activities/tsimlyanskoe-vodokhranilishche-i-vodokhranilishcha-basseyna-nizhnego-dona/?sphrase_id=177953&PAGEN_1=2 (accessed: 27.09.2025).

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[3] *Strategy of Socio-Economic Development of the Rostov Region for the Period up to 2030.* Decree of the Government of the Rostov Region No. 864 dated December 26, 2018. As amended by No. 1100 dated December 19, 2022). The Ecology Section. The Official Portal of the Government of the Rostov Region. (In Russ.) URL: https://www.donland.ru/activity/2158/#pril435 (accessed: 28.10.2025).

Models describing hydrobiological processes in a reservoir can be divided into several classes.

1. Statistical. They are based on monitoring data and are widely used to identify significant relationships between individual factors (fish populations, phytoplankton, and catch). The disadvantages of such models include weak consideration of indirect effects and feedbacks, as well as the need for a large volume of measurements [22].

2. Dynamic (for example, NPZD or NPZD+). They allow for modeling streams, including fish populations, but at the same time require a large amount of input data. They are difficult to calibrate, and poorly take into account some anthropogenic impacts (for example, spot pollution) [23].

3. Agent-oriented. They model the behavior of individual populations. They are extremely resource-intensive and require detailed knowledge about behavior, which limits the scope of their application.

4. Hydrodynamic and ecological (Delft3D, MIKE, Ce-Qual-W2, Azov3D). They allow us to take into account spatial heterogeneity, integrate hydrophysical, biological and chemical processes. However, their use in modeling complex dynamics of fish populations and multiple anthropogenic impacts in an artificial reservoir is a laborious task from the computational point of view [24].

5. Conceptual (DPSIR). They are useful for structuring a problem, but they do not allow for quantitative analysis and forecasting.

Thus, the known models are either too simplified and unsuitable for accounting for complex interactions (as statistical), or excessively complex to construct and resource-intensive for operational use (dynamic, agent-oriented and hydrodynamic), or do not provide quantitative forecasts (conceptual).

Graph models are a relatively simple and flexible tool capable of integrating heterogeneous data (physical, chemical, biological, anthropogenic) and visualizing the structure of their interactions for analyzing and predicting the state of fish resources.

The analysis of ichthyology models made it possible to study in detail the factors determining the production and distraction processes in the reservoir. For example, article [18] considers a graph system of the influence of anthropogenic and biotic factors on reservoir productivity. The author of this work identified twelve factors as the vertices of the graph, which largely determined the dynamics of the sturgeon population. In [25], the role of fishing in population dynamics was shown, taking into account the age and sex of individuals. In [26], in addition to fishing, seasonal changes in the habitat of *Theragra chalcogramma* pollock were taken into account.

The disadvantages of the considered models include the lack of consideration of spatially heterogeneous hydrodynamic processes. In addition, many models ignore an important condition for the reproduction of commercial fish — the mechanism of external hormonal regulation of phyto- and zooplankton.

Based on the analysis of hydrobiological state of the Tsimlyansk Reservoir and some mathematical models of population dynamics, the following factors were taken into account when constructing the graph model: v_1 — state of the spawning part of the fish population; v_2 — annual replenishment of juveniles; v_3 — natural (compensatory) loss of generation; v_4 — favorable puberty conditions; v_5 — specific efficiency of natural reproduction (feeding); v_6 — scale of artificial release; v_7 — level of commercial exploitation of fish biological resources; v_8 — biomass of the dominant type of feed benthos; v_9 — roe oxygen supply in the spawning area; v_{10} — transgression of the level of the Tsimlyansk Reservoir; v_{11} — number of the main natural enemies of juveniles; v_{12} — available length of spawning migration routes; v_{13} — overgrowth of zebra mussels (*Dreissena polymorpha*); v_{14} — eutrophication; v_{15} — state of the Tsimlyansk reservoir waters; v_{16} — changes in bream biomass; v_{17} — changes in the concentration of phyto- and zooplankton; v_{18} — changes in the concentration of biogenic substances (nitrogen, phosphorus, silicon compounds); v_{19} — influence of abiotic factors (salinity, temperature); v_{20} — anthropogenic impact (cleaning of the reservoir bottom from an invasive species — zebra mussels).

Based on the analysis of the hydrobiological state of the Tsimlyansk reservoir, graph $G(V, E, Y)$ was obtained. Here:

– V — set of graph vertices (concepts), $v_k \in V$, $k = \overline{1, 20}$;

– E — set of oriented edges (connections) $e_k = (v_i, v_j)$, given as ordered pairs (tuples) of length 2, $i \neq j$;

– Y — mapping, $Y : V \to V$.

The resulting graph model (cognitive map) of the bioproductivity of the Tsimlyansk Reservoir is presented in Figure 1. In this graph, the dotted lines represent positive effects, and the solid lines represent negative ones. A single arrow indicates a weak impact, while a double arrow indicates a strong impact.

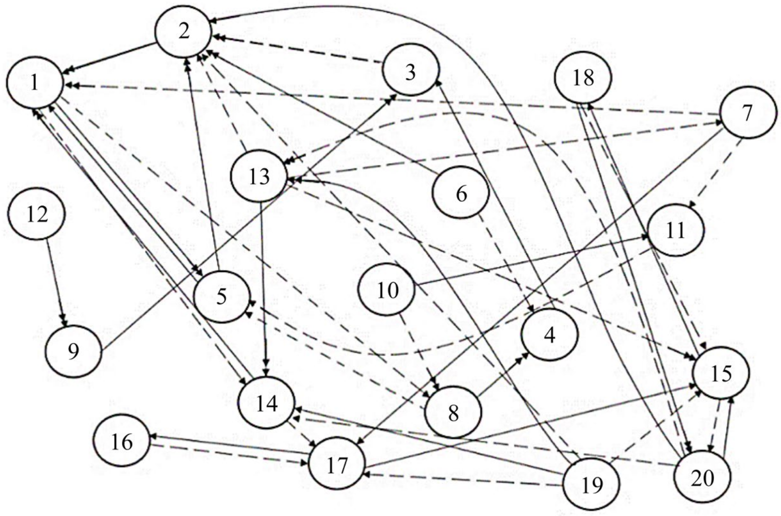

Fig. 1. Graph model of the Tsimlyansk Reservoir bioproductivity

The weight matrix of the graph model was generated based on an integral assessment of expert opinions, considering the significance of each factor's influence. Experts included specialists in fields such as hydrobiology, aquatic ecosystem ecology, ichthyology, mathematical modeling, computational mathematics, programming, etc. When calculating the weighting coefficients of the matrix, a continuously updated information base on hydrobiology and chemistry was utilized. This information was created by the researchers over many years of fieldwork.

In addition, the authors analyzed literary sources, information obtained from remote sensing of the Earth, as well as data on:

– hydrobiochemistry of shallow reservoirs;

– species composition of valuable and commercial fish.

Further, when analyzing the influence of certain factors on the Tsimlyansk Reservoir productivity, the weighting coefficient for a weak impact (single arrow) will be ±0.5, and for a strong impact (double arrow) — ±1.

Results. A Python software package has been developed to numerically implement the graph-based productivity model of the Tsimlyansk Reservoir. This package allows users to work with both individual subgraphs and a complete cognitive map of the Tsimlyansk Reservoir bioproductivity (Fig. 1). This enables a more accurate description of the processes that affect the ecosystem of the reservoir.

The main steps of the algorithm for implementing the graph-based productivity model of the Tsimlyansk Reservoir are outlined below.

Step 1. Determining the set of graph vertices by selecting the vertices of the graph model under consideration (Fig. 1). Setting modeling time interval N (in years) and the time layer number $n = 1$.

Step 2. Assignment of the initial vector of vertex weights (factors) for the constructed graph model:

$$X_{n-1} = \{x_{i(n-1)}\}_{i=1}^{k},$$

where k — number of vertices (factors) considered.

Step 3. Setting the relationship matrix (weight of graph edges) U_n, obtained on the basis of expert opinions, for current time layer n. For mild exposure — ±0.5, for strong — ±1, without exposure — 0

Step 4. Setting the vector of external pulses $Q_{n-1} = \{q_{i(n-1)}\}_{i=1}^{k}$ for current time layer n.

Step 5. Calculation of momentum vector R_n for current time layer n [18]:

$$R_n = X_n - X_{n-1}, \quad n = \overline{1, N}. \tag{1}$$

Step 6. Recalculation of the vertex weight vector (factors) for current time layer n [18]:

$$X_n = X_{n-1} + UR_{n-1} + Q_{n-1}. \tag{2}$$

Step 7. If $n < N$, then go to step 5. Otherwise, the work will be completed and the graph will be build.

Taking into account expression (2), formula (1) can be represented as follows:

$$R_n = UR_{n-1} + Q_{n-1},$$

or

$$R_1 = Q_0, \quad R_2 = U^1 Q_0 + EQ_1, \ldots, \quad R_n = \sum_{k=1}^{n-1} U^k Q_{n-k-1} + EQ_{n-1}. \tag{3}$$

We believe that there are several possible scenarios for increasing the productivity of the Tsimlyansk reservoir. In the first scenario, we consider removing the invasive species — zebra mussels — from the reservoir through one-time cleaning measures (only in the first year).

Scenario 1. Thus, the anthropogenic impact was the cleaning of the bottom of the Tsimlyansk Reservoir from the zebra mussels in the first year.

In the graph model for this scenario, we included the following factors (vertices) from the full model (Fig. 1): v_{15} — state of the Tsimlyansk reservoir waters; v_{18} — changes in the concentration of biogenic substances (nitrogen, phosphorus, silicon compounds); v_{20} — anthropogenic impact (cleaning of the reservoir bottom from an invasive species — zebra mussels).

Figure 2 shows a graph model (a subgraph of the graph from Figure 1) of this scenario. The color highlights the factor that was affected by a positive external pulse.

The situation was modeled over a period of three years.

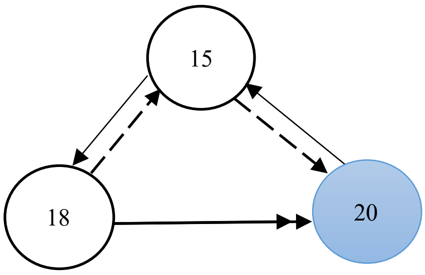

Fig. 2. Graph model for Scenario 1

Let us define relationship matrix U for the graph model (Fig. 2):

$$U = \begin{pmatrix} 0 & -0.5 & 0.5 \\ 0.5 & 0 & -0.5 \\ \infty & -1 & 0 \end{pmatrix}.$$

Let us set the vector of external pulses. Cleaning occurred only in the first year, so we set a positive pulse +1 at the beginning of v_{20} for Q_0. For the remaining years, we do not apply any external pulses:

$$Q_0 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad Q_1 = Q_2 = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}.$$

Let us calculate R_n pulses:

$$R_1 = Q_0 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad R_2 = UR_1 + Q_1 = \begin{pmatrix} 0.5 \\ -0.5 \\ 0 \end{pmatrix}, \quad R_3 = UR_2 + Q_2 = \begin{pmatrix} 0.25 \\ 0.25 \\ 0.5 \end{pmatrix}.$$

Figure 3 shows the results of changes in R_n pulses for water status factors v_{15} and changes in the concentration of nutrients (v_{18}).

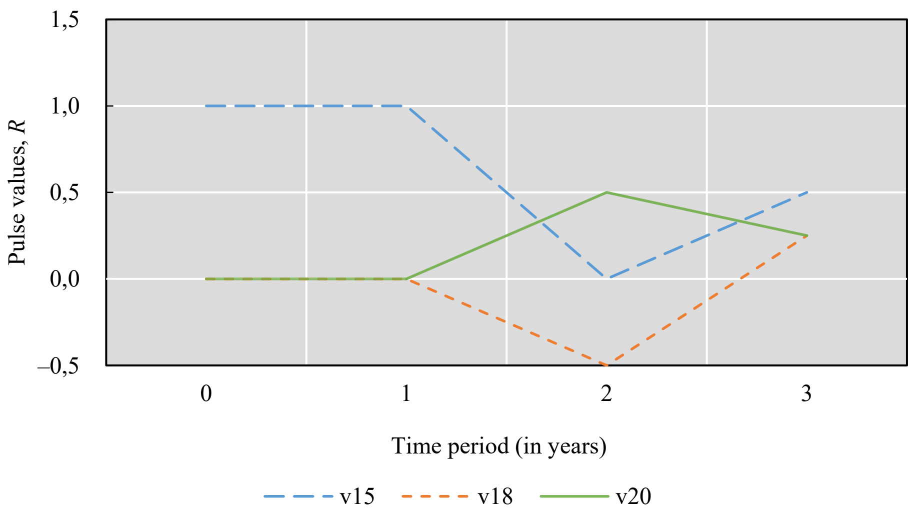

Fig. 3. Simulation results for Scenario 1

Scenario 2. Let us consider the anthropogenic impact — the annual cleaning of the bottom of the Tsimlyansk Reservoir from zebra mussels for three years.

The cognitive map of this scenario is also described in Figure 3. Relationship matrix U is as in Scenario 1.

Let us set the vector of external pulses +1 at vertex v_{20} in each year of the simulation:

$$Q_0 = Q_1 = Q_2 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}.$$

Let us calculate R_n pulses:

$$R_1 = Q_0 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad R_2 = UR_1 + Q_1 = \begin{pmatrix} 0.5 \\ -0.5 \\ 1 \end{pmatrix}, \quad R_3 = UR_2 + Q_2 = \begin{pmatrix} 0.75 \\ -0.25 \\ 1.5 \end{pmatrix}.$$

Figure 4 shows the results of changes in R_n pulses for the three factors considered over time.

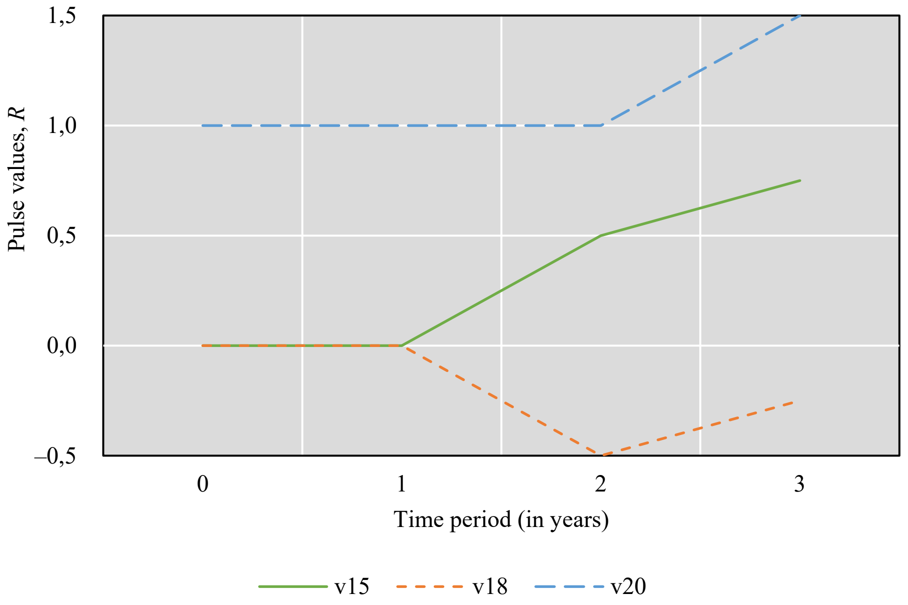

Fig. 4. Simulation results for Scenario 2

Let us consider two scenarios of anthropogenic impact on the specific efficiency of natural reproduction of commercial fish (bream) in the Tsimlyansk Reservoir — for a year and for five years

Scenario 3. Let us imagine the specific efficiency of natural bream reproduction in the Tsimlyansk Reservoir, when using feed additives for their nutrition during the first year.

The graph model included the following factors (vertices): v_1 — state of the spawning part of the fish population; v_2 — annual replenishment of juveniles; v_5 — specific efficiency of natural reproduction (feeding); v_7 — level of commercial exploitation of fish biological resources; v_{14} — eutrophication.

Figure 5 shows a cognitive map of this scenario.

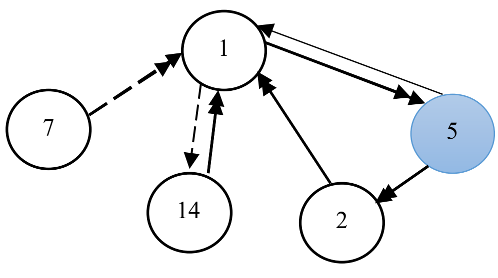

Fig. 5. Graph model for Scenario 3

The dynamics of the situation over a five-year period are modeled.

Let us define relationship matrix U based on expert opinions:

$$U = \begin{pmatrix} 0 & \infty & -1 & \infty & 0.5 \\ -1 & 0 & \infty & \infty & \infty \\ -0.5 & -1 & 0 & \infty & \infty \\ 1 & \infty & \infty & 0 & \infty \\ -1 & \infty & \infty & \infty & 0 \end{pmatrix}.$$

Let us set the vector of external pulses. Feed additives were introduced only in the first year, so we set a positive pulse +1 at the top of v_5 for Q_0. For the remaining years, we did not set external impulses:

$$Q_0 = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \quad Q_1 = Q_2 = Q_3 = Q_4 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}.$$

Let us calculate R_n, $n \in \overline{1.5}$: pulses:

$$R_1 = Q_0 = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \quad R_2 = UR_1 + Q_1 = \begin{pmatrix} -1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad R_3 = UR_2 + Q_2 = \begin{pmatrix} 0 \\ 1 \\ 0.5 \\ -1 \\ 1 \end{pmatrix}, \quad R_4 = UR_3 + Q_3 = \begin{pmatrix} 0 \\ 0 \\ -1 \\ 0 \\ 0 \end{pmatrix}, \quad R_5 = UR_4 + Q_4 = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}.$$

Figure 6 demonstrates how R_n pulses for the considered factors changed over time.

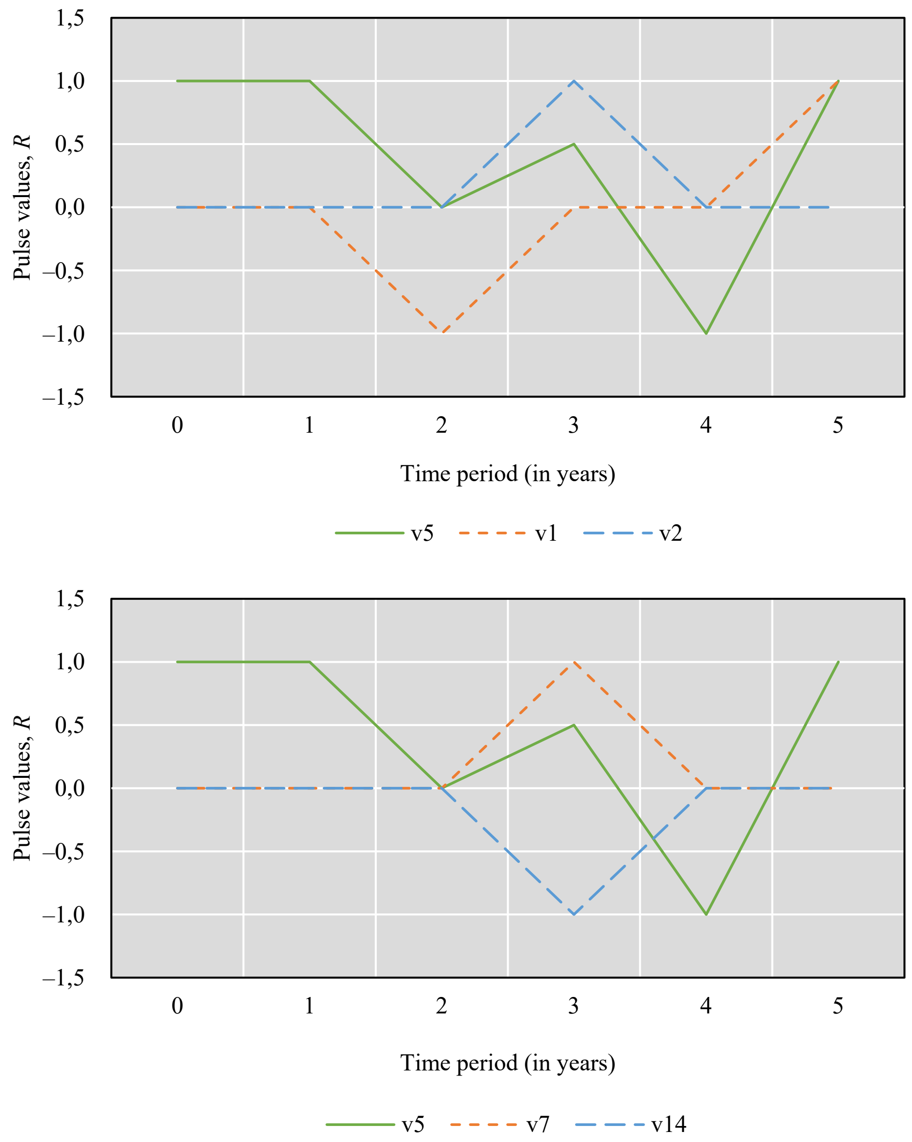

Fig. 6. Simulation results for Scenario 3

Scenario 4. Let us consider the specific efficiency of natural reproduction of commercial bream in the Tsimlyansk Reservoir when using feed additives annually for five years.

The cognitive map for this scenario is also described in Figure 6. Relationship matrix U is similar to Scenario 3.

Let us set the vector of external pulses (+1) at vertex v_5 for each year of the simulation:

$$Q_0 = Q_1 = Q_2 = Q_3 = Q_4 = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}.$$

Let us calculate R_n, $n \in \overline{1.5}$ pulses:

$$R_1 = Q_0 = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \quad R_2 = \begin{pmatrix} -1 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \quad R_3 = \begin{pmatrix} -1 \\ 1 \\ 1.5 \\ -1 \\ 1 \end{pmatrix}, \quad R_4 = \begin{pmatrix} -1 \\ 1 \\ 0.5 \\ -1 \\ 1 \end{pmatrix}, \quad R_5 = \begin{pmatrix} 0 \\ 1 \\ 0.5 \\ -1 \\ 1 \end{pmatrix}.$$

Figure 7 provides the results of the change in R_n pulses for the considered factors over time

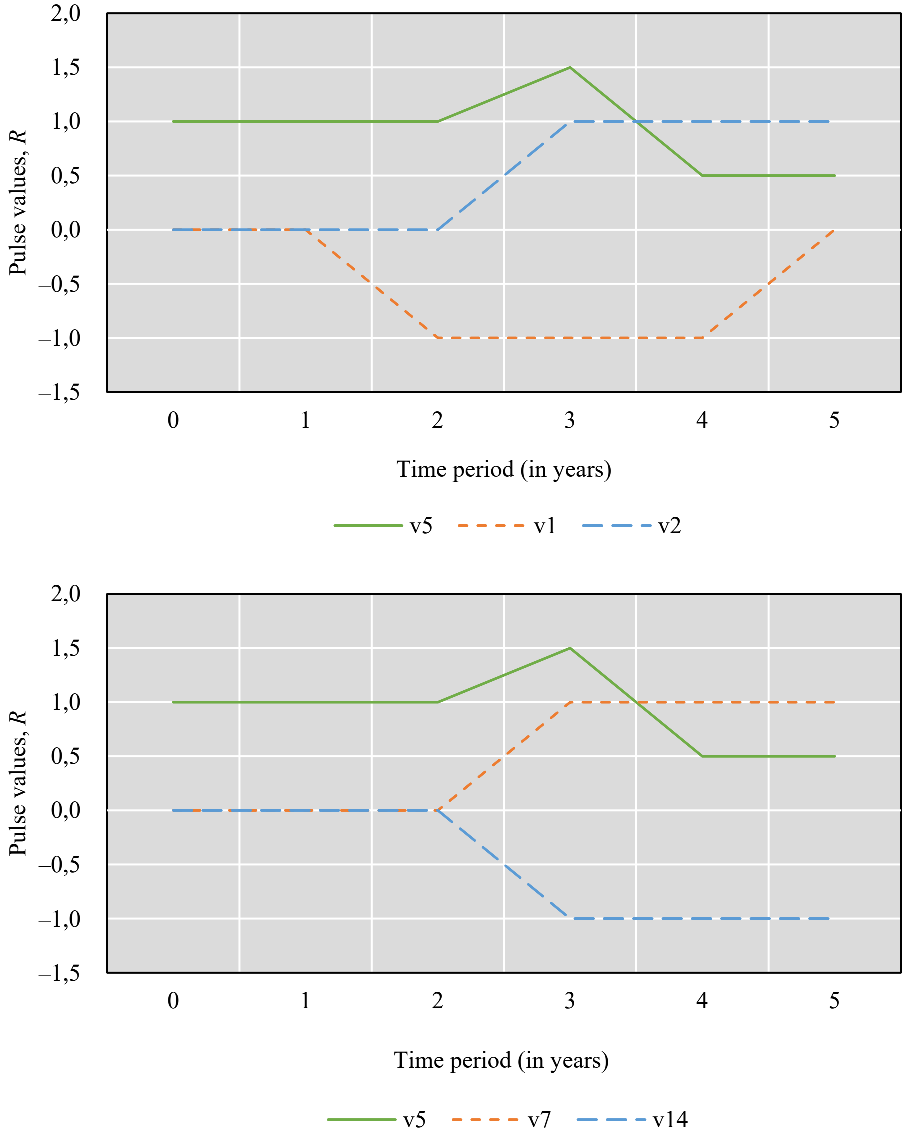

Fig. 7. Simulation results for Scenario 4

Discussion. In summary, the first two scenarios reflect the impact of removing an invasive species, zebra mussels, from the bottom of a reservoir. In the first scenario, the cleaning process was carried out only during the first year of the study. In the second scenario, it was conducted throughout the entire three-year simulation period. A comparison of the results suggests that annual removal of zebra mussels from the reservoir's bottom significantly improved water quality.

Such anthropogenic impact made it possible to reduce the concentration of polluting biogenic substances (nitrogen, phosphorus, and silicon compounds). As a result, eutrophication in the reservoir decreased, overgrowth of aquatic vegetation, waterlogging, and natural aging decreased, and transparency of the water increased. However, positive effects of the one-time cleanup did not last for more than a year. Furthermore, from the second year to the third, the concentration of nitrogen, phosphorus, and silicon compounds would continue to increase if zebra mussels were not removed from the bottom of the reservoir.

Visualization of the simulation results for the second scenario (Fig. 4) showed that the annual cleaning of the bottom of the Tsimlyansk Reservoir over three years significantly improved the quality of waters of the Tsimlyansk Reservoir. The effect was better than in the first scenario, as the pulse of the waters of the Tsimlyansk Reservoir continued to grow more intensively in the third year. In the third year, the pulse in Scenario 2 (Fig. 4) was 0.75, and in Scenario 1 (Fig. 3) it was 0.25. Similar to the first scenario (Fig. 3), the concentration of nutrients (Fig. 4) decreased during the first year. In the second year, the indicator increased, but not as sharply and significantly as in the first scenario, that is, with a single bottom cleaning. For the second scenario, there was no symmetry between the graphs of anthropogenic impact and the concentration of biogenic substances. Thus, annual cleaning of the reservoir bottom from zebra mussels was more effective for improving the water condition and less effective for the concentration of nutrients.

The second set of scenarios focused on the ichthyological aspects of the artificial reservoir. They considered the impact of fish feeding on the spawning population, the annual replenishment of juveniles, the level of commercial exploitation of fish biological resources and the eutrophication of the reservoir were considered. In the first case, additional feeding was used only in the first year of modeling, while in the second scenario it was applied throughout the entire five-year period. One-time feeding had a positive impact on juvenile population growth and commercial exploitation, reducing eutrophication but not achieving sustainable results. Continuous feeding could significantly increase juvenile numbers and reduce eutrophication levels, leading to increased fishing.

According to the data presented in Figure 6, during the first year, additional feeding had no significant effect on the replenishment of juvenile fish, the level of commercial fishing, or the level of eutrophication in the reservoir. This suggests that there was a delayed effect. During the second year, however, there was an increase in the number of spawning fish and both the annual replenishment of juvenile fish and commercial fishing increased. Due to the active fishing during the third year, the volume of juvenile fish being replenished decreased. These factors were interrelated, leading to a decrease in commercial fishing at the same time. The eutrophication of the reservoir decreased during the second year. This can be explained by the fact that with an increased fish population, algae are consumed faster, which leads to smaller juvenile fish, a decline in the spawning population, and as a result, less algae consumption, and an increase in eutrophication during the third year. During the fourth year, there was no increase in the schedules for the replenishment of juvenile fish or eutrophication. The improvement in the condition of the spawning area can be attributed to the growth of juvenile fish.

From the graphs in Figure 7, we can conclude that the condition of the reservoir would change significantly if the additional feeding was extended for five years. During the first three years, the results were similar to those of Scenario 3. However, there was a notable improvement in the annual replenishment of juvenile fish and an increase in the commercial exploitation of fish biological resources. At the same time, there were no obvious cyclical patterns of increase and decrease in fish numbers, as observed in the modeling results of the sixth scenario. The decline in the spawning population before the fourth year may be attributed to increased commercial exploitation. By the fifth year, however, the situation improved, likely due to the growth of juvenile fish. The growing population of fish contributed more to the cleaning of the reservoir by eating more vegetation, leading to a noticeable reduction in eutrophication.

Figures 6 and 7 show the same pulse from feeding fish for the first year, calculated according to formula (1). In the second year, the pulse in Scenario 3 (Fig 6) dropped to 0. Scenario 4 (Fig. 7) reflected the resumption of feeding, so the pulse reached 1, and then increased due to the cumulative effect and the effect of feeding on related factors. The development of this situation led to the fact that there were more juveniles, they needed more food, and feeding no longer gave such a significant pulse.

To interpret the results, it was important to take into account that, according to formula (1), a decrease in pulse (if its value is positive) did not contradict an increase in the value of the corresponding factor. Thus, Figures 6 and 7 mathematically reflect the biological processes under study.

Based on the results obtained, it is possible to judge how to ensure the sustainable ecological development of the Tsimlyansk Reservoir. This requires annual environmental monitoring and measures to reduce anthropogenic impact (with a mandatory assessment of the economic component).

Conclusion. The proposed graph model includes 20 factors (concepts) that significantly affect the water quality and biological productivity of the Tsimlyansk Reservoir. The solution was created in the absence of sufficient expert information and with a rarely updated database of indicators. The matrix of weighting coefficients corresponding to the proposed graph model was based on expert estimates, which may be subjective and may change over time. Additionally, when aggregating data, there is a possibility of errors in estimating the pulse values. Within the framework of the chosen scenario approach, the proposed graph model allows for the incorporation of new information and quick, low-cost analysis of the effectiveness of proposed measures to improve the ecological state of the reservoir.

The results of the study can be used to assess the economic impact and damage caused by human activities on aquatic ecosystems. Ideally, these ecosystems should strive for a state of homeostasis.

To improve the presented model, it is necessary to fine-tune the weighting coefficients. This should take into account nonlinear and threshold effects as well as other relevant indicators.

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Claimed Contributorship:
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Conflict of Interest Statement: **the authors declare no conflict of interest.**

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Заявленный вклад авторов:

И.Ю. Кузнецова: написание черновика рукописи, разработка программного обеспечения, визуализация, написание рукописи — внесение замечаний и исправлений.

А.В. Никитина: разработка концепции, научное руководство, написание рукописи — внесение замечаний и исправлений.

Конфликт интересов, **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 22.09.2025
Reviewed / Поступила после рецензирования 17.10.2025
Accepted / Принята к публикации 26.10.2025

MACHINE BUILDING
МАШИНОСТРОЕНИЕ

UDC 656.2/.4
https://doi.org/10.23947/2541-9129-2025-9-4-319-330

Perspective Article

Reducing the Risk of Container Overturning under Wind Loads by Improving the Parameters of Railway Platform Stops

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Abstract

Introduction. The problem of containers overturning off railway platforms has become more acute with the development of logistics and climate change, and is attracting the attention of researchers. This paper examines the situations at various logistics facilities and different capacities. It is known how the risk of overturning depends on the strength of the wind, the curvature of the track, and the height of the rail. There are methods to calculate losses from these incidents. The results of the survey are useful for logistics management, but implementing such solutions takes time and significant resources, so they are rarely implemented in practice. The approach described in this article addresses these limitations by its technical simplicity. Its aim is to demonstrate the effectiveness of adjusting three platform parameters: the lateral gap at the edge, as well as the height and thickness of the stationary stops.

Materials and Methods. The literature on the subject was analyzed, including state standards, technical specifications, and building codes and regulations. The connection between the fitting and the stop, as well as the container's parameters necessary for calculations, were visualized in diagrams. The equations took into account the strength of the wind, its lateral load on the container, and regional characteristics. We used data on a 40-foot container with dimensions of approximately 12.2 meters in length, 2.6 meters in height, and 3.9 tons in weight, with spacing between fittings of approximately 2.3 meters. Regional wind patterns were determined using the "Zoning of the Territory of the Russian Federation by Wind Pressure" map.

Results. It has been proven that a technically simple change in platform stops would significantly reduce the risks of container overturning under significant wind load. It was necessary to minimize the lateral play at the edge of the platform, increase the height of the stationary stop to 106 mm, and its thickness to 56 mm. Without these upgrades, a 40-foot container would overturn at a wind speed of 120 Pa. With the proposed configuration, the stability of the container on the platform was significantly improved. In dry conditions, the container remained stable under wind forces of ≈834 Pa, with precipitation — ≈500 Pa. This represented a gain of 7 times and 4.2 times, respectively, in stability.

Discussion. In the initial configuration, a 40-foot container overturns at a wind speed of 11.9 m/s, or in wind zone I, as in Moscow or Minsk. The modernization proposed by the author will allow the container to withstand wind speeds of 37 m/s (zone VII). In rain and snow, the container will overturn at a wind speed of 29.5 m/s. This is zone IV (Kazakhstan and the coast of the Caspian Sea). Currently, there is active automobile and railway traffic here. Cargo traffic is expected to increase in the future due to the implementation of the Silk Road project.

Conclusion. The implementation of the proposed innovation will significantly reduce the likelihood of emergencies due to containers falling from railway platforms and, consequently, increase transportation safety. The solution is characterized by technological simplicity and versatility. The container design remains the same. Individual elements of the platform change minimally.

Keywords: container stability on a railway platform, lateral wind load on a container, wind pressure zoning, stationary container support

Acknowledgements. The author would like to thank the Editorial board and the reviewers for their attentive attitude to the article and for the comments that improved its quality.

For Citation. Demyanov AA. Reducing the Risk of Container Overturning under Wind Loads by Improving the Parameters of Railway Platform Stops. *Safety of Technogenic and Natural Systems*. 2025;9(4):319–330. https://doi.org/10.23947/2541-9129-2025-9-4-319-330

Статья-перспектива

Снижение риска опрокидывания контейнеров под воздействием ветровой нагрузки путем совершенствования параметров упоров железнодорожных платформ

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Аннотация

Введение. Проблема падения контейнеров с железнодорожных платформ обостряется с развитием логистики, изменением климата и привлекает внимание исследователей. Рассматриваются ситуации на разных логистических объектах и для разных емкостей. Известно, как риск опрокидывания зависит от силы ветра, кривизны пути и высоты рельса. Есть методики определения потерь от рассматриваемых инцидентов. Результаты изысканий полезны для менеджмента логистики, однако внедрение таких решений требует времени, значительных затрат, поэтому редко реализуется на практике. Подход, описанный в данной статье, преодолевает эти ограничения, благодаря технической простоте. Цель работы — доказать эффективность изменения трех параметров платформы: бокового зазора у ее края, а также высоты и толщины стационарных упоров.

Материалы и методы. Анализировалась литература по проблеме, в том числе госстандарты, технические условия, строительные нормы и правила. В виде схем визуализировались необходимые для расчетов сопряжение фитинга и упора, параметры контейнера. В уравнениях учитывались также сила ветра, его боковая нагрузка на контейнер и региональные характеристики. Использовали данные о 40-футовом контейнере длиной ≈12,2 м, высотой ≈2,6 м, массой 3,9 тонн, с расстоянием между фитингами ≈2,3 м. Региональные особенности ветров определили по карте «Районирование территории Российской Федерации по давлению ветра».

Результаты исследования. Доказано, что технически несложное изменение упоров платформы существенно снизит риски опрокидывания контейнера при значительной ветровой нагрузке. Нужно максимально уменьшить боковой зазор у края платформы, увеличить высоту стационарного упора до 106 мм, толщину — до 56 мм. Без модернизации 40-футовый контейнер опрокинется при ветровой нагрузке 120 Па. В предложенной автором конфигурации устойчивость контейнера на платформе существенно увеличится. В сухую погоду емкость сохранит устойчивость при боковом воздействии ветра силой ≈834 Па, при осадках — ≈500 Па. Таким образом, можно говорить об усилении в 7 раз и 4,2 раза соответственно.

Обсуждение. В изначальной конфигурации 40-футовый контейнер опрокинется при скорости ветра 11,9 м/с, или в I ветровой зоне — как в Москве или Минске. Предложенная автором модернизация позволит контейнеру устоять при скорости ветра 37 м/с (VII зона). В дождь и снег контейнер опрокинется при скорости ветра 29,5 м/с. Это IV зона (Казахстан и побережье Каспийского моря). В настоящее время здесь фиксируется активный автомобильный и железнодорожный трафик. В перспективе ожидается рост грузопотока в связи с реализацией проекта «Шелковый путь».

Заключение. Внедрение предложенной новации значительно сократит вероятность чрезвычайных ситуаций из-за падения контейнеров с железнодорожных платформ и, соответственно, повысит безопасность перевозок. Решение отличается технологической простотой и универсальностью. Конструкция контейнера остается прежней. Отдельные элементы платформы меняются минимально.

Ключевые слова: устойчивость контейнера на железнодорожной платформе, боковая ветровая нагрузка на контейнер, районирование по давлению ветра, стационарный упор для контейнера

Благодарности. Автор выражает благодарность редакции и рецензентам за внимательное отношение к статье и замечания, которые позволили повысить ее качество.

Для цитирования. Демьянов А.А. Снижение риска опрокидывания контейнеров под воздействием ветровой нагрузки путем совершенствования параметров упоров железнодорожных платформ. *Безопасность техногенных и природных систем.* 2025;9(4):319–330. https://doi.org/10.23947/2541-9129-2025-9-4-319-330

Introduction. The growing problem of modern logistics and the risk of containers falling from railway platforms require theoretical and practical research. Both empty and full containers are not able to withstand strong wind forces. As a result, incidents and accidents on the railway are becoming more common. Here are some resonant examples. On April 22, 2014, eleven containers with a total weight of 20 tons were overturned by the wind in the Yamalo-Nenets Autonomous Okrug[1].

On December 29, 2015, on the Vishnevka — Anar section (Karaganda direction), a container fell across the tracks. The traffic of twelve trains was brought to a standstill[2].

On August 13, 2016, wind gusts blew seven empty containers off the platform on the Domikan —Arkharinsk section of the Trans-Baikal Railway. Traffic stopped in two directions[3].

Experts give two reasons for the increased frequency of such incidents. The first is the growth of railway container traffic. The second is climate change, which has led to increased wind loads.

The strategically important East-West transport corridor runs through Russia, and railway transportation, including container transportation, forms the basis of traffic. Since 2019, their volumes have been growing, even under international sanctions[4]. In 2022, Russian Railways transported a record 123 million tons of cargo to China[5], which was almost a third more than in 2021. And in 2023, this indicator increased by another 85%[6].

The high dynamics of traffic volume growth continues. Russian Railways are increasingly working on the Trans-Mongolian route and the transit corridor through Kazakhstan[7].

The instability of global logistics, particularly maritime traffic through the Suez Canal, has increased the demand for overland transportation from Asia to Europe through Russia. To fully develop as an alternative, the Russian railway transport system needs to address several challenges. One such challenge is the risks of damage, loss of cargo and delays in delivery caused by containers falling off platforms.

Meteorologists record changes in wind load in different regions of the planet. Previously uncharacteristic hurricanes and tornadoes are increasingly observed in some territories of Russia[8]. Such weather adversely affects the transport infrastructure, including the railway. It is obvious that overturning containers from platforms reduces the safety of transportation.

According to modern research, about a hundred cases of container overturning occur annually on the roads of Russia under the influence of strong winds. A wind speed of 17 meters per second is enough for a serious incident [1].

In 2024, Russian Railways management ordered that reference and analytical information on the possible strength and intensity of wind on the route should be taken into account when planning transportation[9].

When assessing damage caused by fallen containers, it is important to consider not only the damage to the container and its contents, but also the potential consequences of a container falling onto the way. This will almost certainly result in traffic stop losses. However, more serious consequences are possible, for example, in conditions with poor visibility (at night, during fog, etc.). It is especially dangerous if the container falls off the platform on the bridge.

A review of the literature on this issue revealed that researchers have considered the risks of container overturning under various climatic conditions and at structurally and functionally diverse facilities within the global transportation system. For instance, the movement of rail and road transport platforms carrying containers has been studied, as well as the risks associated with containers not moving during loading and unloading operations while waiting.

In [2], the methods for assessing the stability of containers during transportation on specialized railway platforms are discussed. Paper [3] describes the conditions under which empty containers of different types can overturn. It shows how the probability of such an incident depends on the strength of wind, the curvature of the track, and the height of high rails. Methods have also been developed to estimate the economic, financial, and reputational costs associated with these incidents.

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[1] In Yamalo-Nenets Autonomous District, 11 containers with cargo tipped over due to strong winds. (In Russ.) URL: https://life.ru/p/131740 (accessed: 08.11.2025).

[2] In Akmola region, a container was blown off a freight train by a strong wind. (In Russ.) URL: https://www.zakon.kz/proisshestviia/4766046-v-karagandinskojj-oblasti-silnym-vetrom.html (accessed: 08.11.2025).

[3] On the movement of trains on the Arkhara — Domikan section of the Svobodny region of the Trans-Baikal Railway. (In Russ.) URL: https://zabzd.rzd.ru/ru/2332/page/2452802?id=90092 (accessed: 08.11.2025).

[4] The Russian container transportation market has a threefold potential for growth. (In Russ.) URL: https://www.megaresearch.ru/new_reality/u-rynka-konteynernyh-perevozok-rossii-est-trehkratnyy-potencial-dlya-rosta (accessed: 08.11.2025).

[5] In 2022, Russian Railways increased cargo transportation with China by 28%, to 123 million tons. (In Russ.) URL: https://www.interfax.ru/business/886341 (accessed: 08.11.2025).

[6] Russian Railways increased cargo transportation with China by almost 1.9 times in January-February. (In Russ.) URL: https://www.interfax.ru/business/892180 (accessed: 08.11.2025).

[7] Id.

[8] Gubaeva L. How the climate of Russia will change in the 21st century and why it is necessary to get used to weather anomalies. Real time. (In Russ.) URL: https://m.realnoevremya.ru/articles/184780-kak-globalnoe-izmenenie-klimata-otrazitsya-na-rossii-v-xxi-veke (accessed: 08.11.2025).

[9] Russian Railways. Order No. 2115p dated October 19, 2016. On approval of the Procedure for organizing the safe passage of freight trains with empty containers when predicting a dangerous weather event along their route. (In Russ.) URL: https://docs.cntd.ru/document/456030815 (accessed: 08.11.2025).

In [4], the effects of crosswinds on various types of railway vehicles used for urban and suburban transport are studied. It should be noted that this issue is relevant not only to railway transport, but also to automobile traffic [5]. There have been publications in which authors have determined the minimum speed and angle of the wind relative to the train's direction of movement in the climate conditions of South Australia [6] and Colombia [7], which emphasizes the scale and global significance of the issue.

There are known works on forecasting economic damage caused by disruptions in the operation of ocean container ports due to wind [8], extreme wind events [9]. In [10], methods for modeling the damage to container shipments from wind impacts are presented and the development of long-term weather forecasts is proposed. The results of this study can be extrapolated to the work of other related subjects of port logistics, for example, to companies engaged in the field of freight rail transportation.

A study on improving the safety of water transport in strong wind conditions [11] suggests a comprehensive risk awareness tool for decision makers need to prevent disasters in stormy weather. This approach can be integrated with the principles of safe operation of any transportation system, including railways.

The scientific research described above provides solutions for managerial practice in logistics. These solutions can be useful for solving the problem of container falling off railway platforms. However, the approaches considered are complex or initially stated as part of a large-scale security system. This means that significant financial and time resources are needed to implement them. Improvements are needed, taking into account not only the national specifics, but also the specifics of individual territories through which freight trains with containers travel. Over time, such adapted solutions will undoubtedly appear. In the meantime, some measures can be taken. These measures should be low-cost and easy to implement. The aim of this work is to demonstrate the effectiveness of changing the platform's lateral play, working height, and stationary stop thickness.

Materials and Methods. An analysis of container mounting methods showed that the fitting parameters were uniform and fixed in GOST R 51891-2008, while the designs of the stops were diverse and regulated by various specifications.

The most common designs of stops are listed below:

– stationary stop, welded to the platform frame (Fig. 1);

– folding single welded stop (Fig. 2);

– folding single cast stop (Fig. 3);

– folding double welded stop (Fig. 4);

– folding single stop with additional fastening (Fig. 5).

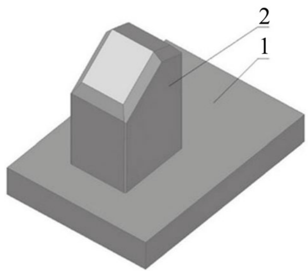
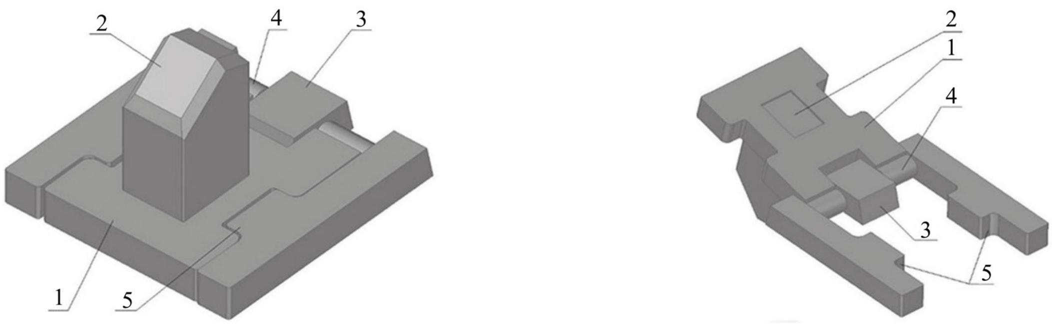


Fig. 1. 31887-NSB non-folding, stationary stop, welded to the platform frame [12]:
1 — base, 2 — stop



a) *b)*

Fig. 2. 31901-NSB single welded folding stop [12]:
a — initial position; *b* — reclined position; 1 — base of the stop; 2 — stop;
3 — hinge; 4 — axial pin; 5 — stop plate

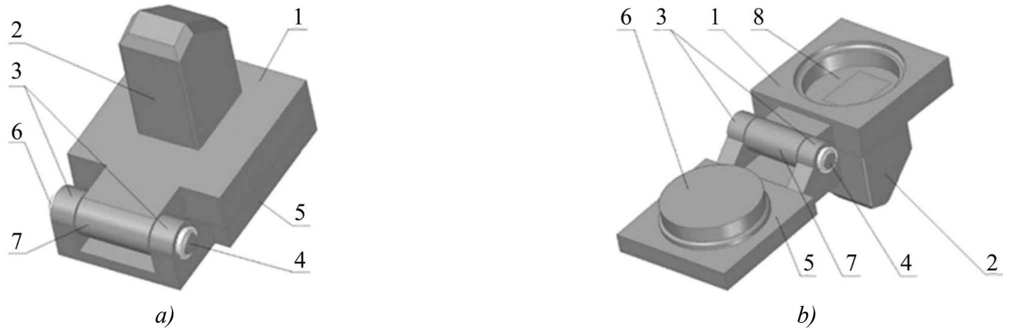


Fig. 3. 31896-NSB single cast folding stop [12]:
a — initial position; *b* — reclined position; 1 — stop base; 2 — stop; 3 — base loop;
4 — axial pin; 5 — stop plate; 6 — centering spigot; 7 — stop loops; 8 — recess for centering spigot

Fig. 4. 31883-NSB folding double welded stop [12]:
a — initial position; *b* — reclined position; 1 — stop base; 2 — stop; 3 — axial pin; 4 — stop plate;
5 — base loop; 6 — holes for stops

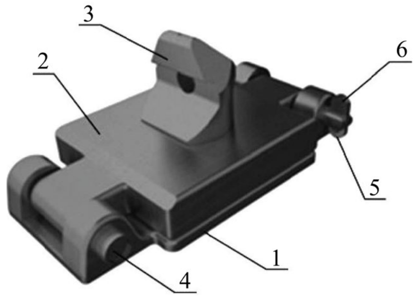


Fig. 5. Single folding stop with additional fastening [12]:
1 — stop plate; 2 — stop base; 3 — stop; 4 — axial pin;
5 — shackle lock; 6 — accidental release lock

Due to lateral play Δ = 11.5–13.5 mm, the fitting can easily slip off the stop and does not prevent the container from overturning (Fig. 6). If the stops are used without additional fasteners, the container may lose stability from the effects of transverse wind loads, as is known from logistics practice.

The analysis of serial fitting stop designs revealed that their height was 85–100 mm, thickness — 50–52 mm, and width — 78 mm. The height of the hole for the stop in the fitting was 108 mm, width — 63.5 mm.

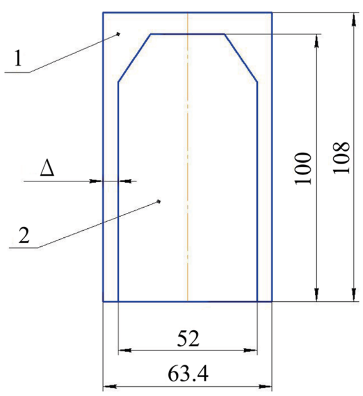


Fig 6. Coupling of the fitting and the stop in the cross section:
1 — size of the fitting hole; 2 — size of the stop

Let us evaluate the stability of the container on the stops of the original structure. The conditions are:

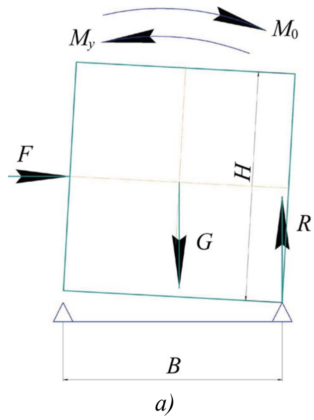
– transportation of an empty container in a straight line;

– wind load is transverse to the movement direction.

Let us perform the calculation for the most common type of stop — 31887-NSB stationary non-folding stop (Fig. 7).

Fig. 7. Stationary stop for the container

In the absence of additional fasteners, stability can be found from the equality of M_O overturning moment and M_Y stabilizing moment (Fig. 8).



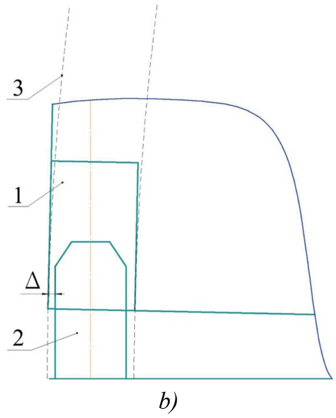


Fig. 8. Cross section of the container:
a — design diagram; *b* — gap between the fitting and the stop when overturning;
1 — fitting hole; 2 — stop; 3 — trajectory of movement when overturning

If the center of gravity is in the middle between the stops, then the stabilizing moment is:

$$M_Y = G \times B / 2,$$

where G — mass of the empty container, kg; B — container width, m.

If the tilting force is in the middle of the height of the container, then the overturning moment is:

$$M_O = F \times H / 2,$$

where F — lateral force of the wind on the container wall, kg; H — height of the container, m.

The wind force can be determined from the ratio:

$$F = P \times S,$$

where P — wind load, kg/m^2; $S = L \cdot H$ — side wall area of the container; L — length of the container, m.

The wind pressure, according to Construction Standards and Regulations 2.01.07-85[10] and 20.13330.2016[11], is determined as follows:

$$P = W_0 \times k \times c,$$

where W_0 — standard wind pressure for a certain region, k — standard coefficient of wind pressure adjustment taking into account the height and ground profile, c — object aerodynamics coefficient.

Let us transform the original formulas:

$$W_0 \cdot k \cdot c \cdot L \cdot H \cdot \frac{H}{2} \ge G \cdot \frac{B}{2}.$$

[10] SNiP 2.01.07-85*. Loads and impacts. (In Russ.) URL: https://www.minstroyrf.gov.ru/docs/13673/ (accessed: 08.11.2025).

[11] SP 20.13330.2016. Set of rules. Loads and impacts. Updated version of SNiP 2.01.07-85*. (In Russ.) URL: https://mchs.gov.ru/uploads/document/2022-03-15/079727a84b6dfc87f4f6c2db1a5693ed.pdf (accessed: 08.11.2025).

Let us simplify it:

$$W_0 \cdot k \cdot c \cdot L \cdot H^2 \geq G \cdot B.$$

Let us transform the resulting expression:

$$W_0 = \frac{G \cdot B}{k \cdot c \cdot L \cdot H^2}.$$

Let us perform the calculation using the example of a 40-foot container dimensions $L \approx 12.2$ m, $H \approx 2.6$ m and a weight of G = 3900 kg. According to GOST R 51891-2008, the spacing between the fittings is $B \approx 2.3$ m (Fig. 8). The calculations are conducted for open space (SNiP 2.01.07-85 and SP 20.13330.2016).

Since the upper size of the container is 5.2 m, we will use the wind pressure correction factor $k = 0.75$.

Given that the ratio of the length to height of the object exceeds 4, the aerodynamic coefficient will be $c = 1.2$ (in accordance with SP 20.13330.2016).

We can estimate the threshold value of wind pressure velocity that could potentially overturn an empty 40-foot container as follows:

$$W_0 = \frac{3{,}900 \cdot 2.3}{0.75 \cdot 1.2 \cdot 12.2 \cdot 2.6^2} = 120 \text{ kg/m}^2 = 120 \text{ Pa}.$$

According to SP 20.13330.2016, this corresponds to a wind speed of approximately 11.9 m/s.

The obtained values allow us to conclude that safety is not ensured even in the I wind zone (Table 1), which includes, for example, Moscow, Minsk, etc.

Table 1

Standard wind pressures depending on the wind area according to SP 20.13330.2016

Wind regions of Russia	Ia	I	II	III	IV	V	VI	VII
W_0, kPa (kg s/m^2)	0.17 (17)	0.23 (23)	0.30 (30)	0.38 (38)	0.48 (48)	0.60 (60)	0.73 (73)	0.85 (85)

According to the average data[12] the wind speed in the north of Russia is 28–35 m/s, in the Far East — 31–38 m/s, in the North Caucasus — 28–31 m/s. At the same time, wind gusts in these regions can exceed 40 m/s.

The level of stability and safety for container transportation increases directly with the workload. Therefore, the risks for empty containers are the highest.

A significant amount of cargo traffic passes through areas with strong wind pressure, zones III and IV (Fig. 9). This means that there is a risk of containers overturning during the majority of transportation journeys. Additionally, many containers travel from Europe to China without cargo [2].

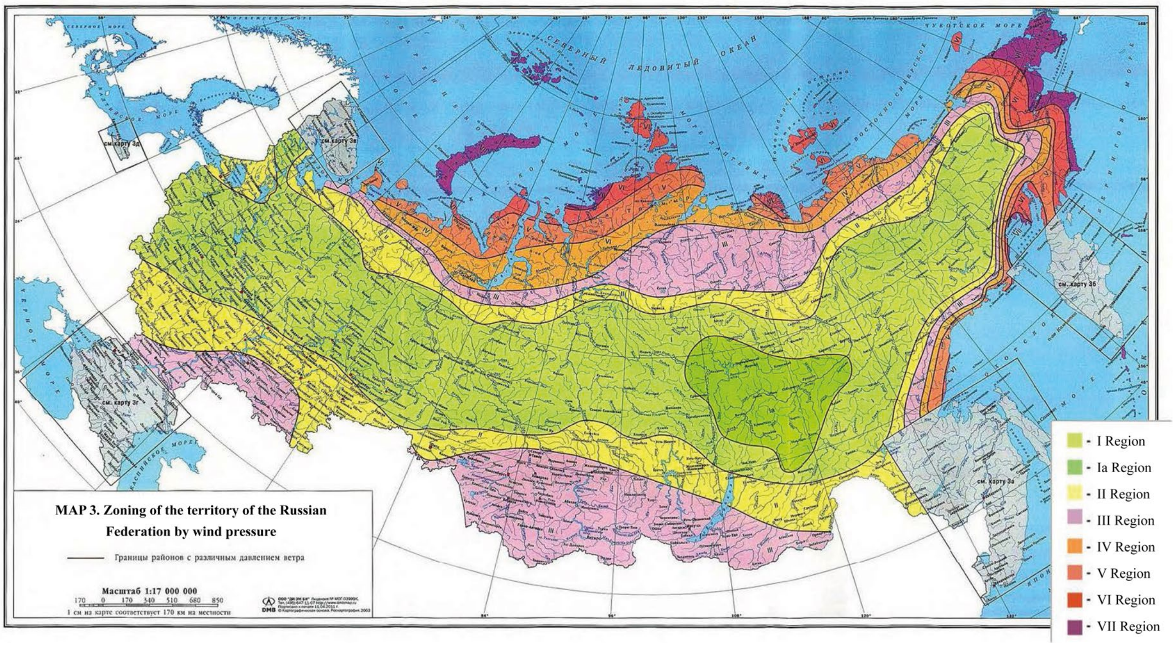


Fig. 9. Wind loads in different regions of Russia

[12] Shoigu SK, Trokhina NB. (eds.) Atlas of natural and man-made hazards and risks of emergency situations in the Russian Federation. Moscow: DIK; 2005. P. 269. (In Russ.)

To solve the problem of containers being overturned by the wind, a proposal has been made to equip the platforms with additional locking mechanisms [13] or additional retaining elements [14].

In the first option, additional assemblies would be placed under each container. It is a shaft transverse to the axis of movement of the car. At each end of the shaft, there would be a lever. One lever would press against the container, while the other lever would turn under the force of that pressure, helping to keep the container from overturning (Fig. 10).

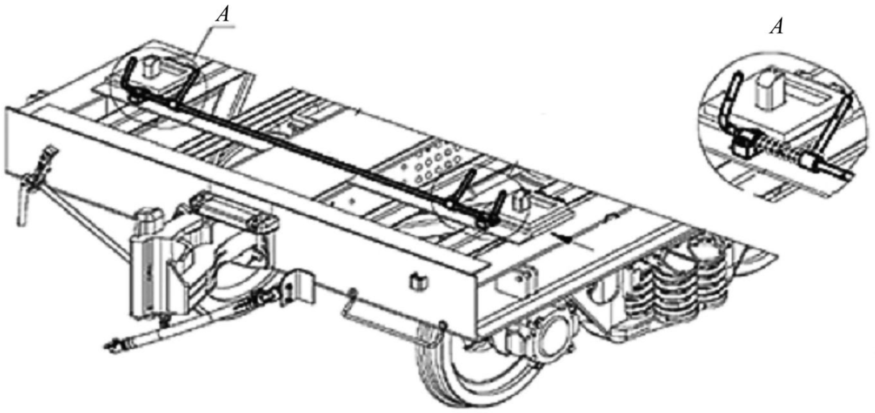


Fig. 10. Torsion shaft with levers [12]: *A* — retaining rotary levers

The second technical solution involves the use of locking devices under each container in the form of additional pins. These pins must be positioned with a minimum clearance to ensure that the container can be moved vertically when placed and removed from the platform (Fig. 11).

a)

b)

Fig. 11. Locking device [13]: *a* — schematic representation; *b* — place on the platform

It should be noted that modernizing standard cars with new components will require significant financial investment. In addition, there is a possibility of misalignments due to wind gusts or incorrect actions by the crane operator. When installed on a platform in a transverse plane, the shaft levers may rotate asynchronously, which can lead to deformation or breakage of the components. These are the weaknesses of the first option.

The main disadvantage of the second solution is its structural inefficiency. It can be seen as an unnecessary complication of the design with several parallel elements (a stop and an external pin) that perform the same function. Additionally, as in the first case, implementation involves significant financial, material, and time costs.

Results. In this paper, we propose to increase the wind resistance of containers on railway platforms without resource-intensive changes to the design of the cars and containers. The problem can be solved by adjusting three parameters (Fig. 12):

– increasing the working height of the stationary stop welded to the car frame from 85–100 mm to 106 mm;

– increasing the thickness of the stop from 50–52 mm to 56 mm;

– reducing the lateral play at the edge of the platform from 11.5–13.5 mm to a minimum technically feasible value;

– the width remains standard — 78 mm.

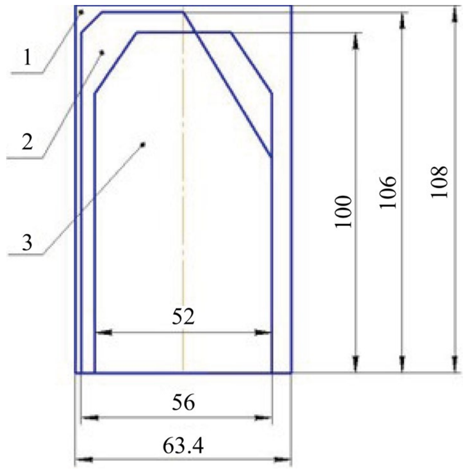


Fig. 12. Dimensions of the modified stop:
1 — size of the fitting hole; 2 — size of the modified stop; 3 — size of the initial stop

This approach will reduce the play of the container on the stops in the transverse plane from the edge of the platform.

As soon as the container begins to tilt, the stop will become jammed in the fitting due to the decreased external gap (Fig. 13).

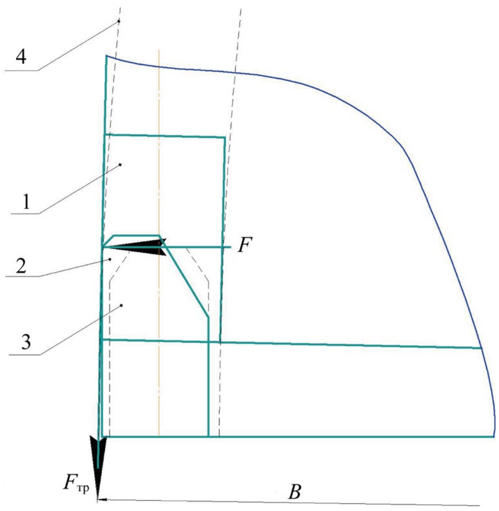


Fig. 13. Contact of the fitting surfaces and the modified stop when the container starts to overturn:
1 — fitting hole; 2 — modified stop; 3 — initial stop; 4 — trajectory of movement when overturning

It should be noted that the suggested maximum height of 106 mm should not be exceeded, as the container will then not be supported by the base of the platform. Instead, it will rest on relatively small stops, which could negatively affect stability. A recommended thickness of 56 mm, in terms of proportion, would fit well with a height of 106 mm

The container will be held by the frictional force F_{TP}. The limiting value of this force will depend solely on the stiffness of the stop. When the container bends under the load, the normal reaction from the support will decrease. This will cause the fitting to slip off the stop, and the container may overturn.

The effectiveness of the solution was determined by calculating the bending stop in the fitting and the maximum normal reaction force F between the interacting surfaces when the stop in the fitting is jammed.

Stops are often made of 10KhSND steel with allowable bending stresses of $[\sigma_{\text{И}}] = 220$ MPa:

$$[\sigma_{\text{И}}] \geq \sigma_{\text{И}} = \frac{F \cdot l}{W}.$$

Here l — height of the force applied to the stop from contact with the fitting. It is equal to 100 mm, however, taking into account chamfers and other elements, the working height is 106 mm, i.e. the maximum recommended in the framework of this scientific work.

This means,

$$F = \frac{[\sigma_{\text{И}}] \cdot W}{l},$$

where $W = \frac{b \cdot h^2}{6}$ — moment of stop resistance.

If the stop width h = 78 mm, and its thickness b = 56 mm, then:

$$F = \frac{220 \cdot 78 \cdot 56^2}{100 \cdot 6} = 89689{,}6 \text{ N}.$$

Thus, before the start of noticeable deformation, the stop will formally withstand 89.7 kN.

Let us calculate the additional friction holding force that occurs due to dry and rainy weather conditions.

According to TU No. TsM-943 dated October 23, 2017[13], the coefficient of friction at rest between steel surfaces cleaned of dirt and snow should be assumed to be 0.3.

In this case, the friction force of the stop on the fitting is:

$$F_{\text{TP}} = N \cdot \mu,$$

where μ = 0.3 — coefficient of friction of steel on steel, $N = F$ — normal pressing force of the surfaces.

Let us substitute the known values:

$$F_{\text{TP}} = N \cdot \mu, F_{\text{TP}} = 89{,}689.6 \cdot 0.3 = 26{,}906.88 \text{ N}.$$

Let us evaluate the effectiveness of the proposed solution by considering the wind load that can overcome the holding moment and cause the container to overturn:

$$M_{\text{У}} = F_{\text{TP}} \cdot B, \tag{1}$$

where F_{TP} — friction force on the surface of the fitting and the stop; B — application shoulder, i.e. the width of the container along the axes of the fittings.

Let us write down the ratio of moments:

$$M_0 = W_0 \cdot k \cdot c \cdot L \cdot H \cdot \frac{H}{2} \quad \text{and} \quad M_{\text{У}} = F_{\text{TP}} \cdot B. \tag{2}$$

This means:

$$W_0 \cdot k \cdot c \cdot L \cdot H^2 = F_{\text{TP}} \cdot B. \tag{3}$$

The value of the wind load:

$$W_0 = \frac{F_{TP} \cdot B}{k \cdot c \cdot L \cdot H^2}, \tag{4}$$

$$W_0 = \frac{2{,}690.7 \cdot 2.3}{0.75 \cdot 1.2 \cdot 12.2 \cdot 2.6^2} = 83.38 \text{ kg/m}^2 \approx 834 \text{ Pa}.$$

In wind and rain, the friction coefficient between the stop and the fitting is 0.15–0.2. For the purpose of this calculation, let us use an average value of 0.18.

$$F_{TP} = 89{,}689.6 \cdot 0.18 = 16{,}144.13 \text{ N}.$$

Let us evaluate the effectiveness of the proposed wind load solution for this situation, which can overcome the stabilizing moment and overturn the container. We use expressions (1)–(4). We get:

$$W_0 = \frac{1{,}614.4 \cdot 2.3}{0.75 \cdot 1.2 \cdot 12.2 \cdot 2.6^2} = 50.03 \text{ kg/m}^2 \approx 500 \text{ Pa}.$$

Discussion. Thus, a stop with a height of 106 mm, width of 78 mm, and thickness of 56 mm will formally withstand an impact of approximately 90 kN (the exact figure is 89.7 kN) before it begins to visibly deform. Therefore, 89.7 kN represents the maximum normal force that can be exerted between the friction surfaces.

Calculations have shown that a 40-foot container could overturn with a wind load of 120 Pa in the initial configuration. This corresponds to a wind speed of 11.9 m/s, which is typical for wind zone I, such as in Moscow and Minsk, for example. An empty container can also tip over under the influence of wind loads on a stationary platform.

The solution proposed by the author will allow the container to stand on a moving platform with a wind load of about 834 Pa. This corresponds to a wind speed of about 37 m/s, typical for the wind zone VII. Obviously, the indicator will be lower for wind and rain conditions, and calculations have confirmed this. The container will tip over at a load of approximately 500 Pa. This corresponds to a wind speed of about 29.5 m/s, which is typical for the wind zone IV, which includes, for example, Kazakhstan and the coast of the Caspian Sea. Currently, there is active automobile and railway traffic there. Cargo traffic is expected to increase in the future due to the implementation of the global multimodal transport project Silk Road.

[13] *Technical Conditions for the Placement and Fastening of Goods in Cars and Containers.* Ministry of Railways of the Russian Federation. May 27, 2003 No. CM-943. (In Russ.) URL: https://company.rzd.ru/ru/9353/page/105104?id=1341 (accessed: 09.11.2025).

The proposed approach to addressing the issue of wind stability for containers in this study is calculated with regard to fixed, stationary stops, which eliminate the possibility of any movement. The calculation is based on an example of a 40-foot container, although the principle can be applied to other form factors.

Conclusion. The proposed solution in real-world transportation conditions (including in windy and rainy weather) will increase the stability of containers on the platform from tipping over due to wind. The calculations primarily took into account data from the wind zones I–IV, as these are the areas where goods are actively moved. However, even in dry weather and in the area with the strongest winds — VII, upgrading the platform would still be beneficial.

The implementation of the proposed innovation will significantly reduce the likelihood of emergencies related to containers falling from railway platforms, and, accordingly, will increase transportation safety.

The solution is characterized by its technological simplicity and versatility. The container design remains unchanged, with only minor adjustments to individual elements of the platform.

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Conflict of Interest Statement: **the author declares no conflict of interest.**

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Конфликт интересов: автор заявляет об отсутствии конфликта интересов.

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 17.09.2025
Reviewed/ Поступила после рецензирования 14.10.2025
Accepted / Принята к публикации 22.10.2025

CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY
ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

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UDC 669.1:66.04
https://doi.org/10.23947/2541-9129-2025-9-4-331-340

Original Empirical Research

Study of the Processes of Electric Heating Using High-Frequency Currents in a Magnetic Field

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Abstract

Introduction. When heating with high-frequency currents (HFCs) at high speeds, more significant strengthening effects can be observed compared to using machine generators. Therefore, hardening at high frequencies is more efficient. However, the increase in the generator frequency results in a decrease in the depth of penetration of eddy currents and an increased unevenness of heating across the cross-section. The application of a constant external magnetic field during HFC hardening can increase the depth of eddy current penetration and create more uniform heating. Unfortunately, there is not enough information available on the effect of the external magnetic field on HFC heating processes and phase transformations in steel. Currently, there are no quantitative estimates for the impact of an external magnetic field on changes in the kinetics of electric heating and the penetration depth of eddy currents. In connection with the above, the aim of this paper is to investigate changes in the kinetics of high-frequency heating of iron-carbon alloys when an external constant magnetic field is applied and, and, based on this, to consider the potential for technological applications.

Materials and Methods. Theoretical assessment of the influence of an external magnetic field on the change in the kinetics of electric heating and the penetration depth of eddy currents is based on the general theory of induction heating kinetics. An experimental study of the influence of a magnetic field on the kinetics of high-frequency current heating was performed on samples of 45 steel, pearlitic gray (SCh30), and ferritic malleable cast iron (KCh30-6). The temperature distribution over the cross-section of ferromagnetic materials during induction heating with an external magnetic field has been studied using special samples of iron, 45 steel, and SCh30 gray pearlitic cast iron. Electric tempering processes have been investigated on samples of U8A steel using a vacuum tube generator (heating temperature — 450°C, heating rate — 750°C/s). Changes in austenite grain size after high-speed heating with external magnetization have been examined on samples of reduced-hardenability 55PP steel. To study the processes of thermal treatment in a magnetic field during experiments involving heating samples using high-frequency currents, a specially designed electromagnet was created to apply an external constant magnetic field.

Results. Theoretical curves were constructed for heating conditions with and without an external constant magnetic field. Experimental data on the effect of an external constant magnetic field on induction heating in the surface layer of various materials were summarized in kinetic diagrams. Evidence that the observed changes were due to increased depth of penetration of eddy currents came from experiments on cylindrical samples of 45 steel with different wall thicknesses. Kinetic curves were provided for estimating the temperature field (at 6 points at different depths) during high-frequency current heating with and without external magnetization. The paper presents experimental data on the micro-hardness distribution across the cross-section of a U8 steel sample after quenching, quenching and electric tempering, quenching and electric tempering with external magnetization, and quenching and bulk tempering. It also includes the results of the study of the austenite grain size of 55PP steel after high-speed heating with external magnetization and conventional (slow) deep heating.

Discussion. The application of a high-intensity external constant magnetic field during the first quasi-stationary process resulted in a decrease in the rate of induction heating of the ferromagnetic material and an increase in the depth of its uniform heating. However, above the Curie point, the effect of the magnetic field was negligible due to the low magnetic susceptibility of the material, and the heating rate remained unchanged as if there was no field present. In addition, due to the insignificant difference in the values of magnetic permeability below and above the Curie point during heating in the field, the thermal curve did not exhibit the characteristic inflection typical of kinetic curves observed during the transition of the surface layer to a paramagnetic state. Experiments with electric tempering have demonstrated that by applying an external field, it was possible to temper a material to the desired depth and it could be done on a single high-frequency current setup. The size of the austenite grains after high-speed heating with magnetization was reduced compared to conventional deep heating of steel with low hardenability, eliminating the issue of induction heating for low-hardenability steel.

Conclusion. The results of the study demonstrated that the use of an external magnetic field enabled the achievement of strengthening effects during heating at higher frequencies, thereby eliminating the drawbacks of such heating methods.

Keywords: steel, cast iron, magnetic field, high-frequency current, electric tempering, high-speed heating, hardening

Acknowledgements. The authors would like to thank the Editorial team of the journal for their valuable comments on the content of the article. They also express their gratitude to the staff of the Department of Materials Science and Technology of Metals at Don State Technical University, especially to Head of the Department, M.S. Egorov, Professor Yu.M. Dombrovsky, and Associate Professor S.A. Grishin, for their assistance in obtaining and interpreting the results.

For Citation. Pustovoit VN, Dolgachev YuV, Pivchenkov AS. Study of the Processes of Electric Heating Using High-Frequency Currents in a Magnetic Field. *Safety of Technogenic and Natural Systems*. 2025;9(4):331–340. https://doi.org/10.23947/2541-9129-2025-9-4-331-340

Оригинальное эмпирическое исследование

Исследование процессов электронагрева токами высокой частоты в магнитном поле

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Аннотация

Введение. При нагреве железоуглеродистых сплавов токами высокой частоты (ТВЧ) на высоких скоростях могут наблюдаться более значимые эффекты упрочнения, чем при применении машинных генераторов. Поэтому проводить закалку в таких условиях было бы целесообразнее, однако повышение частоты генератора влечет за собой уменьшение глубины проникновения вихревых токов и ведет к большей неравномерности прогрева по сечению. Наложение постоянного внешнего магнитного поля при закалке ТВЧ может приводить к увеличению глубины проникновения вихревых токов и более равномерному прогреву. Но в научной литературе еще недостаточно сведений о влиянии внешнего магнитного поля на процессы нагрева ТВЧ, а также на фазовые превращения в сталях. В настоящий момент количественных оценок влияния внешнего магнитного поля на изменение кинетики электронагрева и глубины проникновения вихревых токов не имеется. В связи с вышесказанным цель авторов настоящей статьи — изучить изменения в кинетике нагрева ТВЧ железоуглеродистых сплавов при наложении внешнего постоянного магнитного поля и на этой основе рассмотреть возможности применения данной технологии.

Материалы и методы. Теоретическая оценка влияния внешнего магнитного поля на изменения кинетики электронагрева и глубины проникновения вихревых токов дана на основе общей теории кинетики индукционного нагрева. Экспериментальное изучение влияния магнитного поля на кинетику нагрева ТВЧ проводилось на образцах из стали 45, перлитного серого (СЧ30) и ферритного ковкого чугуна (КЧ30-6). Исследование распределения температуры по сечению ферромагнитного материала при индукционном нагреве во внешнем магнитном поле осуществлялось на специальных образцах из технического железа, стали 45 и серого перлитного чугуна СЧ30. Изучение процессов электроотпуска проходило на образцах из стали У8А с использованием лампового генератора (температура нагрева — 450 °C, скорость нагрева — 750 °C/с). Исследовались изменения балла аустенитного зерна после скоростного нагрева с внешним подмагничиванием на образцах стали с пониженной прокаливаемостью 55ПП. Для исследования процессов термической обработки в магнитном поле при проведении экспериментов с нагревом образцов токами высокой частоты создан электромагнит специальной конструкции для наложения внешнего постоянного магнитного поля.

Результаты исследования. Построены теоретические кривые для условий нагрева без поля и с наложением внешнего постоянного магнитного поля. Экспериментальные данные о влиянии внешнего постоянного магнитного поля на индукционный нагрев в поверхностном слое различных материалов были сведены в кинетические диаграммы. Доказательством того, что наблюдаемые изменения связаны именно с увеличением глубины проникновения вихревых токов, являются опытные данные, полученные на цилиндрических образцах из стали 45 с разной толщиной стенки. Приведены кинетические кривые оценки температурного поля (по шести точкам на разной глубине) в процессе нагрева ТВЧ с внешним подмагничиванием и без него. Получены экспериментальные данные, показывающие распределение микротвердости по сечению образца из стали У8 после закалки, закалки и электроотпуска, закалки и электроотпуска с внешним подмагничиванием и закалки и объемного отпуска, а также результаты исследования балла аустенитного зерна стали 55ПП после скоростного нагрева с внешним подмагничиванием и обычного (медленного) глубинного нагрева.

Обсуждение. Наложение внешнего постоянного магнитного поля высокой напряженности на этапе первого квазистационарного процесса приводит к снижению скорости индукционного нагрева ферромагнитного материала и увеличению глубины его равномерного прогрева. Выше точки Кюри влияние магнитного поля не сказывается из-за малой магнитной восприимчивости материала, поэтому скорость нагрева остается такой же, какая была бы в этом температурном интервале без поля. Кроме того, ввиду незначительной разницы значений магнитной проницаемости ниже и выше точки Кюри при нагреве в поле термическая кривая не имеет столь заметного перегиба, характерного для кинетических кривых при переходе поверхностного слоя в парамагнитное состояние. Эксперименты с электроотпуском доказали, что с наложением внешнего поля удается отпустить материал на необходимую глубину и появляется возможность его проведения на одной установке ТВЧ. Размер зерен аустенита после скоростного нагрева с подмагничиванием уменьшается, по сравнению с обычным глубинным нагревом стали с пониженной прокаливаемостью, что устраняет проблему индукционного нагрева сталей с пониженной прокаливаемостью.

Заключение. Результаты исследования показали, что наложение внешнего магнитного поля позволяет реализовать эффекты упрочнения при нагреве с более высокими частотами и устранить недостатки такого нагрева.

Ключевые слова: сталь, чугун, магнитное поле, ТВЧ, электроотпуск, скоростной нагрев, закалка

Благодарности. Авторы благодарят редакцию журнала за ценные замечания по содержанию статьи, сотрудников кафедры «Материаловедение и технологии металлов» ДГТУ: заведующего кафедрой М.С. Егорова, профессора Ю.М. Домбровского и доцента С.А. Гришина, за помощь в получении и обсуждении результатов.

Для цитирования. Пустовойт В.Н., Долгачев Ю.В. Исследование процессов электронагрева ТВЧ в магнитном поле. *Безопасность техногенных и природных систем.* 2025;9(4):331–340. https://doi.org/10.23947/2541-9129-2025-9-4-331-340

Introduction. The basic principles of the heat treatment technology of steel in a magnetic field (HTMF) are described in the monograph [1]. This technology allows obtaining structural states and properties that are not achievable under normal conditions. One of the advantages of HTMF is its efficiency in the piecewise processing of products [2], for example, by using high-frequency currents (HFCs) as a heating source [3].

Due to the fact that more noticeable hardening effects can be observed when heating with HFCs at high speeds compared to using machine generators, it would be beneficial to harden at higher frequencies. However, the increase in the frequency of the generator results in a decrease in the depth of penetration of eddy currents and an increase in unevenness of heating across the cross-section. The theoretical and practical aspects of HFC heating of metal products have been well presented in [4, 5]. Meanwhile, there is a lack of information about changes that occur during high-speed induction heating with an external permanent magnetic field, especially in the context of ongoing phase transformations in steels.

Qualitative data have been experimentally obtained [4] that the application of a constant external magnetic field during HFC quenching can lead to an increase in the penetration depth of eddy currents, which, in turn, increases the uniformity of heating at the stage of the first quasi-stationary electric heating process [6]. From a technological point of view, the most appropriate application of this phenomenon is for high-speed electric tempering [7, 8], since there is a problem of insufficient HFC heating depth of the ferromagnetic hardened layer, which makes it necessary to use another generator operating at a lower frequency for heating for tempering. Currently, there are no quantitative estimates of the effect of an external magnetic field on changes in the kinetics of electric heating and the depth of penetration of eddy currents.

In connection with the above, the authors of this research aim to study changes in the kinetics of HFC heating of iron-carbon alloys under the influence of an external permanent magnetic field, and based on the results obtained, consider the possibilities for their technological application.

Materials and Methods. Theoretical assessment of the influence of an external magnetic field on changes in the kinetics of electric heating and the depth of penetration of eddy currents was based on the general theory of induction heating kinetics [9, 10]. The equation of thermal conductivity in the case of heating steel to the temperature of magnetic transformations in the surface layer was used with the introduction of dimensionless quantities of time (Fourier criterion $F_0=\frac{\alpha\cdot\tau}{R^2}$), temperature (Kirpichev criterion $K_i=\frac{PR}{\lambda[T(x,\tau)-T_0]}$), without taking into account the transient process of power redistribution (P) and had the form:

$$K_i^{-1} = F_0 + \frac{1}{2}\left(\frac{x}{R}\right)^2 - \frac{1}{6} + \frac{1}{4k^2} - \frac{ch2k\frac{x}{R}}{2ksh2k}, \tag{1}$$

where R — cylindrical sample radius.

$$k = \frac{R}{\delta} = R\sqrt{\frac{\mu_0 \mu f}{2\rho}},$$

where δ — eddy currents penetration depth; μ — relative magnetic permeability of the material; μ_0 — magnetic permeability of air; f — current frequency; ρ — electrical resistivity of the material; λ — thermal conductivity coefficient; α — temperature conductivity coefficient; $T(x, \tau)$ — temperature as a function of time (τ) and distance from surface (x); T_0 — initial temperature.

The experimental study of the effect of the magnetic field on the kinetics of HFC heating was conducted on samples of 45 steel, pearlitic gray (SCh30) and ferritic ductile iron (KCh30-6). Thermocouple readings from the surface layer were recorded using an analog-to-digital converter (ADC) L-CARD E14—440 (bit depth – 14 bits, conversion frequency — up to 400 kHz). Solid cylindrical samples of ∅ 0.8 mm made of various materials were used, as well as hollow samples of 45 steel with wall thicknesses of 1 and 2 mm.

The temperature distribution over the cross-section of a ferromagnetic material during induction heating in an external magnetic field was studied on special samples (Fig. 1) made of technical iron, 45 steel and gray pearlitic cast iron SCh30. As can be seen in Figure 1, temperature control was carried out on a sample at six points located at distances from the edge of 1, 3, 5, 7, 9, and 11 mm. In each of the ∅ 0.6 mm holes, a ∅ 0.2 mm chromel-alumel thermocouple was installed, connected to one of the 16 differential ADC L-CARD E14–440 input channels, which transmitted data to a PC with simultaneous recording of all channels in the LGraph2 software.

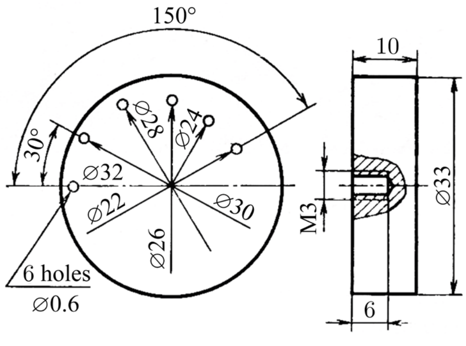


Fig. 1. Design of samples for temperature field assessment

The study of electric tempering processes was conducted on U8A steel samples using a lamp generator. Electric tempering was performed at 450°C, the heating rate was 750°C/s. The usual oven tempering process lasted for one hour. Microhardness was measured on a PMT-3 device at a load of 100 g.

Changes in the austenitic grain score after high-speed heating with external magnetization were studied on 55PP steel samples of ∅ 18 mm. Heating was carried out to a temperature of 950°C using machine (heating rate in the field of phase transformations — 8°C/s) and lamp (90°C/s) generators. The boundaries of the austenitic grain were studied by chemical etching in a one percent picric acid solution heated to 60°C with the addition of detergent. Histograms were constructed based on the measurement results of the largest grains d_j visible in the plane of the slot in 20 fields of view at magnification × 1000. The average true grain diameters were calculated using the formula:

$$\bar{D} = \frac{\pi}{2}\frac{\sum n_j}{\sum_{j=1}^{k}\frac{n_j}{d_j}}, \tag{2}$$

where n_j — number of measured sections in the j[th] dimension group; k — number of groups.

The task of studying the processes of high-speed HTMF in relation to high-speed HFC heating had a number of technical difficulties associated with the imposition of an external permanent magnetic field around the inductor, and therefore a special electromagnet was designed with a number of features. The axes of the cores were as close as possible to the panel of the high-frequency generator, which determined the use of a core and coils of rectangular cross-section. The magnetic circuit of the electromagnet had a double reverse yoke. Water-cooled conical pole tips were used. The core cross-section relative to the yoke was increased by 130%, which reduced its magnetic resistance and minimized the dissipative flow. The conical shape of the tips made it possible to increase the field strength in the working air gap of 50 mm to 600 kA/m.

Results. Based on equation (1), theoretical curves were constructed for heating conditions without a field and with an external permanent magnetic field (Fig. 2). The calculation was performed for a cylindrical sample with a diameter of 8 mm made of steel with a ferritic structure: $\rho = 36 \cdot 10^{-8}$ Ohm·m; $\mu = 1000$ — at a temperature of 20°C; $\mu = 1$ — above the Curie point; $\mu = 7$ at a temperature of 20°C in a magnetic field with a strength of 160 kA/m (taking into account the external demagnetizing factor of the sample); $f = 440$ kHz; assuming that the Curie point corresponded to dimensionless temperature $K_i = 1.13$. From the appearance of the curves, it was possible to judge about the greater uniformity of the heating process in the presence of external magnetization.

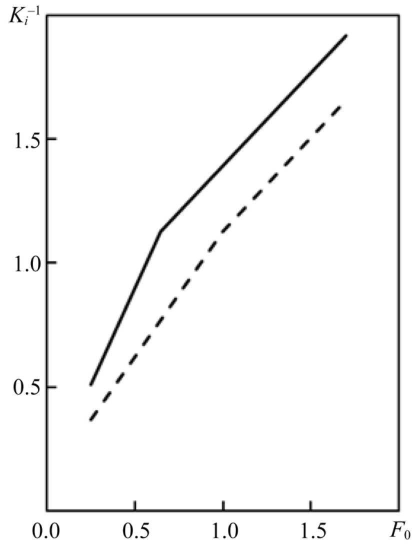


Fig. 2. Theoretical curves of high-speed heating without an external magnetic field (solid line) and with it (dashed line)

Experimental data on the effect of an external permanent magnetic field on induction heating in the surface layer of various materials were summarized in kinetic diagrams and shown in Figure 3.

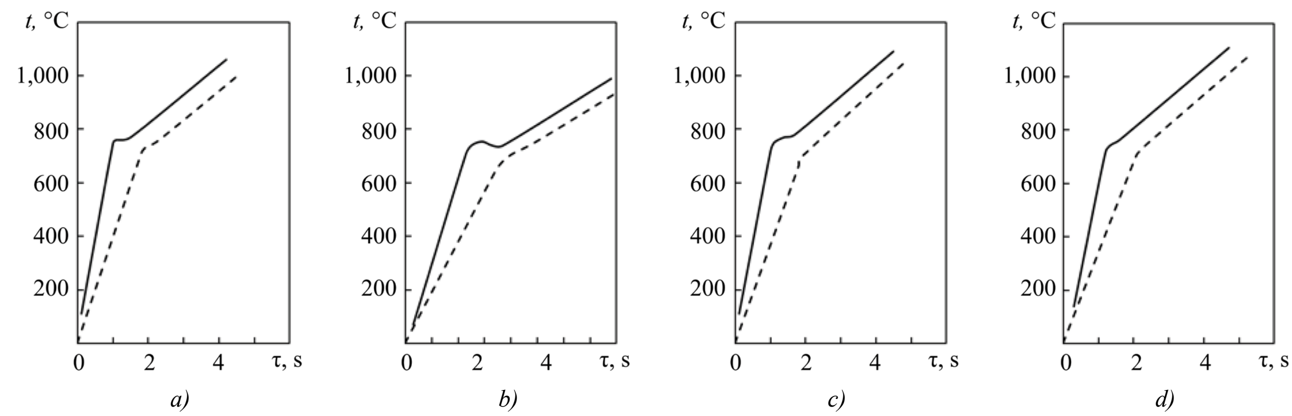


Fig. 3. Thermal curves of induction heating without a magnetic field (solid line) and with a magnetic field (dashed line) on samples made of: *a, b* — 45 steel; *c* — KCh30-6; *d* — SCh30

The proof that the observed changes were associated precisely with an increase in the penetration depth of eddy currents was experimental data obtained on cylindrical samples made of 45 steel having different wall thicknesses (1 and 2 mm and a solid cylinder ∅ 8 mm). Figure 4 provides their heating curves.

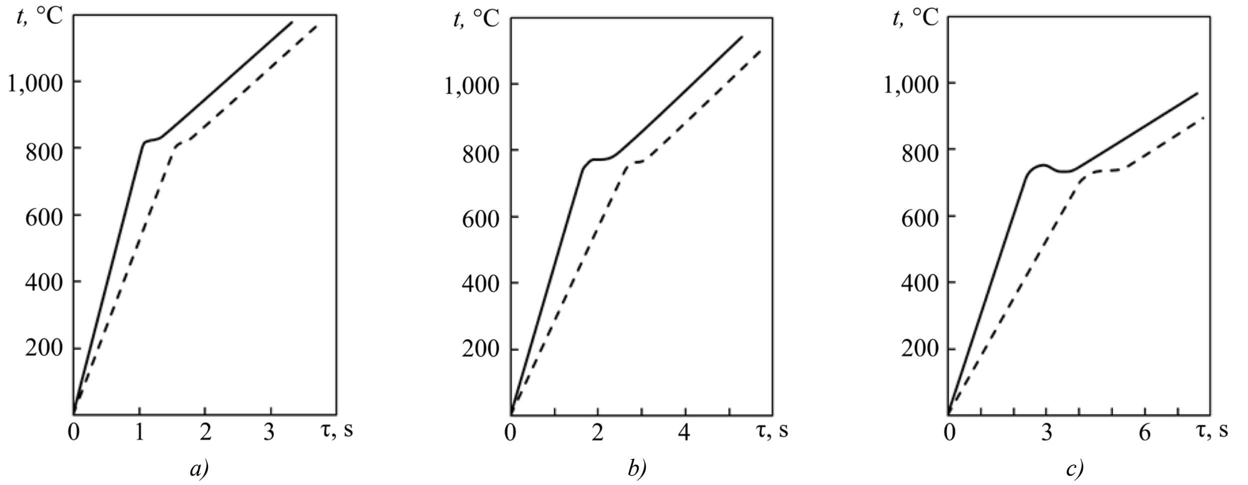


Fig. 4. Thermal curves of samples without an external field (solid line) and in a magnetic field (dashed line) with a wall thickness of: *a* — 1 mm; *b* — 2 mm; *c* — solid cylinder of ∅ 8 mm

The temperature field assessment results (at six points at different depths) during HFC heating with and without external magnetization are shown in Figures 5 and 6. Figure 5 shows kinetic curves for perlite gray cast iron SCh30, and Figure 6 — for 45 steel.

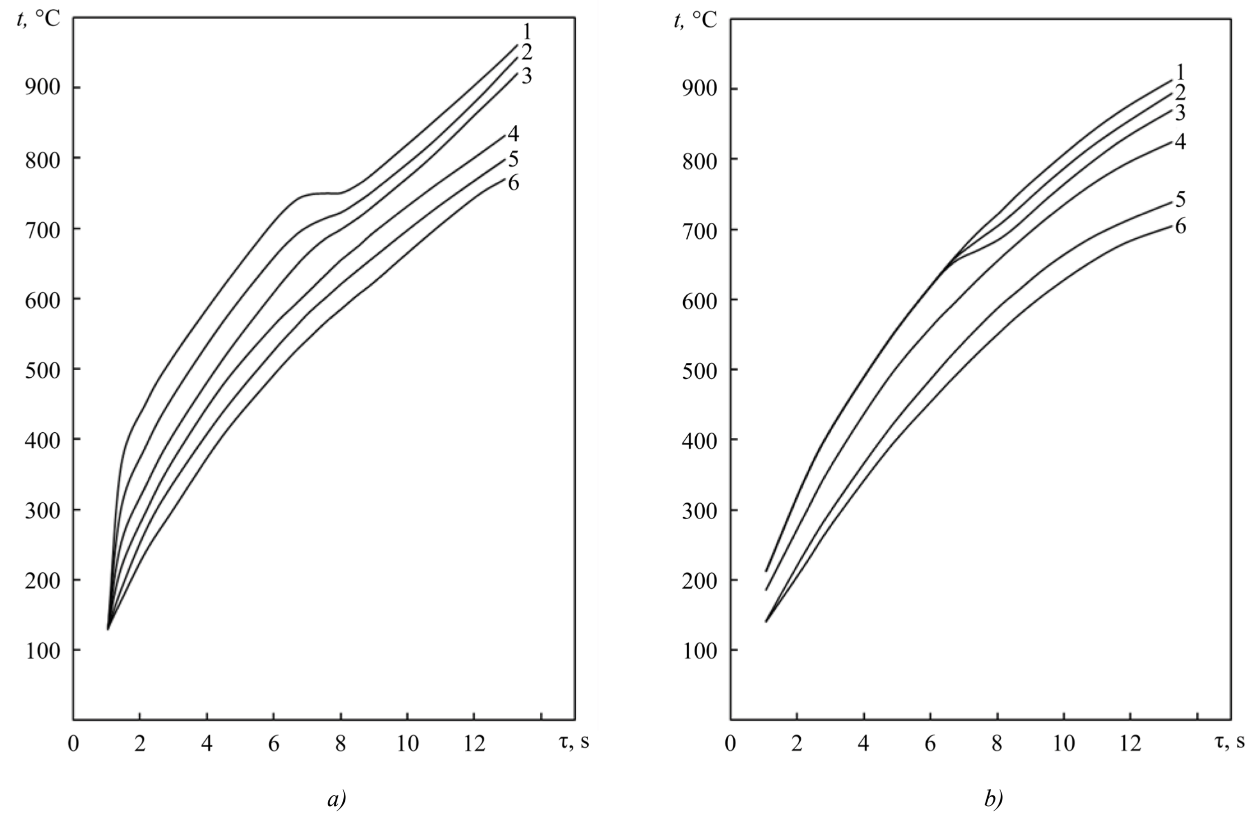


Fig. 5. Heating curves of SCh30 (*a* — without a field; *b* — in a magnetic field) at a distance from the surface: 1 — 1 mm; 2 — 3 mm; 3 — 5 mm; 4 — 7 mm; 5 — 9 mm; and 6 — 11 mm

When heated in a magnetic field, the penetration depth of eddy currents did not depend on the structure of the material and turned out to be ~10 (for pearlite) and 17 (for ferritic) times more than when heated without a field. This indicated the possibility to implement in practice the quenching mode with electric tempering when heated from a single generator, since without magnetization it was impossible to warm up the entire hardened zone. Figure 7 shows experimental data showing the distribution of microhardness over the cross section of a U8 steel sample after quenching, quenching and electric tempering, quenching and electric tempering with external magnetization, quenching and volumetric tempering.

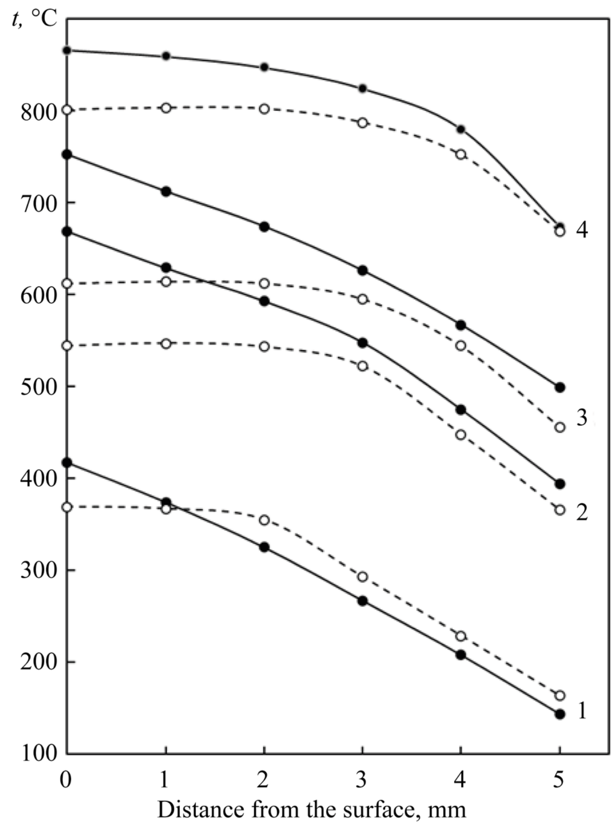


Fig. 6. Temperature distribution at different distances from the surface under normal heating (solid line) and with external magnetization (dashed line) at time points
1 — 3 s; 2 — 6 s; 3 — 7 s; 4 — 11.5 s

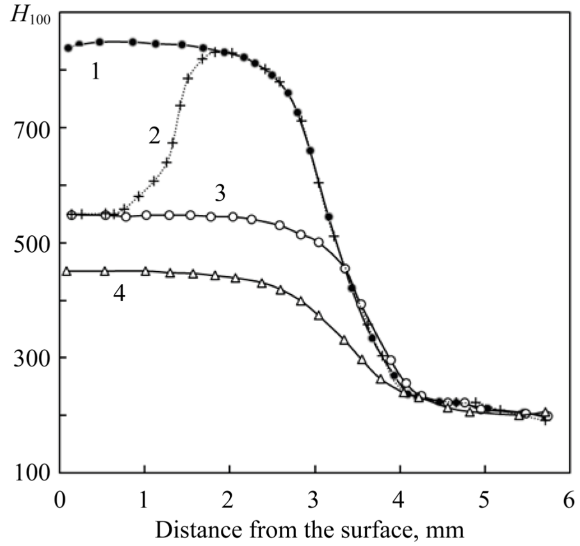
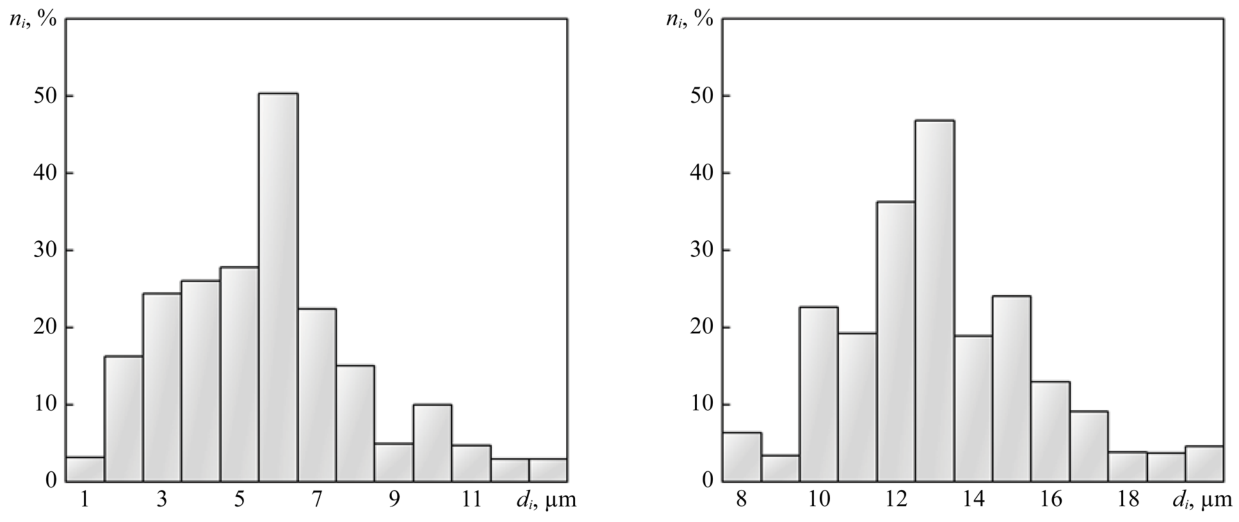


Fig. 7. Microhardness distribution over the cross section after:
1 — HFC quenching; 2 — HFC quenching and electric tempering without magnetization; 3 — HFC quenching and electric tempering with magnetization; 4 — HFC quenching and volumetric tempering in the furnace

Carbon steels with reduced through-hardening capability can be subjected to HFC surface quenching [11, 12], but they have low heating rate in the region of phase transformations, which leads to a large austenite grain size (and, consequently, reduced mechanical properties in the surface layer). It turns out that the characteristic features of the fine structure of austenite, which are caused by induction heating, are offset by grain growth — high structural strength is lost. Figure 8 shows the results of a study of the austenitic grain score of 55PP steel after high-speed heating with external magnetization and conventional (slow) deep heating.



a) *b)*

Fig. 8. Size distribution of γ-phase grains with HFC heating: *a* — with an external magnetic field; *б* — without a field

Discussion. Changes in the kinetics of heating by high-frequency currents were observed when an external magnetic field was applied, the strength of which was sufficient for magnetic saturation. This effect led to a change in the magnetic properties of the processed steel, specifically, to a decrease in its magnetic permeability [13]. This behavior was natural for magnetization at the paraprocess stage; it, in turn, caused a decrease in *k* coefficient, which was inversely proportional to the depth of eddy current penetration and the specific thermal power. This can be compared to the increase in the current penetration depth into a metal during its transition from a ferromagnetic to a paramagnetic state. However, there is a physical difference in the nature of the paramagnetic state of a metal and the state of a ferromagnetic magnetized in the paraprocess region. They are similar only in terms of their small relative magnetic permeabilities. Thus, the presence of an external magnetic field at the stage of the first quasi-stationary process lead to a decrease in the rate of induction heating of the ferromagnetic material and an increase in the depth of its uniform heating.

The magnetic susceptibility drops sharply above the Curie point, so the external magnetic field does not affect the heating rate at these temperatures. At the same time, due to the small difference in magnetic permeability below and above the Curie point in the presence of an external field, there is no change in the heating curve that would indicate a transition of the surface layer to a paramagnetic state. In fields with higher intensities, the heating curve turns into a straight line (with the tangent of the angle of inclination to the time axis corresponding to the heating rate above the Curie point). A comparison of the dependencies in Figures 2 and 3 shows the similarity of the general patterns and confirms the validity of the earlier conclusions.

Regardless of the material used, in all the cases shown in Figure 3, the following patterns are observed: at the initial stage of heating, if an external magnetic field is applied, the heating rate decreases up to the Curie point. In the presence of an external magnetic field, the difference in the heating rate near the critical point in the diagram is less abrupt. At the end of the phase transformation, the heating rates with and without a field are practically compared.

As can be seen in Figure 4, the heating curves for conventional HFC heating and with the application of an external field converge as the wall thickness of the sample decreases, until they almost completely coincide for a thickness of 1 mm. This phenomenon can be explained by the fact that the wall thickness approaches the penetration depth of eddy currents in the absence of external magnetization.

Figure 5 clearly demonstrates that the influence of a magnetic field significantly reduces the temperature variation near the surface during the initial stages of heating. Without the use of a magnetic field, the variation is approximately 250℃ over the entire depth under study and about 50℃ from the surface to a point at a distance of 1 mm. However, after reaching the Curie point, the patterns of temperature distribution become similar, although there is a more significant decrease in surface temperature for the sample processed without applying an external field.

As can be seen in Figure 6, a similar pattern is observed in the 45 steel sample, with a greater uniformity of heating across the cross-section when an external magnetic field is applied up to the Curie point. When the surface layer of the sample heated in the field reaches the Curie temperature, the depth of current penetration into the material changes slightly (curves 3 and 4), since there is no sharp decrease in magnetic permeability. And in a sample that was heated without a field, after the transition to the paramagnetic state, the induced power is redistributed and heat is removed from the surface to the core, which causes a decrease in the temperature difference across the cross section. In this case (curve 4), the temperature distribution patterns turn out to be the same for both heating modes, but with greater uniformity of heating in the case of magnetization.

As shown by experiments with electric discharge (Fig. 7), it is not possible to harden the material to the desired depth without applying an external field. The hardening occurs at a maximum depth of 1 mm, with a hardened layer that is three times deeper. At the same time, electric discharge with magnetization allows for a greater depth of hardening, which can be achieved using the same setup. Additionally, the hardness achieved through electric tempering with magnetization is greater than that achieved through conventional furnace tempering.

Histograms of the distribution of austenite grain sizes after high-speed magnetization and conventional deep heating of steel with reduced hardenability show that, in the first case, the average grain diameter is 12.96 μm smaller (Fig. 8). Therefore, problems with austenite grain growth that occur during induction heating of steels with reduced hardenability can be avoided by using external magnetization.

Conclusion. The results of the study show that the application of an external magnetic field at temperatures below the Curie point increases the penetration depth of eddy currents, which, in turn, contributes to a more uniform heating of the material. This allows for the realization of hardening effects when heating at higher frequencies, eliminating the disadvantages of this type of heating that occur without magnetization. The observed changes in the presence of magnetization during heating of HFC are explained by a decrease in the magnetic permeability of the processed material, which is directly proportional to the depth of penetration of eddy currents. When the Curie point is reached, this effect levels off. It has been demonstrated that with the application of an external magnetic field, it becomes technologically possible to conduct high-speed electrical tempering on a single generator to achieve higher hardness values compared to conventional tempering. It is also recommended to use high-speed magnetization for HFC surface hardening of steels with reduced hardenability, as it eliminates the problem of coarse austenitic grains that can occur during conventional deep heating.

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AS Pivchenkov: calculations, text preparation, correction of conclusions.

Conflict of Interest Statement: **the authors do not have any conflict of interest.**

All authors have read and approved the final version of manuscript.

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Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 31.08.2025
Reviewed/ Поступила после рецензирования 19.09.2025
Accepted / Принята к публикации 29.09.2025